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THE JUNE 19, 2007 DELAWARE COUNTY FLASH FLOOD: A METEOROLOGICAL AND HYDROLOGICAL ANALYSIS

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Abstract

A meteorological and hydrological analysis of an extreme flash flood event in central New York is presented. The meteorological analysis indicated that the environment associated with this event evolved to include many characteristics previously found with convective flash floods. Important elements included a moist atmosphere favorable for high precipitation efficiency, a strong low-level jet associated with significant moisture flux convergence over the flash flood zone, weak mid-level wind shear, and a thermal structure characterized by a tall, skinny convective available potential energy profile.

The hydrological analysis indicated that extreme flash flooding occurred in small, steep, heavily forested stream basins with 3-hour rainfall that doubled the 24-hour 100 year rainfall extreme for the area. Minor flooding began when estimated rainfall totals exceeded 2.00 inches, while major flooding began when estimated rainfall totals exceeded 4.00 inches. Peak rainfall during this event eventually exceeded 10 inches. An estimation of the flow along one of the streams involved in the flood was in excess of a 500-year return flow, consistent with extreme rainfall rates. Brief, extremely rapid rates of rise on area streams were likely caused by debris pileups giving way behind highway bridges.

1. INTRODUCTION

This paper presents an extreme flash flood event that affected the upper Delaware River watershed of Delaware County, New York on June 19-20, 2007. The setting of the event was several headwater basins that drain into either the Beaver Kill creek or Pepacton Reservoir. Eyewitness reports of walls of water and scenes of houses being washed away and bridges overtopped characterized the event.

Data sources for this study are provided in section 2. A meteorological analysis of the event, including an examination of the synoptic and meso-scale environment, is given in section 3. Section 4 contains a hydrological analysis of the event, including an examination of basin response to extreme rainfall, the initiation of flash flooding in headwater basins, and impacts downstream along mainstem rivers. Finally, section 5 contains a summary and conclusion.

2. DATA

Meteorological data including WSR-88D radar reflectivity and precipitation products were obtained from National Weather Service Advanced Weather Interactive Processing System (AWIPS) workstations. Rain gage and bucket survey rainfall was obtained from local residents. Streamflow and reservoir elevation records were obtained from the US Geological Survey (USGS), New York City Department of Environmental Protection (NYC DEP), and the Mid Atlantic River Forecast Center (MARFC). Eyewitness reports and slope-conveyance indirect discharge estimation were incorporated into the work.

3. METEOROLOGICAL ANALYSIS

a. Previous Research on Convective Flash Flood Environments

Junker et al. (1999) examined several heavy convective rain producing systems over the Midwest U.S. in 1993, and found that these systems typically occurred in areas where a veering, southerly to southwesterly low-level flow resulted in a significant flux of moist, unstable air poleward across a low-level boundary aligned parallel to the mean flow. The width of the axis of strong moisture flux correlated positively with the magnitude of the event. Upward vertical motion was often enhanced over the flood area by divergence in the upper-troposphere associated with the right entrance region of an upper-level jet-streak, however the heaviest rain typically fell south of the maxima of upper-level divergence. These features match well with characteristics of convective systems identified as “frontal” or “meso-high” by Maddox et al. (1979). Similar features were also identified by Moore et al. (2003) in a study on heavy rain producing elevated convective systems.

Several previous studies have also indicated that flash flood producing convective systems are often characterized by slow system movement (Senesi et al. 1996, Petersen et al. 1999). Corfidi et al. (1996) examined 103 mesoscale convective systems and determined that system movement can be approximated by the vector addition of the mean wind and the opposite of the low-level jet. This implies that a low-level jet that has the same magnitude and direction as the mean wind could lead to very slow system movement. Another factor that can lead to slow system movement is anchoring of convection by terrain (Maddox et al. 1978, Petersen et al., 1999, Nicosia et al. 1999).

Other studies have emphasized that flash flooding frequently occurs in environments that are favorable for efficient rainfall processes. For example, the presence of high environmental relative humidity decreases the potential for evaporation and dry-air entrainment within a convective storm (Doswell et al. 1996). Market et al. (2003) found a significant correlation between precipitation efficiency and the relative humidity between the surface and the lifting condensation level.

Another factor that may be related to an environment's potential for producing convective heavy rain is the shape of the vertical profile of convective available potential energy (CAPE; (Davis 2001)). Tall, skinny CAPE profiles may be more favorable for heavy rain than shorter, fat CAPE profiles, since storms that form in relatively skinny CAPE environments have relatively deep, but weak, updrafts, which result in ample precipitation production, but less precipitation being propelled into the upper part of the storm, where it may be carried away by strong winds aloft.

Jessup and DeGaetano (2008) confirmed that many of the aforementioned factors shown to be favorable for heavy convective rainfall in other areas of the U.S. are also favorable for central New York and northeast Pennsylvania. In addition, they found high correlations between the occurrence of flash flooding and large values of antecedent precipitation. Local operational experience with flash flood-producing storms in central New York and northeast Pennsylvania has also generally confirmed the findings from the aforementioned studies. Several unpublished local case studies have shown that common features associated with many significant flash floods in this area include a rapidly veering wind profile in the lowest 1 to 3 km of the troposphere, capped by a low-level southerly or southwesterly jet, then a deep mid-tropospheric layer of small shear above the jet. The rapidly veering profile in the lowest 1 to 3 km is indicative of lower-tropospheric warm advection, and the south-southwesterly low-level jet has frequently proven to be an effective transporter of low-level moisture northward, from the Gulf coast region. Finally, the pattern of a low-level jet, capped by a weakly sheared middle troposphere is ideal for producing small system movement, based on the conceptual model introduced by Corfidi et al. (1996). This pattern becomes particularly favorable for heavy convective precipitation when the environment includes favorable conditions for efficient rain production.

b. The 19 June 2007 Event

The large-scale environment over the northeast U.S. on 19 June 2007 was characterized by ridging in the middle to upper troposphere, with an eastward moving trough to the west over the Great Lakes region (Fig. 1). The lower-troposphere was characterized by southwesterly flow and a southwest-northeast thermal ridge over the Appalachian Mountains (Fig. 2). A weak surface trough was forecast to move east across Pennsylvania through 00 UTC on 20 June, with the primary cold front still located well to the west over Lake Erie. The southwesterly low-level flow resulted in increasing deep-layer moisture across the mid-Atlantic region, with a broad axis of precipitable water values over Pennsylvania and southern New York increasing to over 4.5 cm (1.8 inches) by 00 UTC 20 June (Figs. 3a-b; approximately 175 percent of normal for mid-June). The axis of high precipitable water was associated with the development of a broad zone of moisture flux convergence across Pennsylvania and New York (Figs. 3c-d).

Figure 4a shows the Rapid Update Cycle (RUC, Benjamin et al. (2002)) model forecast evolution of the wind speed at Avoca (AVP), in northeast Pennsylvania (about 70 km southwest of the flash flood location) during the late afternoon and evening on 19 June. Wind speeds were forecast to increase through a deep layer between 18 UTC and 00 UTC, as the trough over the Great Lakes moved east toward the area, with a 30 kt low-level jet forecast to develop by 00 UTC June 20.

In order to examine the evolution of the convective environment prior to and during the development of the flash flood producing convection, two RUC model soundings are shown in Figs. 4b and 4c. The first sounding, from the 21 UTC June 19 RUC model valid at AVP at 22 UTC, was chosen to represent the environment prior to the development of convective rain. The mean relative humidity of the sounding was 63 percent, the precipitable water value was 3.78 cm (1.47 inches) and the lifted condensation level was at 1.2 km (4000 ft). A moderately fat CAPE profile was forecast (indicated by a normalized CAPE value of 0.18 ms^{-2}). Also shown is a veering lower tropospheric wind profile, capped by a 20 kt southwesterly flow at 2 km, and a weakly sheared layer from 3 to 6 km.

The second sounding, from the 01 UTC June 20 RUC model valid at AVP at 02 UTC, was chosen to represent the environment during the time that convection was developing across the area. In comparison to the first sounding, more moisture was forecast (indicated by a precipitable water value of 4.56 cm (1.78 inches), a mean relative humidity of 85 percent and a lifted condensation level below 0.5 km (1500 ft)). Nearby real-time surface observations also indicated high lower-tropospheric moisture and a low lifted condensation level. For example, the 00 UTC observation at Monticello, about 30 km south of the flood area, indicated a surface dew point of 20° C, and a dew point depression of 6° C, implying a lifted condensation level of about 0.8 km (approximately 2500 ft). A tall, skinny CAPE profile is shown (indicated by a normalized CAPE value of 0.11 ms^{-2}). A strongly veering low-level wind profile is also indicated, culminating in a speed maxima of 25 to 30 kts just below 2 km, with weak speed and directional wind shear above 3 km.

In summary, the RUC model forecast soundings shown in Fig. 4 indicate a rapidly changing environment as convection was developing over the area of interest. Specifically, conditions were forecast to become increasingly favorable for organized convection and heavy rain, as moisture increased rapidly while the magnitude of the low-level jet increased, and shear remained small in the mid-troposphere. The rapid evolution of the characteristics of the model forecast soundings in this case illustrates the difficulty that is sometimes associated with choosing appropriate proximity soundings for forecasting convection.

The rapid evolution of the convective environment in this case also helps to explain how radar rainfall estimates (described in Section 4a) during the event turned out to be an *underestimate* of actual rainfall, when operational forecasters had anticipated the opposite, given hail reports received earlier in the evening (a report of hail was received at 2051Z in the same general location where the flash flooding occurred later that evening; from STORM DATA), and the knowledge that radar estimates of precipitation become erroneously large when the radar beam encounters hailstones (Austin 1987). Based on the soundings shown in this section, hail producing storms were indeed favored at the onset of the event, given the large amounts of CAPE in the “hail growth zone” of -10°C to -30°C (Knight and Knight 2001, Fig. 4b). This coincided with the time of the aforementioned hail report. As the event continued, the environment transitioned to the one depicted in Fig. 4c, characterized by deep moisture, skinny CAPE and substantially increased warm cloud depths. This warmer and moister environment would have favored warm-rain processes (i.e. collision coalescence; Wallace and Hobbs 1977), rather than hail production, as well as increased precipitation efficiencies (Davis 2001). The KBGM WSR-88D, using a convective Z-R relationship ($Z=300R^{1.4}$), would be expected to underestimate rainfall rates and totals when warm-rain processes dominate, something more conducive of a tropical environment (Ulbrich and Lee

1999). Therefore, not only did the rapidly changing environment challenge forecasters to anticipate the most pressing severe weather threats, but it also greatly impacted how the KBGM radar was "seeing" the event, adding another level of complexity to the warning process.

The evolution of convection in this case from a radar perspective is shown in Figs. 5-7. Figures 5a-d show reflectivity data from the Binghamton National Weather Service WSR-88D Doppler radar (KBGM) from 1830 UTC through 2030 UTC 19 June 2007. The area of interest at this time is over central Pennsylvania near Williamsport, where isolated storms appeared to re-generate across the same location for a couple of hours. Figures 6a-d show a similar evolution for storms over central New York, just east of Binghamton, later in the afternoon. In this case, storms appeared to develop along an outflow boundary that moved southeast across the area. The boundary was progressive, and the storms appeared to dissipate once the boundary moved off to the south. (Note that the storms over central Pennsylvania were too distant from the radar for any associated low-level boundaries to be detected).

Thunderstorms in central New York and northeast Pennsylvania through 2200 UTC on 19 June were mainly isolated in nature, and were associated with scattered occurrences of wind damage and large hail, but no significant flooding. After 2200 UTC, there was a pronounced change in this tendency, as storms began to show a trend toward mergers and increased organization. It can be hypothesized that this change was related to the increasingly strong wind field and vertical wind shear associated with the approaching mid-to-upper level trough (Fig. 4a). Figures 7a-d show that new storms began to develop just ahead of the southward moving outflow boundary across southern Delaware County, New York around 2200 UTC. Once the boundary caught up to these storms, additional storms developed and merged into a large, quasi-stationary cluster around 2300 UTC. Meanwhile, a line of storms originating over northeast Pennsylvania merged into the cluster from the west around 00 UTC on 20 June, with heavy rain continuing across the flash flood area until around 0100 UTC. It is unclear whether or not the low-level boundary continued to progress southward during this time, as its increasing distance from the radar may have made it undetectable after 2300 UTC.

In contrast to the stationary movement of storms over the flash flood area, the northern part of the convective system that developed over eastern and central New York during the early evening on the 19th was characterized by rapid eastward propagation (Figs. 7c-f). Corfidi (2003) noted that systems characterized by rapid down-shear propagation in one part of the system and stationary or up-shear movement in another part of the system most typically occur in environments featuring largely unidirectional mean flow and minimal cloud layer shear, which appears to be a good description of the environment in this case, based on the soundings shown in Fig. 4b and Fig. 4c. He noted that strong winds often occur in the down-shear propagating portion of these systems, while heavy rain occurs in the stationary or up-shear propagating portion.

In summary, the atmosphere on this day appeared to transition from an environment supportive of isolated strong wind and hail producing storms, to an environment that became more favorable for storm mergers, organization and heavy rain. Isolated stationary and back-building storms occurred throughout the day, but it was not until the environment changed to being more supportive of organized convection that stationary and back-building storms resulted in a major flash flood. Finally, it should be noted that terrain likely played a role in determining where all of the back-building storms occurred on this day. Figure 8a shows a plot of radar estimated precipitation ending at 00 UTC on the 20th. Figure 8b shows a map of the topography of the area, with the locations of the back-building storms annotated. In all 3 instances, back-building storms appeared to develop on the southwest slope of significant topographical features, in locations that were favorable for the moist southwesterly flow on this day to attain a significant upslope component.

4. HYDROLOGICAL ANALYSIS

a. Radar-indicated Basin Average Rainfall

Due to a request from local users to leave times in local time in Eastern Daylight Time (EDT), local times will be provided in addition to UTC.

Rainfall developed across the flood zone around 2100 UTC (5:00 PM EDT). The bulk of the rain fell within a three-hour period from 2130 to 0030 UTC (5:30 PM to 8:30 PM EDT). Radar-indicated rainfall totals ranged from 6.0 to 8.0 inches over the upstream half of the study watersheds. Radar-indicated rainfall totals ranged between 2.0 to 6.0 inches over the downstream half of the study watersheds (Fig. 9). The maximum rainfall intensity, observed on a pixel-by-pixel basis, was approximately an inch within 15 minutes.

Radar-indicated rainfall was averaged over each basin (Fig. 10 and Table 1) on a 15-minute sampling interval. Spring Brook and Berry Brook had extremely consistent basin average rainfall throughout the event. Holliday Brook accumulated the largest basin average rainfall totals and Cat Hollow the lowest. Holliday Brook held the highest intensity rainfall for the longest time of any study watershed.

b. Ground Truth Rainfall Reports

Rainfall reports were received from residents in the impacted watersheds (Table 2 and Fig. 11). Most of the reports were taken from buckets and other containers open to the air. The diameter of each bucket was not reported. Two reports were in the 11.00 inch range. All rainfall reports from buckets were in excess of radar rainfall estimates. Rainfall reports lead credence that the radar represented a minimum rainfall estimate and the radar underestimating has credibility.

c. Rainfall Frequency

The Northeast Climate Center provides a 3-hour 100-year rainfall extreme as 2.5 to 3.0 inches and a 24-hour 100-year rainfall extreme between 5.0 to 7.0 inches (http://www.nrcc.cornell.edu/pptext/). With radar-indicated basin average rainfalls ranging from 4.0 to 6.5 inches, basin average rainfalls were about 2 times the 3-hour 100-year rainfall extreme for this area and in the range of a 24-hour 100-year rainfall extreme. Ground truth bucket reports indicate nearly double the 24-hour 100-year rainfall extreme.

d. Rainfall Thresholds

The first report of minor flooding near Spring Brook came in at 2305 UTC (7:05 PM EDT) with water over a roadway. This corresponds to 2.6 inches or 50 percent of total basin average rainfall for Spring Brook. Moderate flash flooding occurred in Spring Brook with Route 206 impassible at 2333 UTC (7:33 PM EDT). This amounted to 3.85 inches or 73 percent of the total basin average rainfall had fallen by the time this report was received. Major flash flooding is said to have encompassed the entire Spring Brook watershed at about 2350 UTC (7:50 PM EDT). At 2350 UTC (7:50 PM EDT), 4.40 inches of basin average rainfall or 84 percent of total basin average rainfall had reached the ground. Minor flooding was reported to the NWS during the event by amateur radio operators. Moderate and major flash flood times were discussed at the Town of Colchester meeting that NWS Binghamton attended on August 1, 2007.

A resident of lower Berry Brook, David Barnes, reported water began to rise at 2230 UTC (6:30 PM EDT) and crested one foot over the local bridge over Berry Brook between 0030 and 0045 UTC (8:30 and 8:45 PM EDT). This amounts to 1.25 inches and 5.60 inches, respectively, or 22 and 100 percent of total basin average rainfall respectively.

The Town of Colchester supervisor believes that Holliday Brook and Berry Brook had major flash flooding about the same time as Spring Brook. This amounts to between 72 and 84 percent of total basin average rainfall for Holliday Brook and 61 to 88 percent for Berry Brook.

The Middle Atlantic River Forecast Center (MARFC) had in effect a countywide 1- and 3-hour flash flood guidance value, for Delaware County, of 3.3 and 4.5 inches respectively. Gridded 3-hour flash flood guidance for the basins flooded was 4.0 to 6.0 inches (Fig. 12).

e. Watershed Characteristics

Study watersheds were relatively small at between 3.8 and 9.0 square miles (Figs. 13a-d). Stream channels intersected watershed divides between 2271 feet and 2767 feet. Holliday Brook and Berry Brook have the steepest channel slopes from watershed divide to point of discharge. Basin characteristics were developed from 1:24,000 scale USGS topographic maps using Maptech Terrain Navigator software. A list of characteristics for each basin can be found in Table 3. Watershed land use is generally state preserve forest. Development is confined to a narrow corridor in valley bottoms near each brook.

f. Watershed Impacts

Damage throughout the study watersheds was indicative of a major flash flood. The flash flood was so massive that it washed 4 houses away killing 3 occupants. Another person drowned as she apparently tried to find shelter. At least 30 people were evacuated from this area to Roscoe, NY that night.

Additional persons in the Spring Brook and Berry Brook watershed were caught in the flash flood while in their vehicles. One couple in Spring Brook reported multiple logs hitting the side of their vehicle and having to spend the night in their vehicle before rescue the following morning. New York State Trooper Joe Decker, of the Roscoe Substation, encountered the flash flood in Spring Brook while responding and had to abandon his vehicle and swim for his life. Another couple was driving along the Berry Brook Road and encountered a wall of water as high as their car hood.

A total of 37 homes were affected by the flash flood, with 30 homes sustaining severe damage and deemed unlivable with 4 homes completely washed away. Roads and bridges in this area took on severe damage (Fig. 14). Route 206 between Rockland, NY and Downsville, NY was completely washed away in one section with a 25-foot high embankment formed by the floodwaters. Holiday Brook, Spring Brook and Berry Brook roads were also heavily damaged. There were 10 other roads in this area that received flood damage as well. Four bridges were completely washed out. Twenty-two transformers and 47 power poles were damaged by the floods. This left 160 homes without power. Phone service was out in the disaster area.

Total damage estimates range from 25 to 30 million dollars in Delaware and Sullivan Counties. Both counties received Presidential Disaster Declarations along with neighboring Ulster County.

g. Basin Response

Eyewitness and news accounts portray an extremely rapidly responding event along lower Spring Brook. Joe Decker reported encountering a 4-foot wall of water while driving his vehicle. Other witnesses reported upwards of an 8-foot wall of water traveling down the brook. Floodwaters rose about 2-feet per second according to another eyewitness account.

Scour and fill along Spring Brook varied widely. One area of Route 206 was replaced by a 25-foot gully. Along one section of lower Spring Brook, channel capacity was reduced significantly by 12 feet of fill. Debris was observed in enormous amounts in both Spring Brook and Holliday Brook. Residents along Spring Brook report hearing what was interpreted as debris dams giving way at bridge locations along Route 206. An 18-foot high debris pile was reported by emergency management near the top of the Spring Brook watershed along Route 206.

h. Slope-conveyance Discharge Estimate

None of the study watersheds contain stream gages. As a result, it was necessary to estimate discharge after the fact. Berry Brook was selected for this purpose. The above-mentioned scour, fill, and debris bulking make a discharge estimate along either Spring Brook or Holliday Brook problematic.

A location was selected about a half of a mile downstream from the end of the old airstrip along Berry Brook. One cross section was estimated at this point. Excellent high water marks were located on the right bank (Fig. 15). These high water marks were at a uniform height throughout the reach near the cross section indicating relatively steady state channel conditions. High water elevations were also estimated using debris associated with trees within the floodplain. This debris was consistent in height with high water marks on the banks (Fig. 16). It was assumed that water depth in the main channel was twice that observed along the roadway.

Discharge (Q) was calculated by multiplying the cross sectional area of the flood (A) at peak flow by the average flow velocity (V) at peak flow:

$$\mathbf{Q = A \times V} \qquad \textbf{(1)}$$

Cross sectional area was determined for the main channel and a right bank high-flow channel (Fig. 17). Cross sectional area was 213 ft^2 for the main channel and 138 ft^2 for the right bank high-flow channel.

Average flow velocity was calculated, for the main and high-flow channels using the Manning flow equation:

$$\mathbf{V = 1.49R^{0.66}\, S^{0.5} / n} \qquad \textbf{(2)}$$

where R is the hydraulic radius, S is the channel slope, and n the Manning roughness coefficient. A hydraulic radius of 3.05 ft was used for the main channel. A hydraulic radius of 2.56 ft was used for the right-bank high-flow channel. A channel slope of 0.02 ft/ft was used for both the main channel and the high flow channel. The value of n was determined in the field. An n of 0.050 was assigned to the main channel. The USGS had verified a value of n of 0.033 for the next downstream USGS stream gage located along the Beaver Kill at Cooks Falls (Barnes 1967). A higher n was selected for this cross section due to the presence of vegetation, including trees, on the right bank of the main channel. An n-value of 0.060 was assigned to the right-bank high-flow channel. This value represents an average of several n-value extremes present including grass, road/eroded road surface material, and a wooded area.

Using the above values, an average velocity of 8.8 feet per second was calculated for the main channel and 6.5 feet per second for the right-bank high-flow channel. The above velocities do not include the effect of obstruction / retardation caused by vegetation other than the value of *n* itself. Using these velocities, a peak discharge of 1,874 cfs was obtained for the main channel and 897 cfs for the right-bank high-flow channel. This yields a total discharge of 2771 cfs.

The above slope-conveyance discharge estimate should be considered a rough discharge estimate. Due to an estimation of the cross sectional area, experience-based selection of Manning roughness value, and an assumption that channel slope approximates surface water elevation slope, the discharge estimate will have more error than that of a multiple cross section slope-area indirect discharge estimate or a discharge estimate taken from a step-backwater model. As a result, the authors assigned error of approximately 25 to 50 percent.

i. Flood Frequency

The equations for ungaged basins in New York region 3 (Limia et al. 2006) were used to assign flood frequency for Berry Brook. A drainage area of 4.6 square miles was used (Table 4). Peak discharge for Berry Brook was in excess of the 500-year flood frequency (less than a 0.2% chance of exceedance chance in a given year).

j. Probable Maximum Flood

The probable maximum flood (PMF) is an extreme flood based on the most severe hydrologic and meteorological conditions considered reasonable for the site. In general, exceedance probabilities are not assigned to PMFs. The National Flood Frequency program calculates the PMF using the methods of Crippen and Bue (1977). PMF for Berry Brook was 13,100 cfs for region 4 and a 4.6 square mile watershed. As a result, Berry Brook's peak discharge was less than 25% of the PMF.

k. Comparison to USGS Gage on Beaver Kill

The USGS stream gage located along the Beaver Kill at Cooks Falls registered a rapid rise (Fig. 18). In a 15-minute time span, it rose 5.40 feet (5,000 cfs). The USGS gage registered the crest at 8.64 feet (6,840 cfs) at 0400 UTC (12:00 AM EDT), June 20th. The USGS, using the crest-stage gage located at the site, recorded a peak of 10.16 feet (9,900 cfs). This was defined as a provisional peak at the time of this technical attachment. Considering the flash flood nature of this event, a rise to a crest of 10.16 feet was not inconceivable considering the 15-minute data resolution from the USGS stream gage. It was hypothesized that the rate of rise of the river stage, in the Beaver Kill, was too rapid for the water in the USGS stilling well to keep up with.

The USGS stream gage is located a short distance downstream from the outlet of Spring Brook and Berry Brook (7.9 and 11.9 miles). While some attenuation may have occurred prior to reaching the stream gage, the crest was likely representative of the sum of base flow at the time plus the individual flash flood peak discharges from Spring Brook, Berry Brook, and Pelnor Hollow (a small watershed situated between Spring and Berry Brook). Due to the relative uniformity of rainfall mentioned above between Spring and Berry Brook, it was assumed that a ratio of drainage area allows for the estimation of peak discharge from Spring Brook and Pelnor Hollow. With Spring Brook at 9.0 square miles and Pelnor Hollow at 2.0 square miles, peak discharge should be 196% and 43% of that of Berry Brook respectively or 5,431 cfs and 1,192 cfs. With a base flow at the time of 120 cfs, a total of 9,514 cfs or 96% of the peak flow was accounted for using this method. It should be noted that Berry Brook, Spring Brook, and Pelnor Hollow have a combined drainage area of about 16 square miles or 6.6 percent of the total drainage area for Beaver Kill at Cooks Falls of 241 square miles. This further demonstrates the extreme nature of this flash flood.

The Beaver Kill at Cooks Falls crest continued to travel downstream for a period of 48-hours and could be picked out as far downstream as Montague as a significant rise (Fig. 19).

I. Inflow into Pepacton Reservoir

Runoff from the Holliday Brook, Cat Hollow, and nearby north-facing watersheds flowed into Pepacton Reservoir. NYC DEP reported inflow into Pepacton Reservoir peaked at about 16,000 cfs at 0140 UTC (9:40 PM EDT) on June 19th (Fig. 20). The presence of Downsville Dam prevented flooding in the community of Downsville downstream to Harvard (Fig. 21). The reservoir did not spill and stayed below the spillway crest throughout the multi-day period of the rise (Fig. 22).

Using the ratio of drainage area described above for the Beaver Kill watersheds, the peak flows can be estimated for Holliday Brook, Cat Hollow, and Miller Hollow (a small watershed, of 1.25 square miles, situated between Holliday Brook and Cat Hollow). Due to rainfall not being uniform between Holliday Brook and Cat Hollow and with respect Holliday Brook, it is prudent to take this into account in addition to simply applying the ratio of watershed drainage areas to Berry Brook. Holliday Brook has a drainage area of 4.8 square miles and basin average rainfall of 115% of Berry Brook, thus a peak discharge of 3,326 cfs was obtained. Since Cat Hollow has a drainage area of 3.8 square miles and basin average rainfall of 71% of Berry Brook, a peak discharge of 1,625 cfs was obtained. Miller Hollow yields a peak discharge of 748 cfs using watershed drainage area ratios alone. Since Miller Hollow is situated half way between Holliday Brook and Cat Hollow, it is assumed that its basin average rainfall is transitional between the two watersheds basin average rainfall and hence similar to what was seen for Berry Brook. Basin average rainfall comparisons between Berry Brook and Holliday Brook and Cat Hollow with respect to calculating peak discharges was done by comparing radar rainfall values.

5. SUMMARY, DISCUSSION AND CONCLUSIONS

The extreme flash flood event of June 19, 2007 occurred in the type of meteorological environment that has previously been found to be favorable for flash flooding in upstate New York. Key environmental factors included an unusually moist atmosphere, and a wind field that evolved to promote increased organization of convection into a large cluster of nearly stationary thunderstorms. The sudden change on this day from isolated convective storms to an organized, stationary cluster presented warning meteorologists with a difficult challenge, as they were forced to "shift gears" midway through the event, from warning for pulse severe convection, to warning for a major flash flood.

Regarding the hydrology of this event, we described an extreme rainfall event and resultant headwater flash flood that translated into rapid rises on downstream rivers. Basin average rainfall greatly exceeded a 3-hour 100-year rainfall. Results of the bucket survey point to upwards of twice the 24-hour 100-year rainfall extreme compressed into a three-hour timeframe. Flood frequency for Berry Brook in excess of a 500-year return flow is consistent with extreme rainfall frequencies.

Rates of rise up to 2 feet per second, along lower Spring Brook, point to structural failure immediately upstream. Reports of debris pileups giving way behind highway

bridges were the likely cause. No evidence was found of dams or ponds breaching.
Basin average rainfall of 2.00 to 2.50 inches initiated stream rises and reports of minor flooding. Moderate flooding was reached by 4.00 to 5.00 inches. Major flooding was witnessed in the 5.00 to 8.00 inch range. Bucket survey reports upward to 11.00 inches point to the radar underestimation of rainfall.

A timeline for the event can be viewed in Table 5.

DISCLAIMER

Mention of a commercial company or product does not constitute an endorsement by the National Weather Service. Use of information from this publication concerning proprietary products or tests of such products for publicity or advertising purposes is not authorized.

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TABLES

Table 1. Basin average accumulated rainfall (in.) derived from KBGM WSR-88D radar plotted against time on about a 15-minute time interval.

Time (UTC)	Time (EDT)	Spring Brook	Berry Brook	Holliday Brook	Cat Hollow
2134	5:34 PM	0.37	0.10	0.56	0.45
2147	5:47 PM	0.86	0.25	0.78	0.62
2159	5:59 PM	1.11	0.73	1.25	1.03
2216	6:16 PM	1.42	1.11	2.06	1.55
2232	6:32 PM	1.66	1.27	2.74	2.09
2244	6:44 PM	1.94	1.44	3.46	2.42
2301	7:01 PM	2.59	2.12	3.81	2.44
2313	7:13 PM	3.13	2.57	4.09	2.46
2330	7:30 PM	3.85	3.44	4.65	2.59
2342	7:42 PM	4.32	4.17	5.11	2.71
0000	8:00 PM	4.56	4.92	5.49	3.13
0016	8:16 PM	5.12	5.49	6.11	3.75
0037	8:37 PM	5.25	5.61	6.50	4.00

Table 2. Rainfall reports (in) throughout flash flood area.

Basin Location	Elevation (ft)	Source	Gage type	Rainfall (inches)
Cat Hollow	2200	Town of Colchester	Bucket	8.25
Lower Spring Brook	1600	Town of Colchester	Bucket	> 11.00
Upper Holliday Brook	1900	Town of Colchester	Bucket	9.00
Upper Spring Brook	2100	Edward Hamerstrom	Bucket	11.00
Upper Berry Brook along Henderson Road	2100	Edward Hamerstrom	Rain gage	6.00
Lower Berry Brook along Berry Brook Road	1600	Eric Hamerstrom	Rain gage	2.00
Pelnor Brook about 0.5 miles up from Beaver Kill	1600	Edward Hamerstrom	Swimming pool	9.50
Upper Beaver Kill near Lew Beach	1800	Edward Hamerstrom	Bucket	9.50

Table 3. Basin characteristics derived from 1:24,000 scale USGS Topographic maps using Maptech Terrain Navigator software.

Basin Name	Drainage Area (sq mi)	Linear profile slope (ft/ft)	Maximum channel flow length (miles)	Maximum elevation (ft)	Minimum elevation (ft)
Spring Brook at Landing Strip	9.0	0.034	4.97	2271	1391
Berry Brook below old Airstrip	4.6	0.069, 0.02 at indirect discharge location	3.00	2767	1650
Holliday Brook at Route 30	4.8	0.076	3.51	2703	1299
Cat Hollow near Route 30	3.8	0.059	3.39	2409	1351

Table 4. Stream flow return frequency, for Berry Brook.

Stream flow return frequency	Discharge
2-year	334 cfs
5-year	527 cfs
10-year	675 cfs
25-year	901 cfs
50-year	1095 cfs
100-year	1314 cfs
500-year	1904 cfs

Table 5. Timeline of hydrologic events.

Date	Time (UTC)	Time (EDT)	Description
6/19	2130	5:30 PM	Rain begins to fall in Spring Brook and Cat Hollow watersheds.
6/19	2230	6:30 PM	Water began to rise along lower Berry Brook.
6/19	2301	7:01 PM	Flash flood warning issued for south-central Delaware County
6/19	2305	7:05 PM	First report of minor road flooding received.
6/19	2310	7:10 PM	Approximate time that MARFC 3-hour gridded Flash Flood Guidance was exceeded.
6/19	2333	7:33 PM	Moderate flash flooding with Route 206 impassible.
6/19	2350	7:50 PM	Major flash flooding along lower Spring Brook.
6/19	0030	8:30 PM	Major flash flooding along lower Berry Brook.
6/19	0140	9:40 PM	Peak inflow into Pepacton Reservoir.
6/20	0400	12:00 AM	Peak flow at USGS gage along Beaver Kill at Cooks Falls.

FIGURES

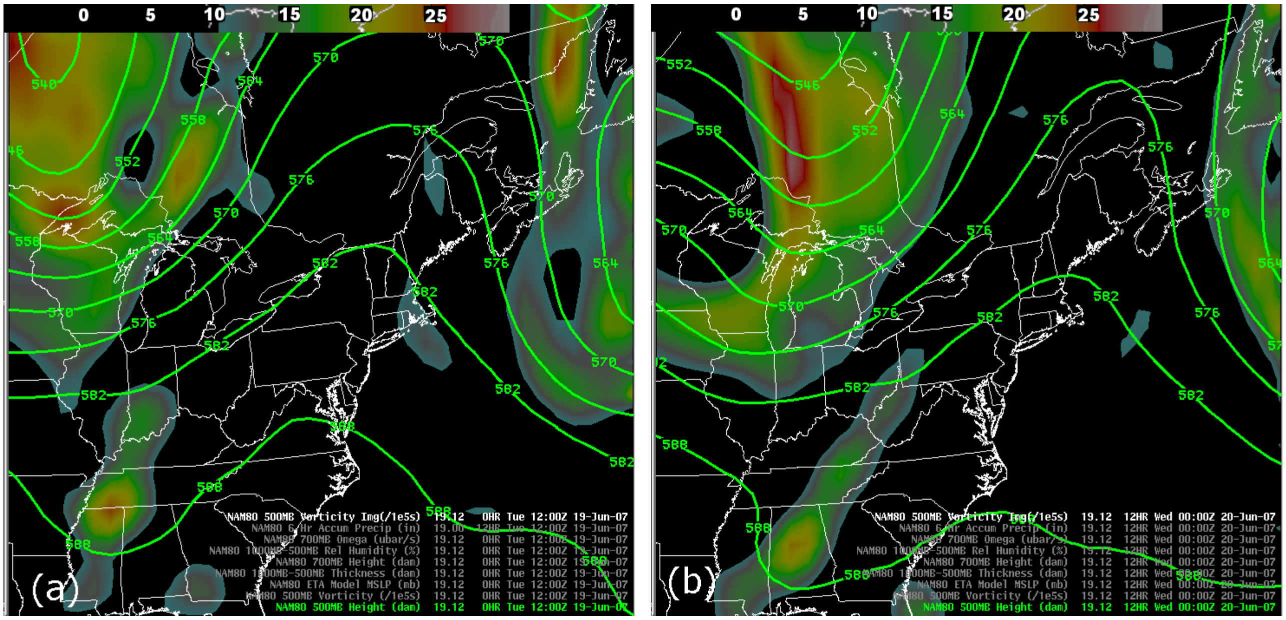


Figure 1. NAM 00 h and 12 h forecast 500 hPa heights (dm) and vorticity (1x10^{-5} s^{-1}, positive values shaded) valid at (a) 12 UTC June 19, 2007 and (b) 00 UTC June 20, 2007.

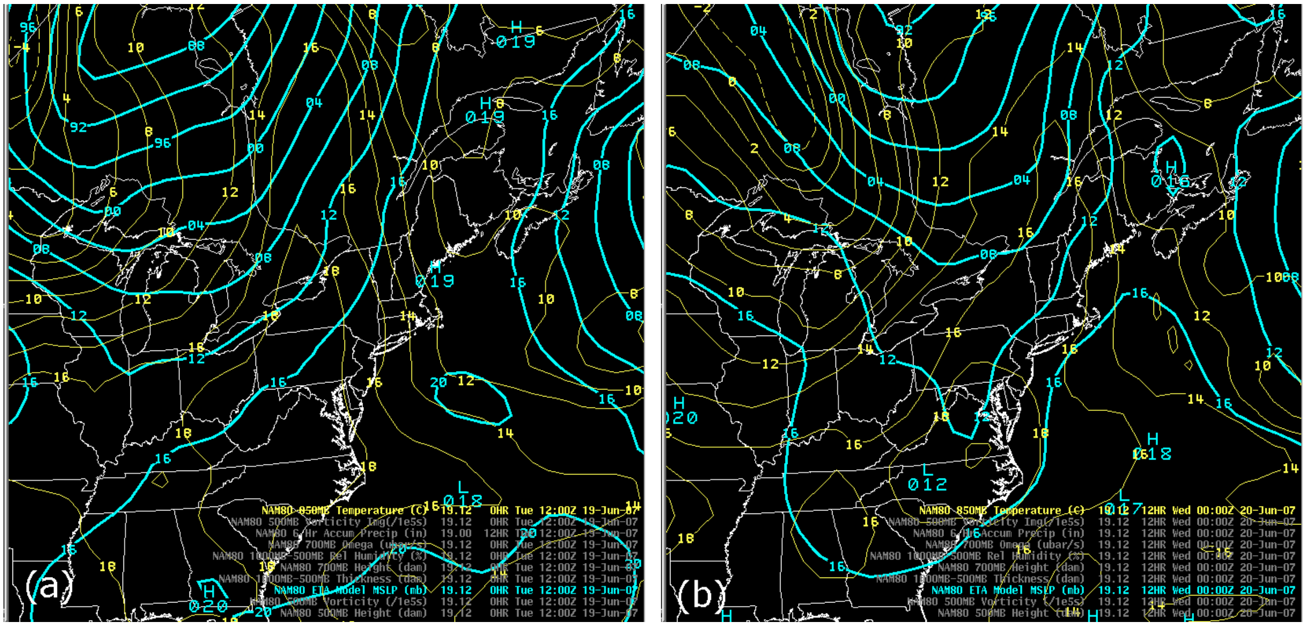


Figure 2. NAM 00 h and 12 h forecast sea-level pressure (hPa, blue contours) and 850 hPa temperature (ºC, yellow contours) valid at (a) 12 UTC June 19, 2007 and (b) 00 UTC June 20, 2007.

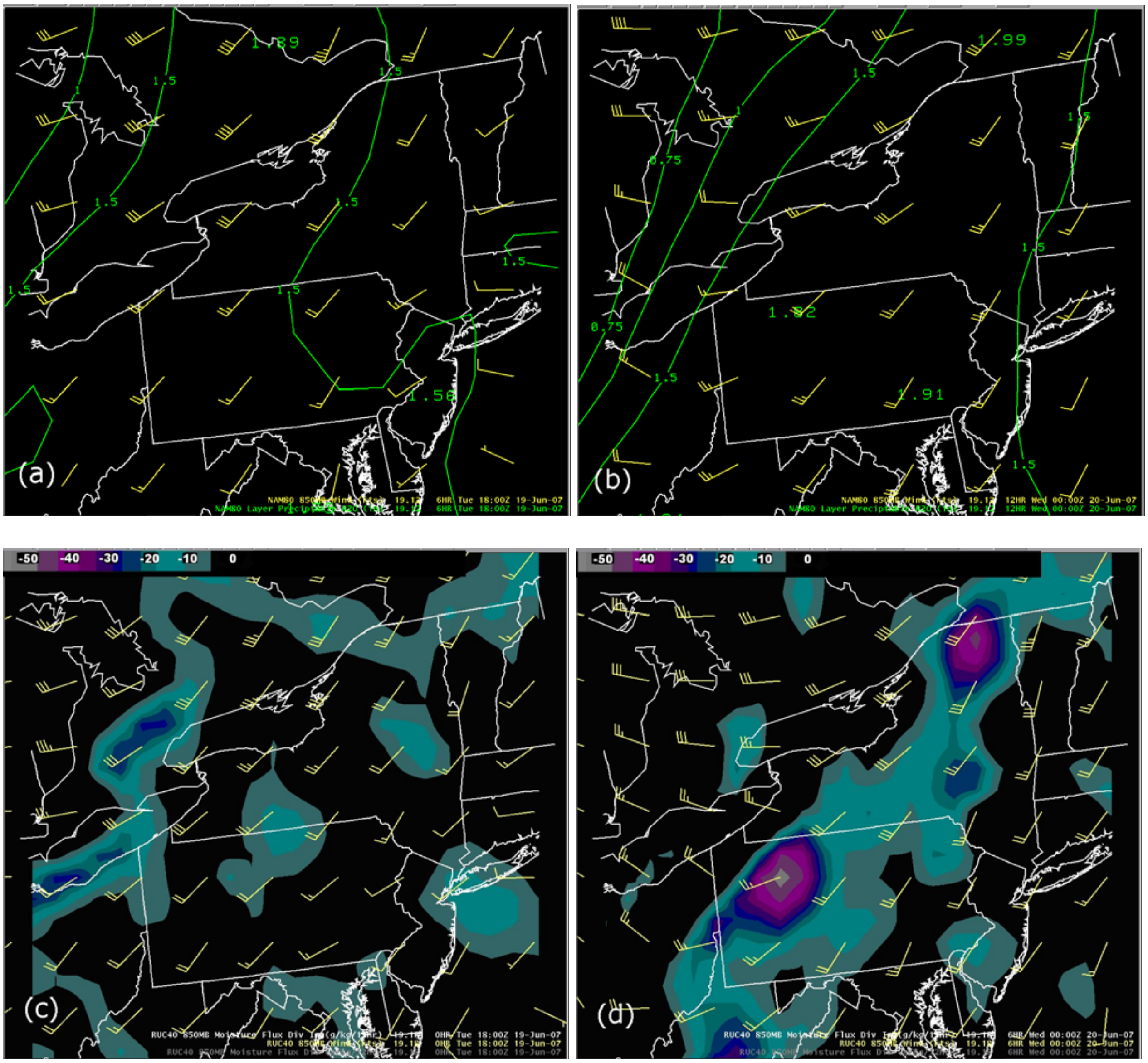


Figure 3. NAM 06 and 12 h forecast precipitable water (in) and 850 hPa wind (kts) valid at (a) 18 UTC June 19, 2007 and (b) 00 UTC June 20, 2007. RUC 00 h and 6 h forecast 850 hPa moisture flux convergence (g kg^{-1}12 hr^{-1}, values > 5 shaded) and 850 hPa wind (kts) valid at (c) 18 UTC, June 19, 2007 and (d) 00 UTC June 20, 2007.

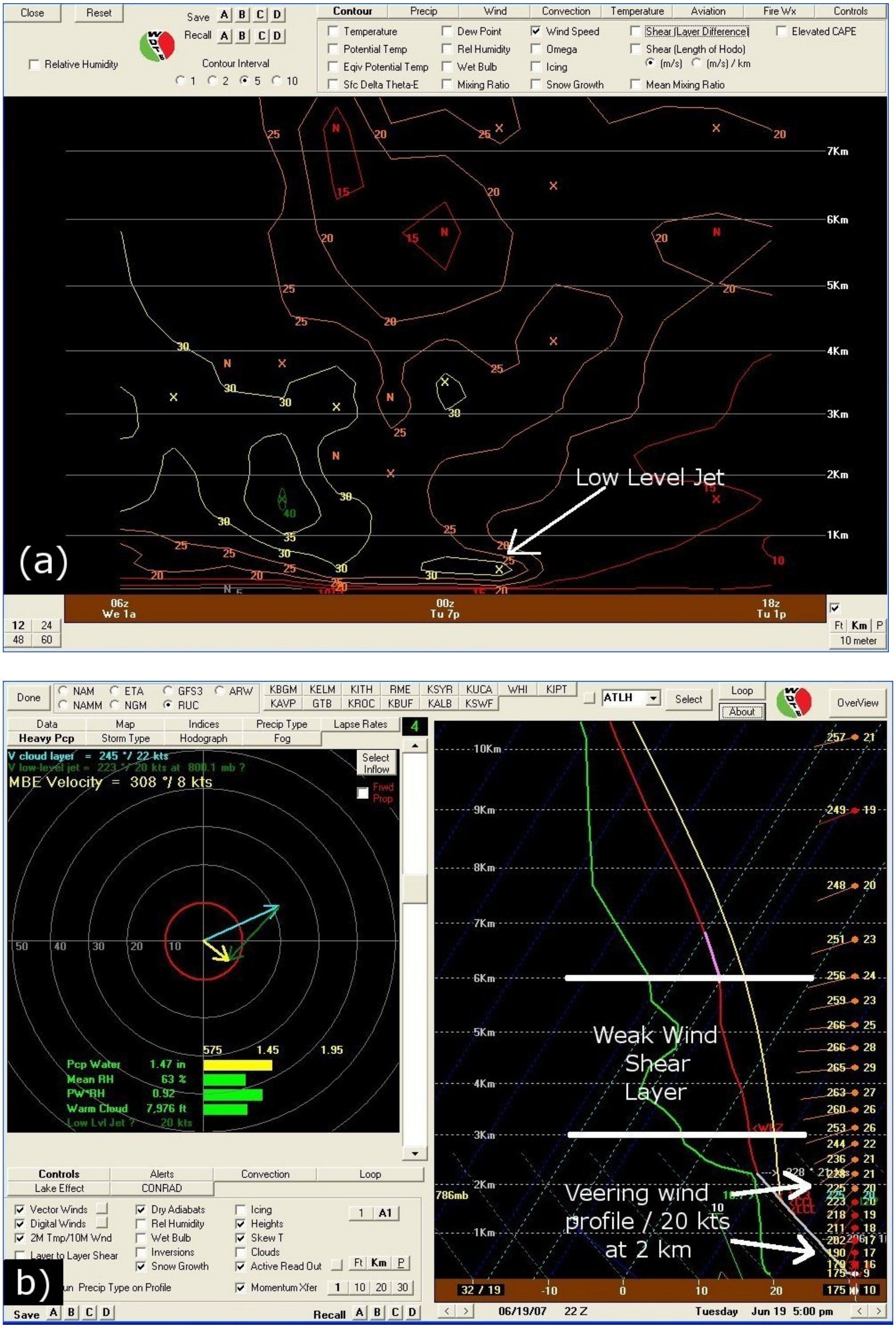
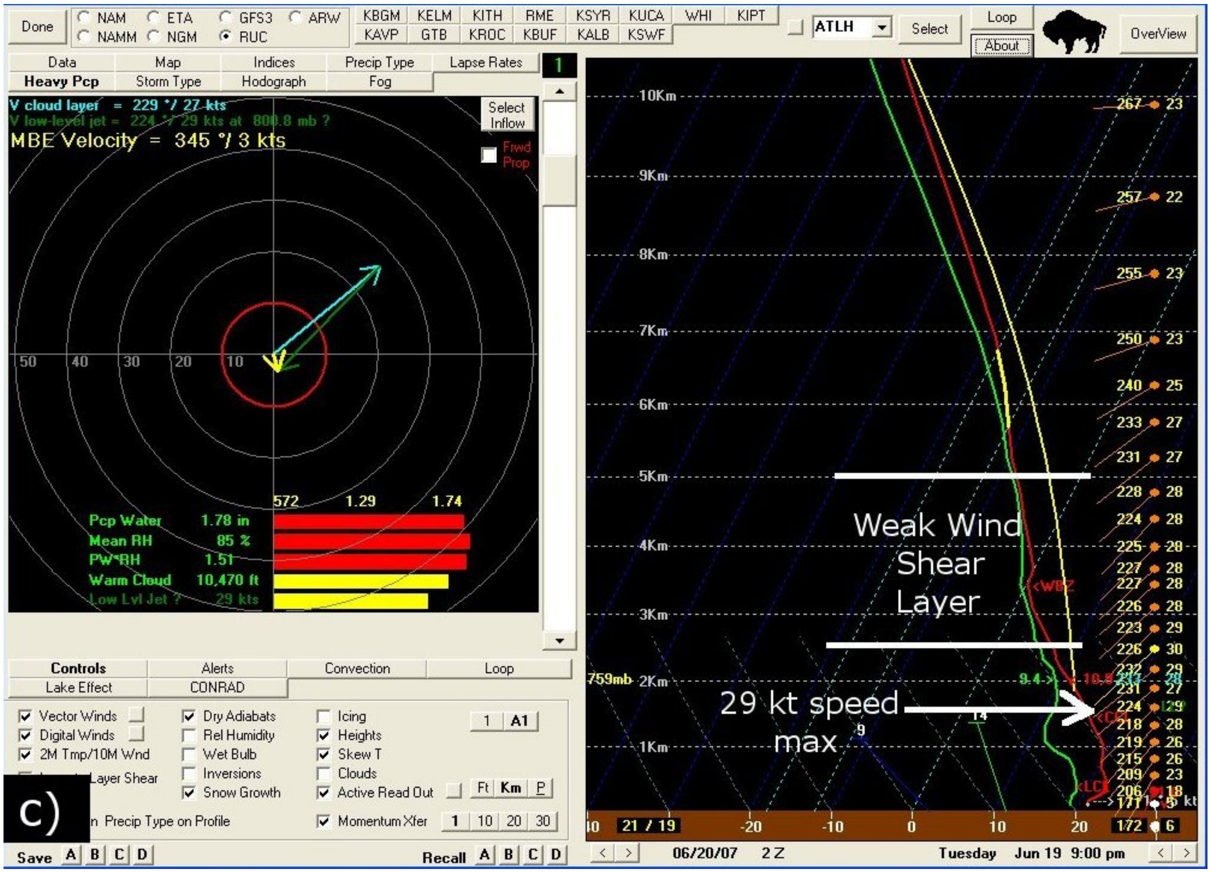


Figure 4. (a) BUFKIT time-height display of 18 UTC June 19, 2007 RUC forecast wind speed (kts.) at Avoca, Pa (AVP) from 18 UTC through 00 UTC. (b) BUFKIT display of the 21 UTC June 19, 2007 RUC forecast sounding at AVP valid at 22 UTC on June 20.



V cloud layer = 229 °/ 27 kts
V low-level jet = 224 °/ 29 kts at 800.8 mb ?
MBE Velocity = 345 °/ 3 kts

Pcp Water 1.78 in
Mean RH 85 %
PW*RH 1.51
Warm Cloud 10,470 ft
Low Lvl Jet ? 29 kts

267 23
257 22
255 23
250 23
240 25
233 27
231 27
228 28
224 28
225 28
227 28
227 28
226 28
223 29
226 30
232 29
231 27
224 29
218 28
219 26
215 26
209 23
206 18
171 5 kt
172 6

☑ Vector Winds
☑ Digital Winds
☑ 2M Tmp/10M Wnd
Layer Shear
☑ Dry Adiabats
☐ Rel Humidity
☐ Wet Bulb
☐ Inversions
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Figure 4. (c) BUFKIT display of the 01 UTC June 20, 2007 RUC forecast sounding at AVP valid at 02 UTC on June 20, 2007.

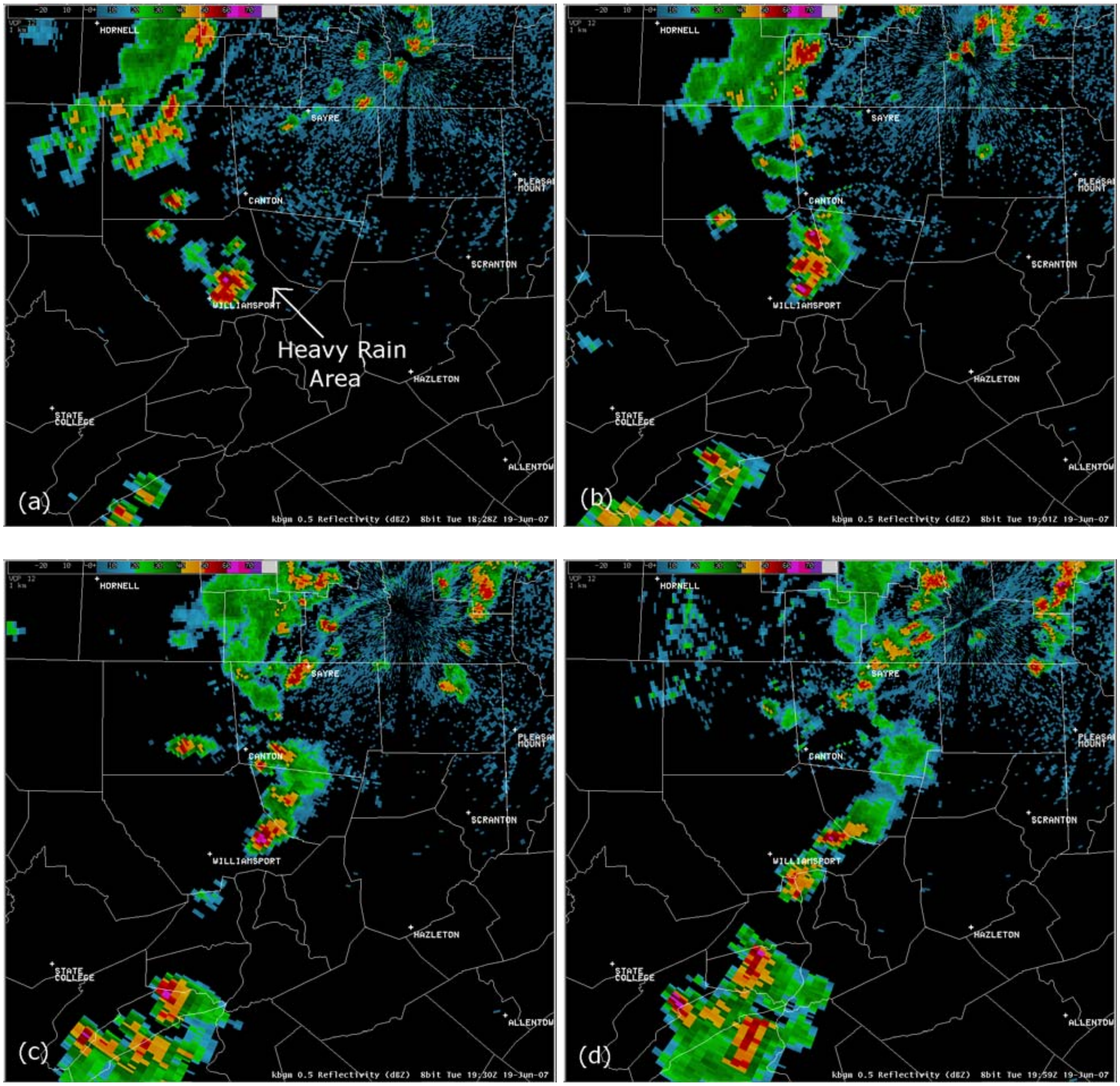

Figure 5. KBGM WSR-88D reflectivity at (a) 1830 UTC June 19, 2007 (b) 1900 UTC June 19, 2007 (c) 1930 UTC June 19, 2007 and (d) 2000 UTC June 19, 2007.

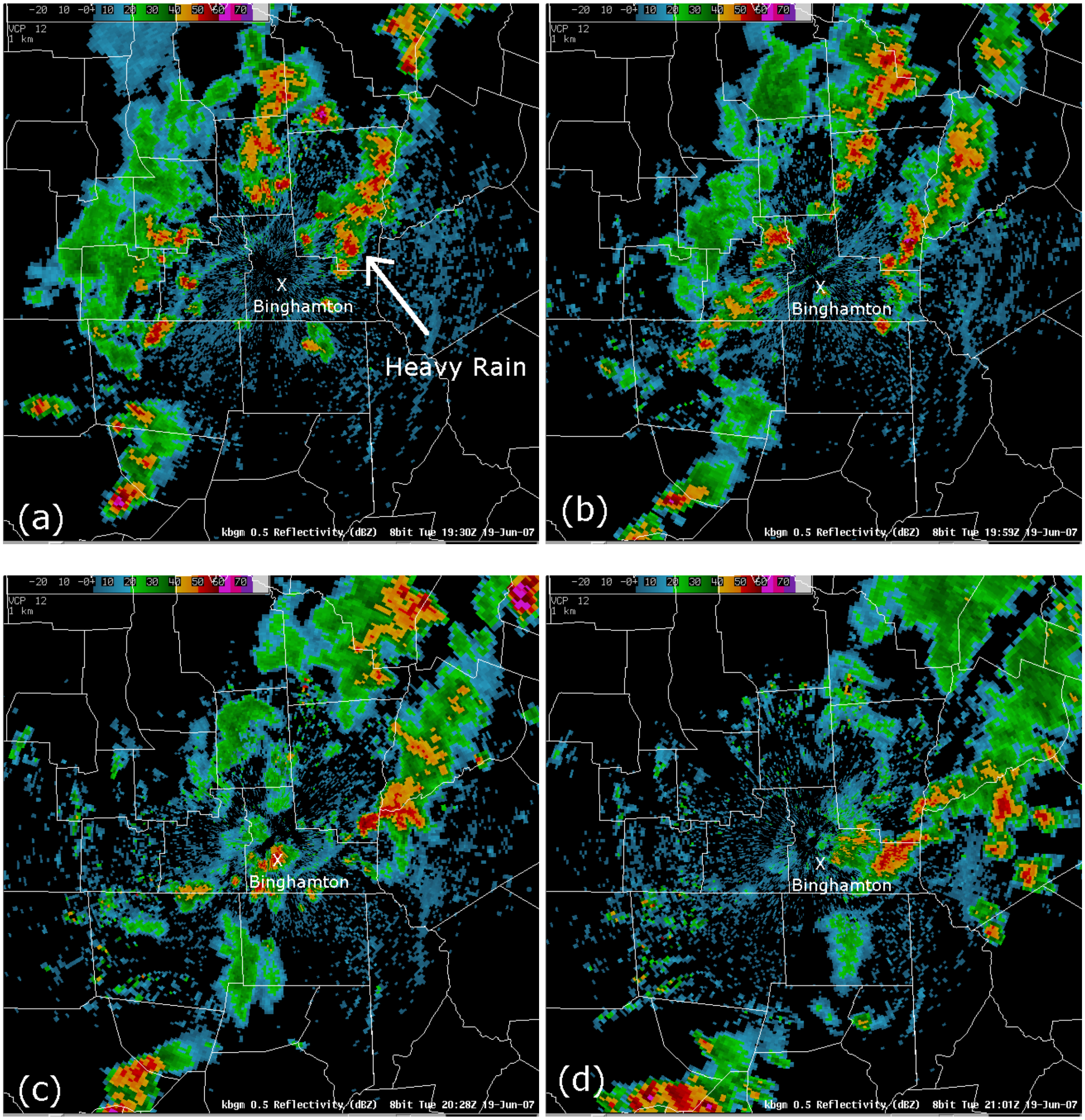

Figure 6. KBGM WSR-88D reflectivity at (a) 1930 UTC June 19, 2007 (b) 2000 UTC June 19, 2007 (c) 2030 UTC June 19, 2007 and (d) 2100 UTC June 19, 2007.

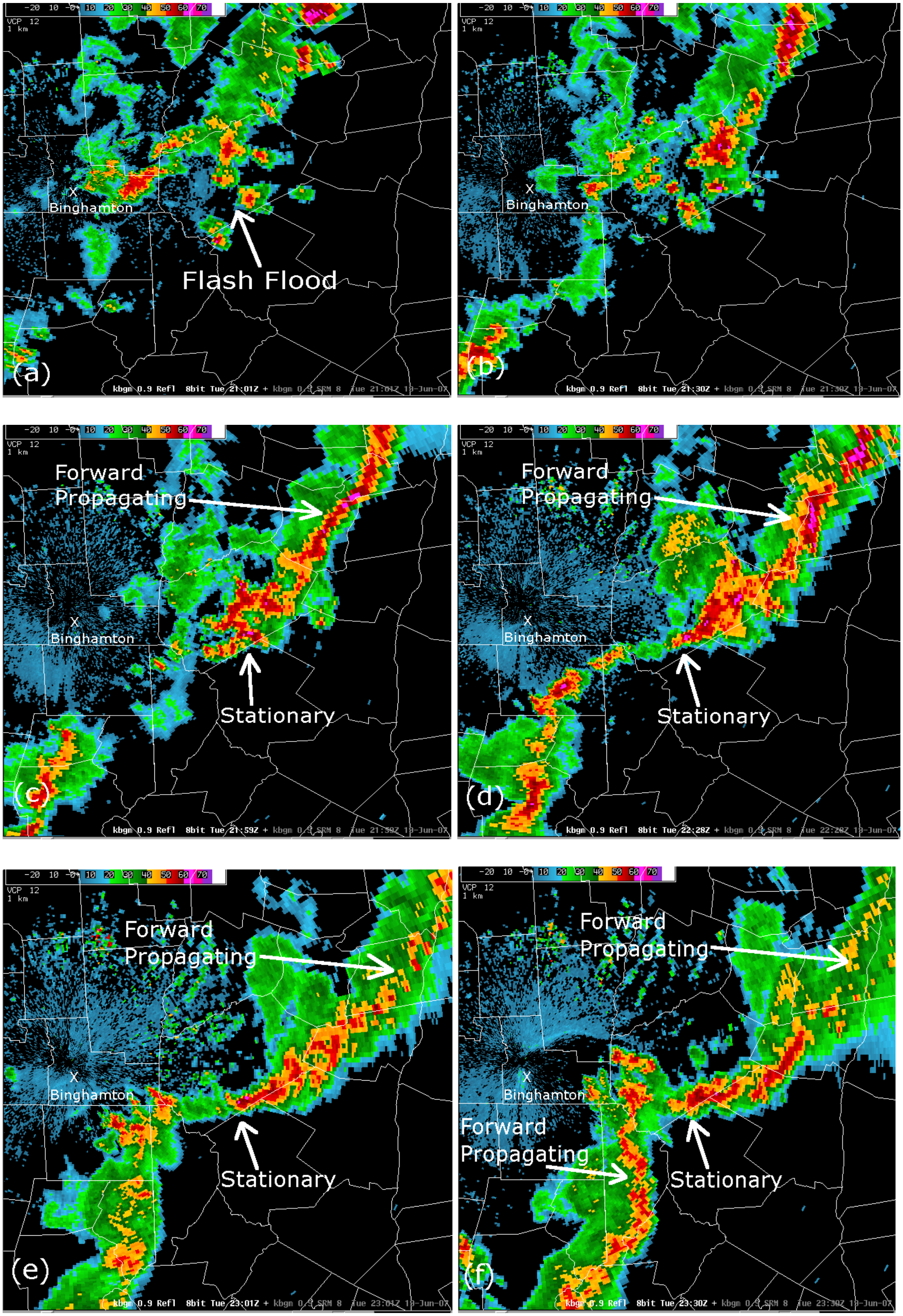

Figure 7. KBGM WSR-88D reflectivity at (a) 2100 UTC June 19, 2007 (b) 2130 UTC June 19, 2007 (c) 2200 UTC June 19, 2007 (d) 2230 UTC June 19, 2007 (e) 2300 UTC June 19, 2007 (f) 2330 UTC June 19, 2007.

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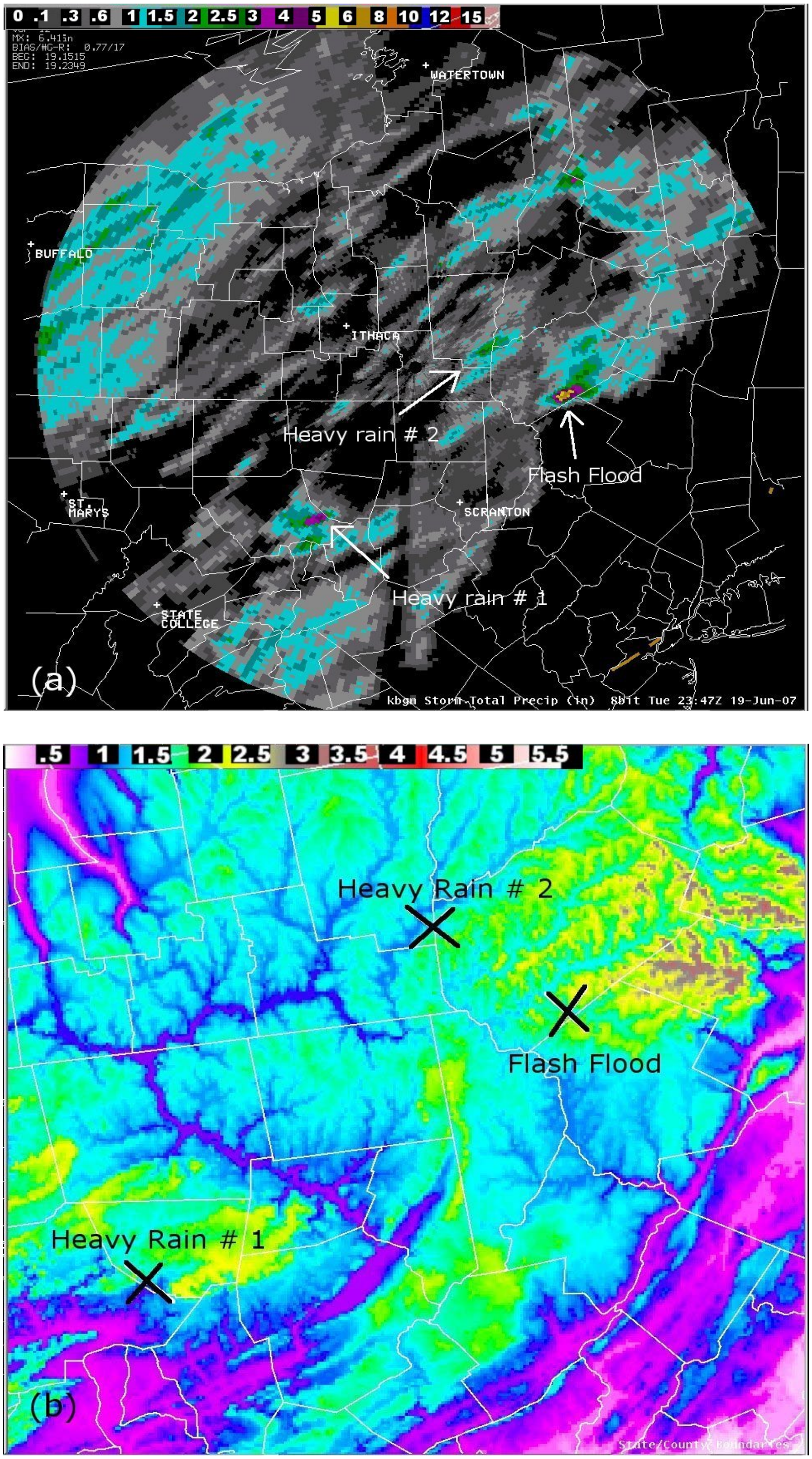

Figure 8. (a) KBGM WSR-88D radar estimated rainfall through 00 UTC June 20, 2007. (b) Topography of central New York and northeast Pennsylvania (shaded; kft), with the location of the heavy rain events on June 19-20 annotated.

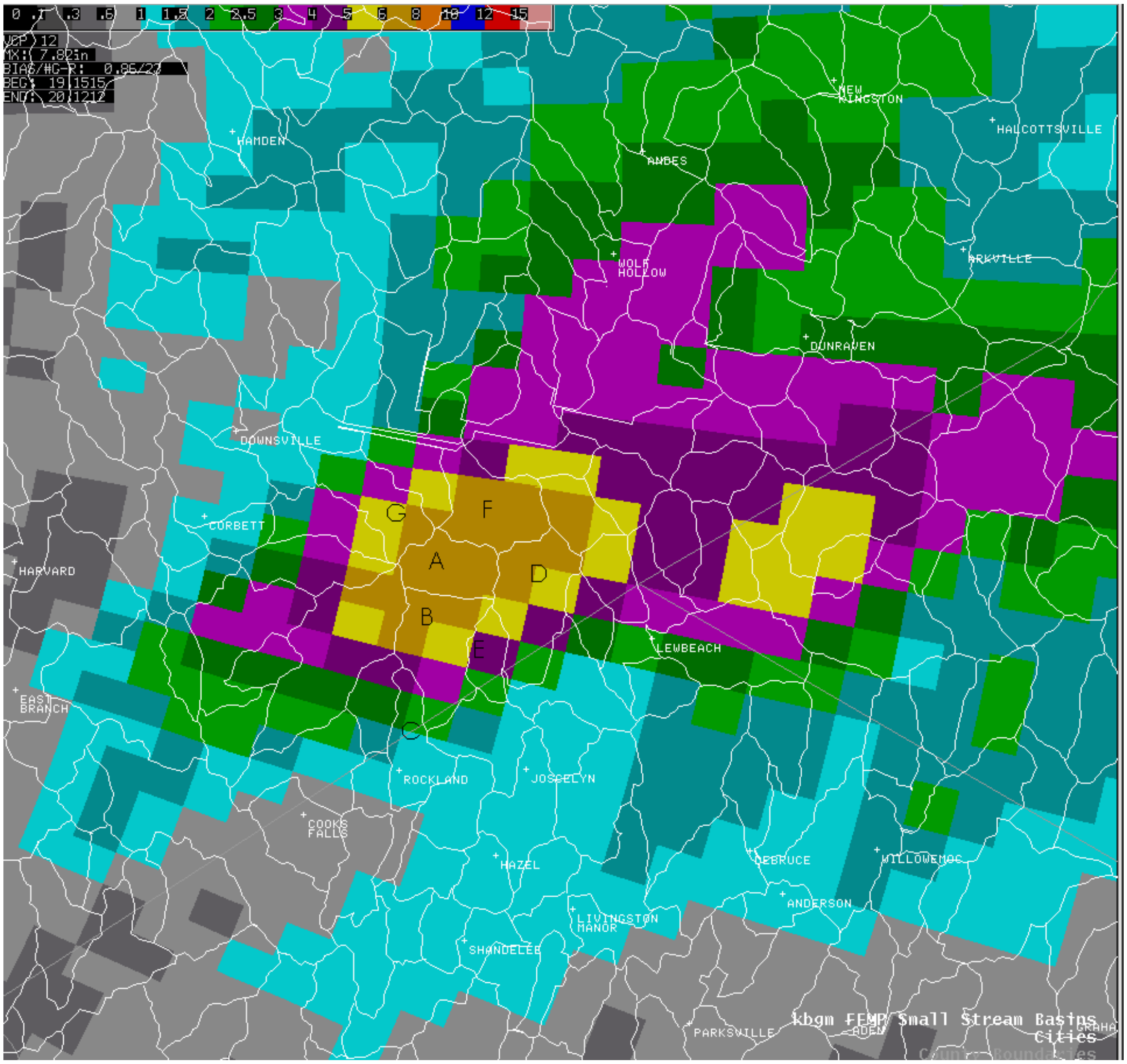

Figure 9. Storm total precipitation from June 19th overlaid with NWS Flash Flood and Monitoring Program (FFMP) small basin outlines. Basins are labeled for upper Spring Brook (A), middle to lower Spring Brook (B), lower Spring Brook near airfield (C), Berry Brook (D), Pelnor Hollow (E), Holliday Brook (F), and Cat Hollow (G).

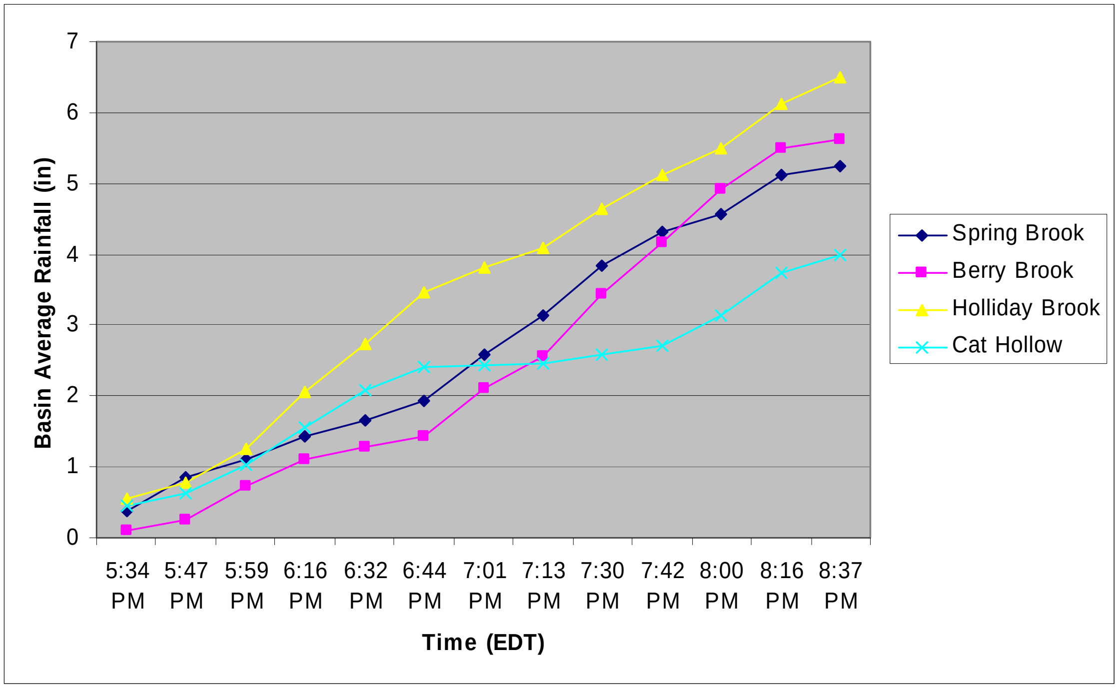

Figure 10. Basin average accumulated rainfall derived from KBGM WSR-88D radar plotted against time on about a 15-minute time interval.

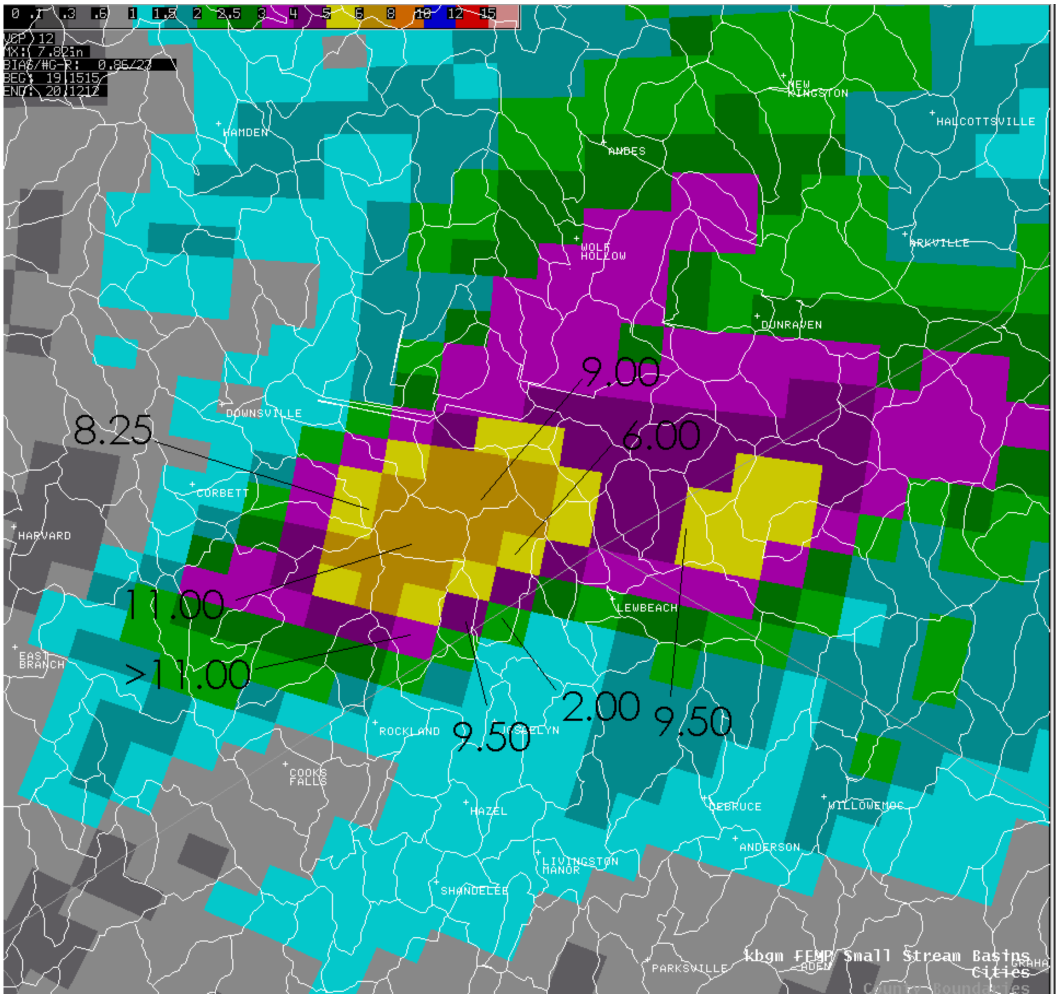

Figure 11. Rain gauge and bucket reports received from throughout the flash flood area.

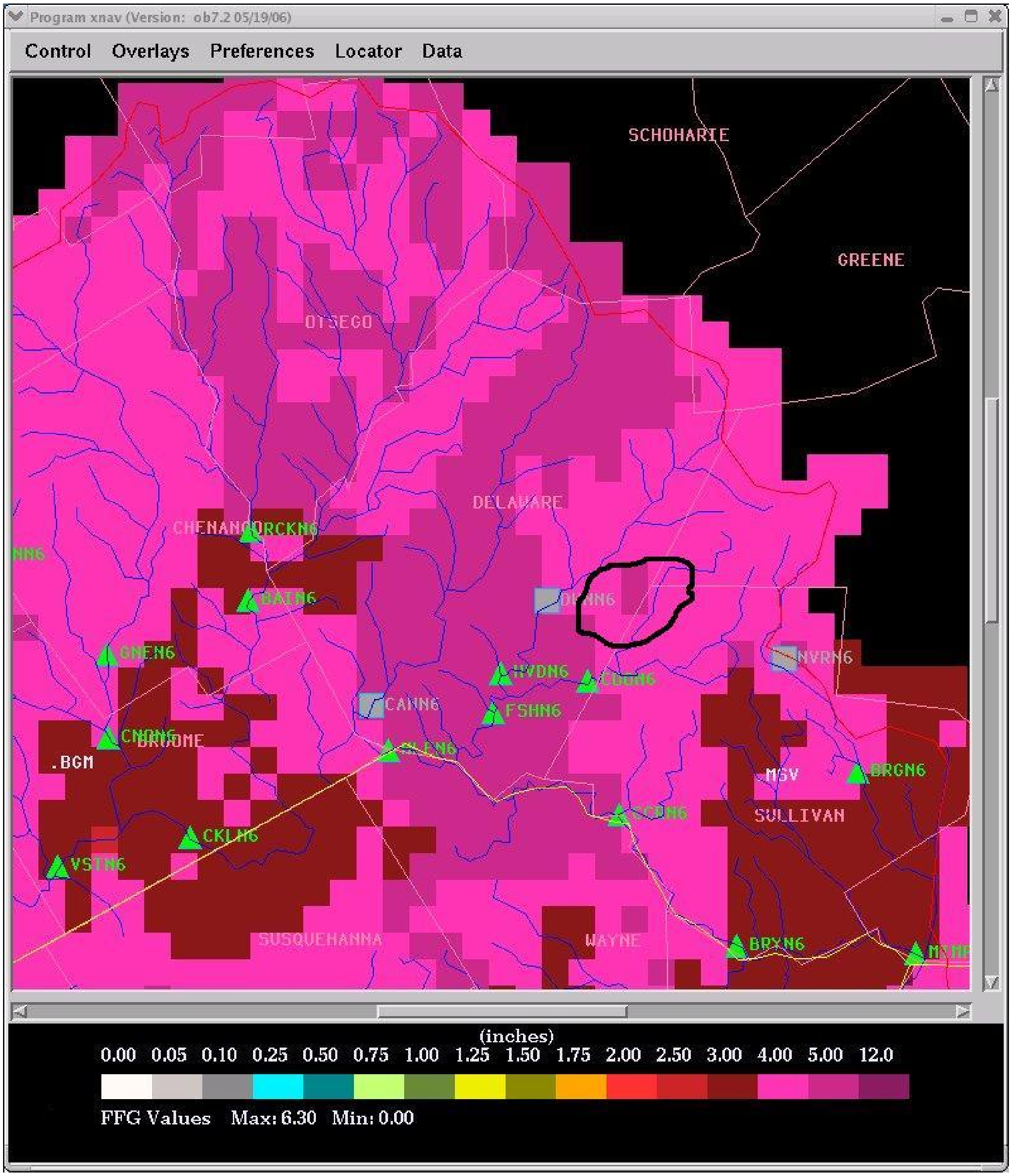

Figure 12. MARFC 3-hour Flash Flood Guidance. Black outline shows area of flash flooding of Delaware, Sullivan, and Ulster counties.

Figure 13a. Watershed boundary created from Maptech Terrain Navigator software of Spring Brook at landing strip. Arrow indicates direction of streamflow.

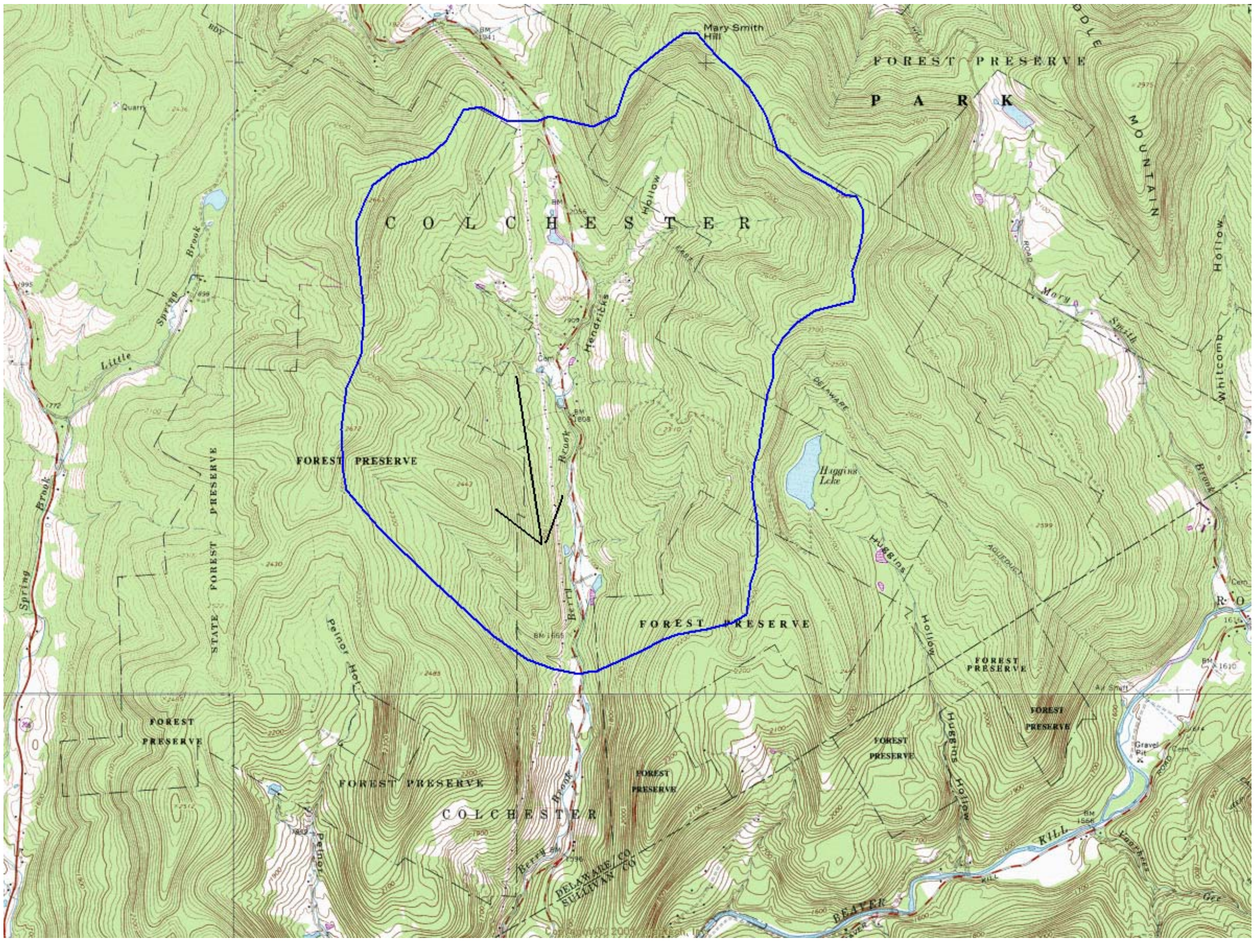

Figure 13b. Watershed boundary created from Maptech Terrain Navigator software of Berry Brook half-mile below old airstrip. Arrow indicates direction of streamflow.

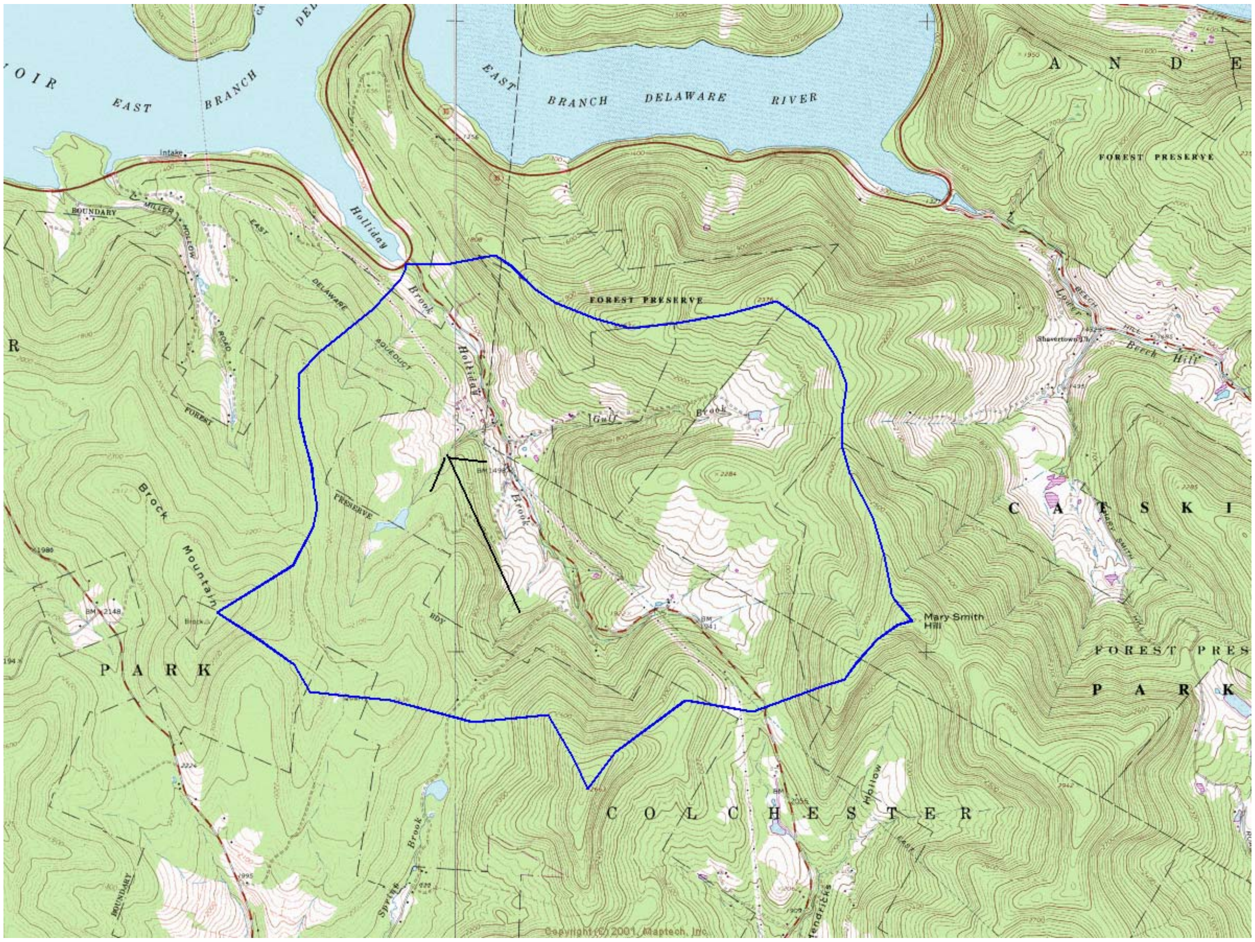

Figure13c. Watershed boundary created from Maptech Terrain Navigator software of Holliday Brook at Route 30. Arrow indicates direction of streamflow.

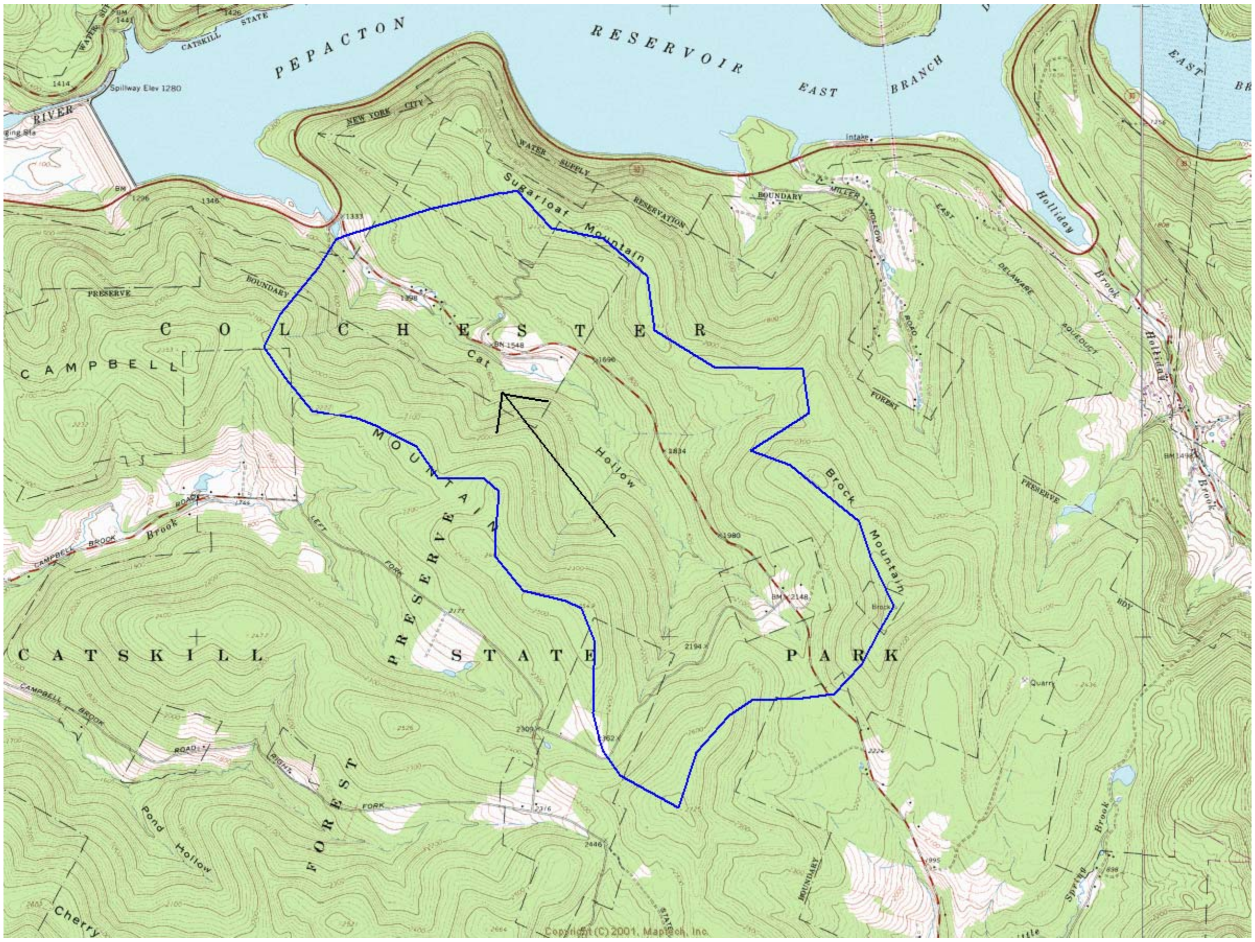

Figure 13d. Watershed boundary created from Maptech Terrain Navigator software of Cat Hollow at Highway 30. Arrow indicates direction of streamflow.

Figure 14. Binghamton Weather Forecast Office Senior Service Hydrologist standing at roads' end along Berry Brook just downstream from old airstrip. Photo looking upstream.

Figure 15. Berry Brook indirect discharge location located about a half mile downstream from end of old landing strip. Photo taken looking upstream from right bank.

Figure 16. Berry Brook indirect discharge location. Black line drawn in to show water surface elevation consistent between right bank high water mark and in-channel debris.

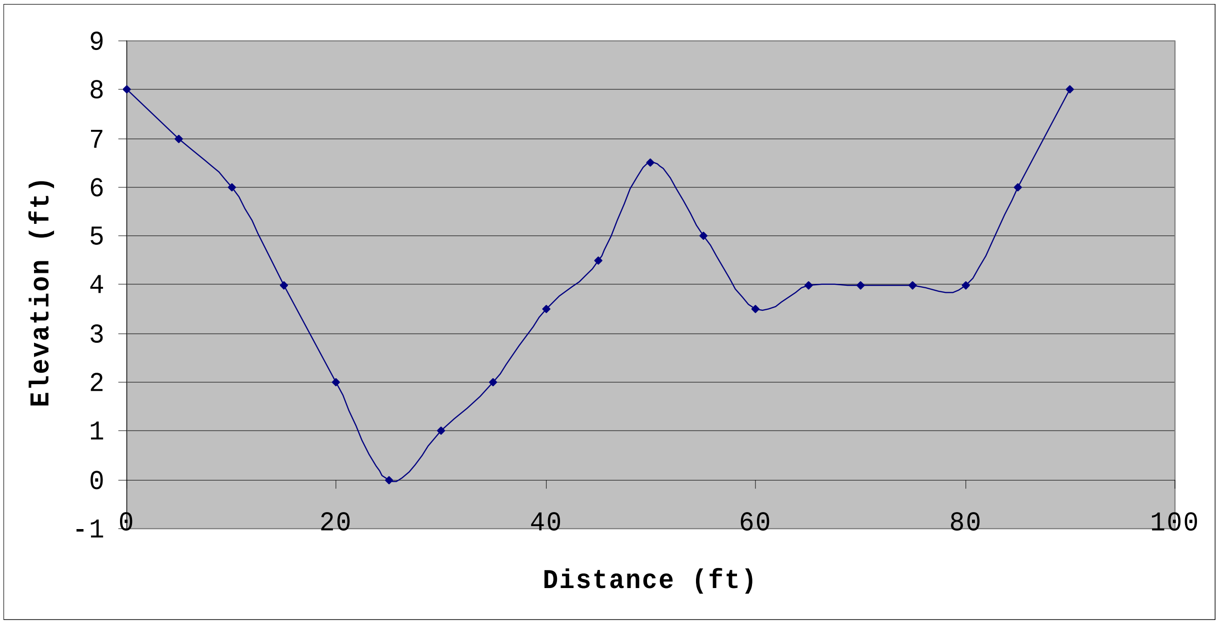

Figure 17. Channel cross section for Berry Brook looking in the downstream direction. Graphic is vertically exaggerated.

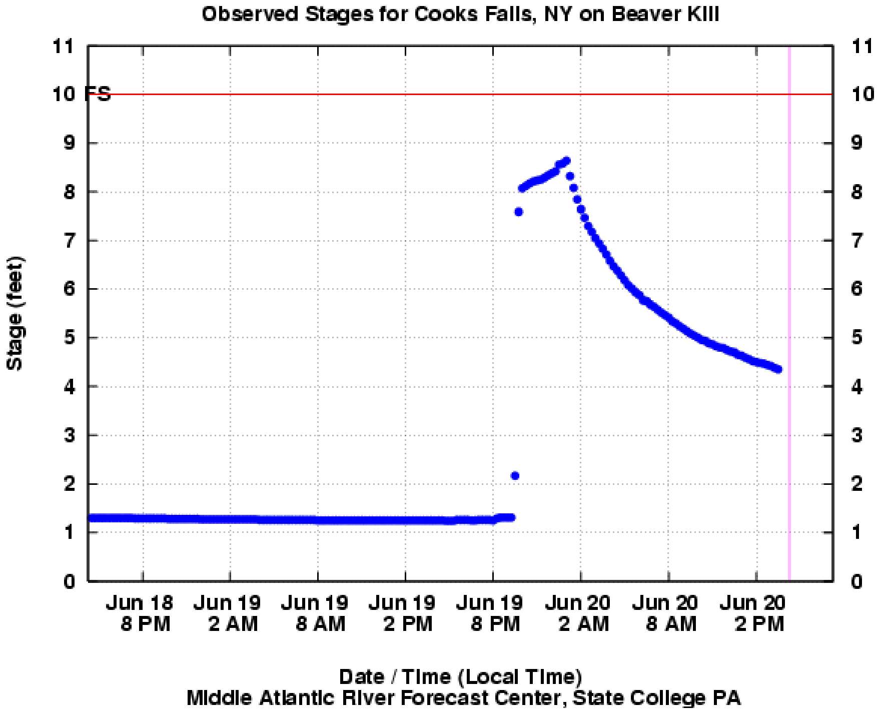

Figure 18. Observed river stages at the USGS stream gage at Cooks Falls along the Beaver Kill. Rapid rise of 5.4 feet in 15-minutes can be seen. USGS crest stage gage at the site recorded a crest of 10.16 feet. National Weather Service flood stage of 10.00 feet shown on graph in red.

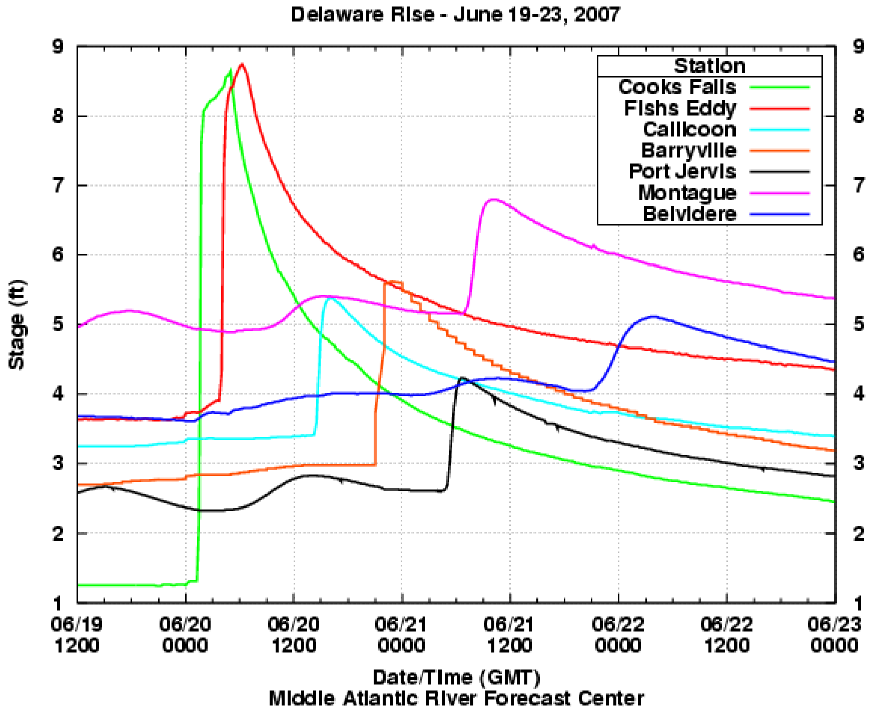

Figure 19. River stages from 19-23 June 2007. Flash flood crest at Cooks Falls is depicted in green and progression of the flood wave downstream along the Delaware River is evident.

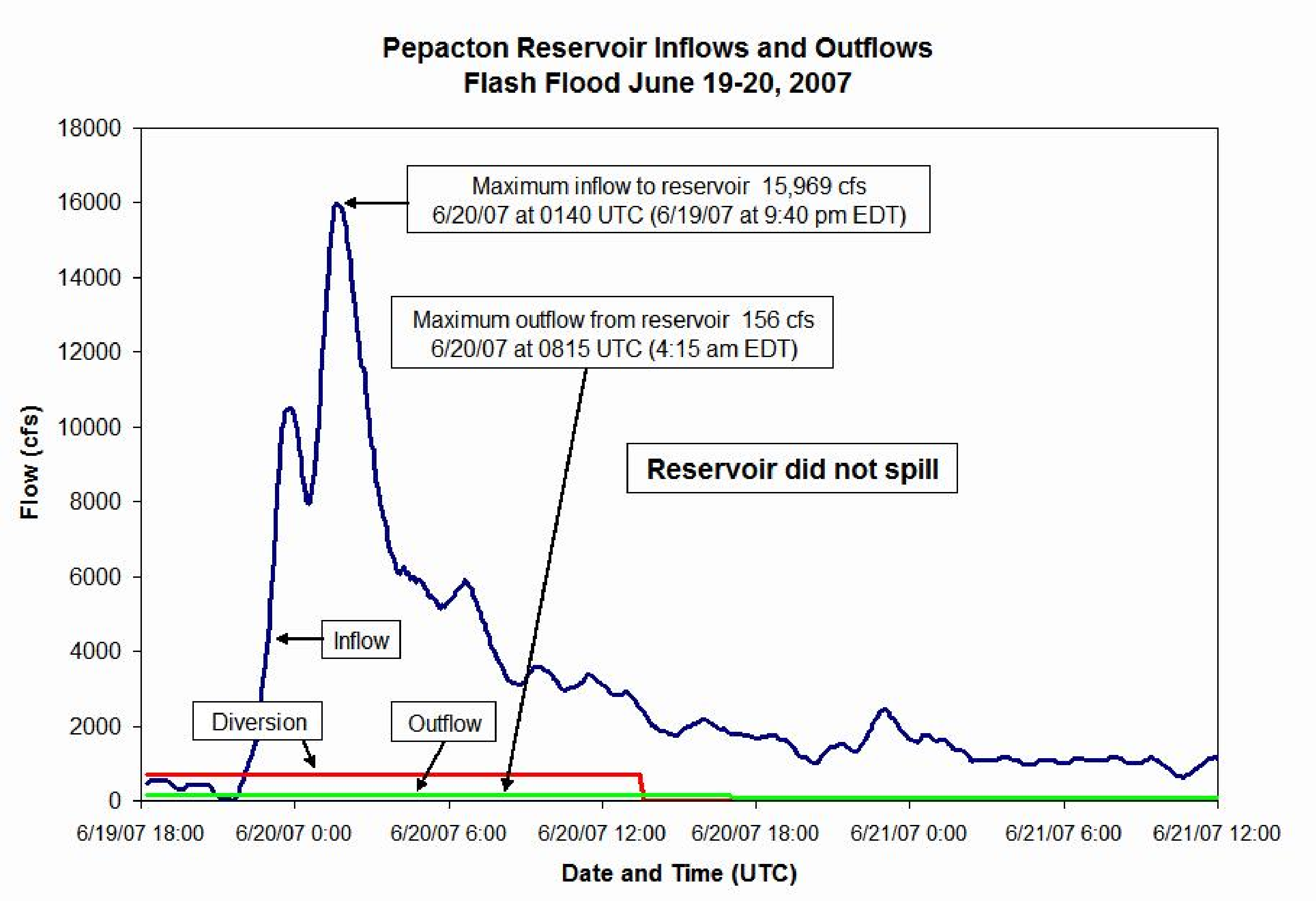

Figure 20. Inflow into Pepacton Reservoir (graphic prepared by NYC DEP). Maximum inflow into reservoir of 15,969 cfs was reached at 0140 UTC (9:40 PM EDT) on June 19, 2007. Holliday Brook, Cat Hollow, and several smaller north-facing watersheds are thought to have contributed the majority of this water.

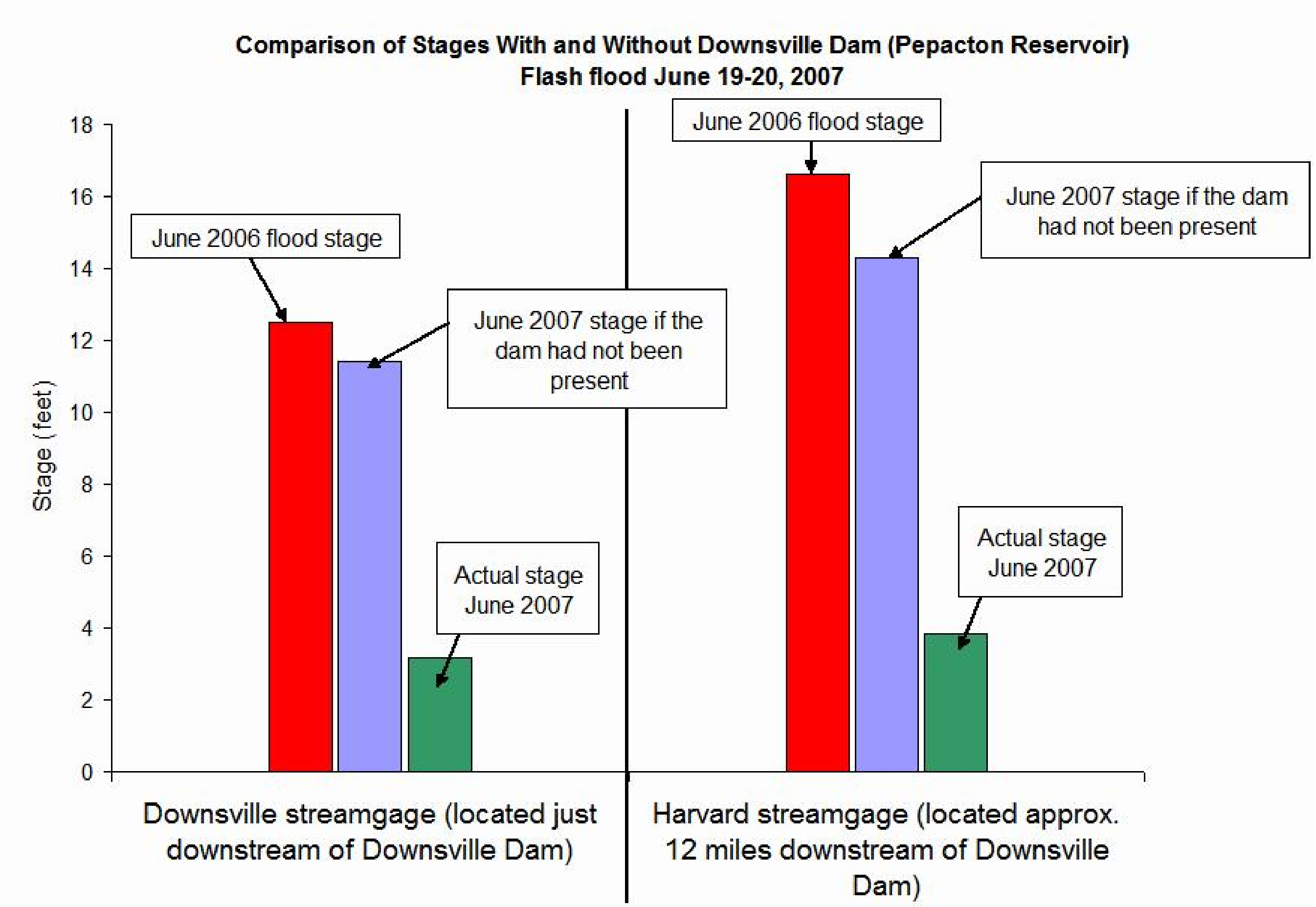

Figure 21. Analysis conducted by NYC DEP to show mitigating effects of Downsville Dam on flood crest. Flood stage reached during flood of June 2006, hypothetical stage if dam was not present during June 19-20 flood, and actual stage reached from June 19-20 flood. Flood stage at USGS gage at Harvard is 10 feet. Hypothetical flood stage assumes the inflow hydrograph into Pepacton Reservoir coalesced into a flood peak of equivalent discharge in the Pepacton reach of the upper Delaware River and traveled downstream without significant attenuation as far as Harvard located approximately 12 miles downstream from the Downsville Dam. This hypothetical stage of 14 feet is a maximum possible stage. Attenuation of peak flow downstream of the site of Downsville Dam and/or peak flow hydrograph generation, which differs from the inflow hydrograph for Pepacton Reservoir, could lead to a lower crest at Harvard.

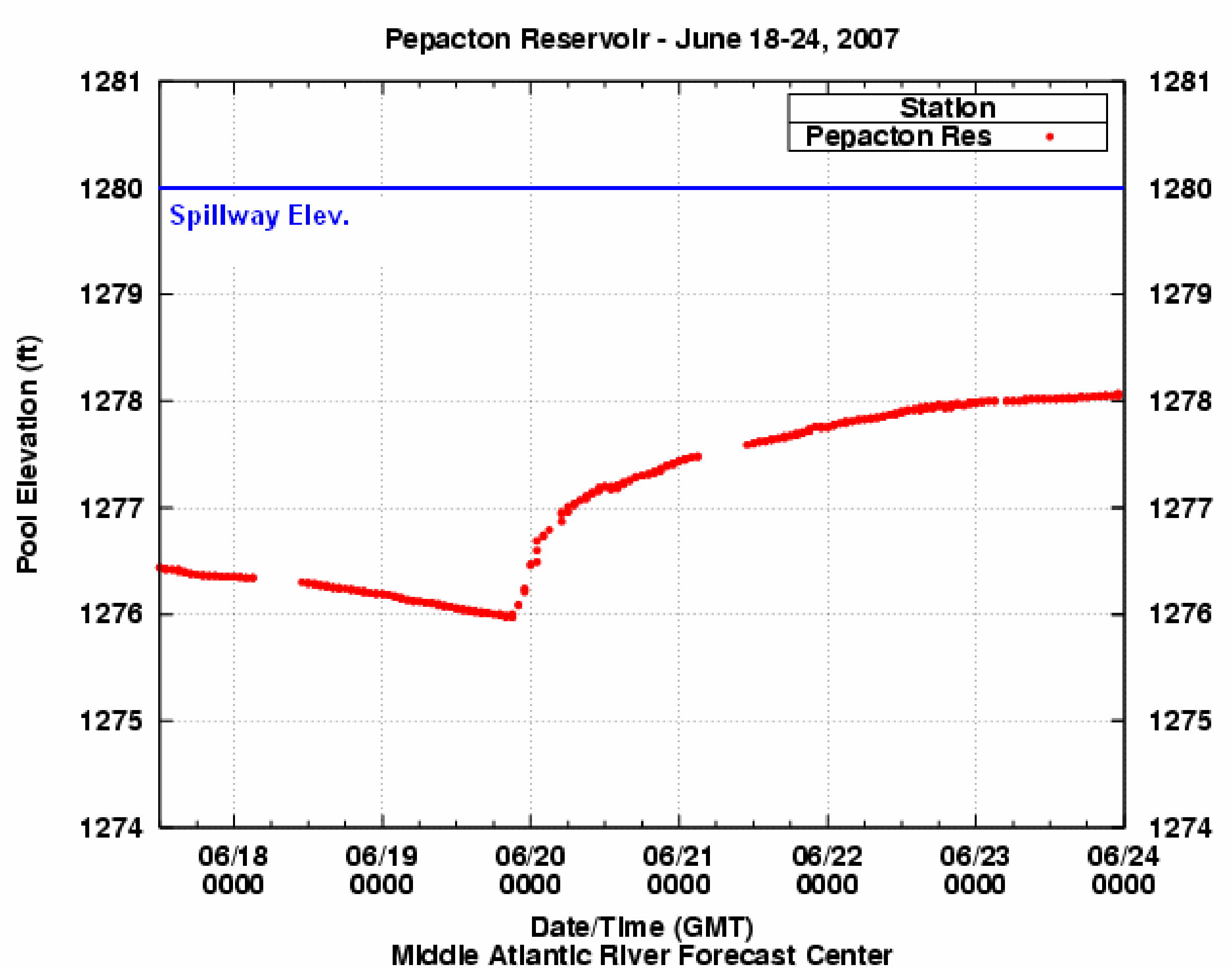

Figure 22. Pool water elevation at Pepacton Reservoir. It took a total of 4 full days for the rise in pool water elevation to level off after the evening of rainfall event of June 19, 2007.