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AN ABBREVIATED FLASH FLOOD/FLOOD CLIMATOLOGY (1994-2007) FOR THE WFO BLACKSBURG, VIRGINIA COUNTY WARNING AREA

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ABSTRACT

WFO Blacksburg first opened in 1994 as part of the National Weather Service modernization. With modernization, there was an increased emphasis on verification for Storm Data, published by the National Climatic Data Center (NCDC). Fourteen years of flood event data from 1994 to 2007 for the WFO Blacksburg County Warning Area (CWA) were studied. Each flood event listed in a county with a unique time and date was counted as a separate event. The data consisted of 1168 events, which were categorized as a flash flood, areal flood or river flood. The impact description in Storm Data for each event was used to stratify all of the events by the severity of flooding. The date, time, location and severity of each event was then used to develop a short term climatology of the flooding in the WFO Blacksburg CWA during the 14 year period. The purpose of the study is to provide forecasters with an improved understanding of the frequency, severity and geographical distribution of seasonal and diurnal flood events across the CWA.

1. INTRODUCTION

The purpose of this study is to provide forecasters with a climatological knowledge of the likelihood of flash flooding and/or flooding across WFO (Weather Forecast Office) Blacksburg, Virginia's County Warning Area (CWA). The National Weather Service's (NWS) primary responsibility is to provide warnings for the protection of life and property. The NWS issues warnings for, and documents, three types of flooding; flash flooding, areal flooding, and flooding on main stem rivers (river flood). The WFOs are tasked with issuing flash flood and flood warnings for their area of responsibility or CWA. The NWS definition of a flash flood (NWS, 2007a) is that it applies to those short-term flood events which require immediate action to protect lives and property, such as dangerous small stream flooding or urban flooding, and dam or levee failures. A more detailed definition used for Storm Data (NWS, 2007b), is as follows:

Within six hours (often within one hour) of a causative event such as intense rain, dam break, or ice jam formation, one or more of the following occurs:

- River or stream flows out of banks and is a threat to life or property.
- Person or vehicle swept away by flowing water from runoff that inundates adjacent grounds.
- A maintained county or state road closed by high water.
- ≥6 inches of fast-flowing water over a road or bridge. This includes low water crossings in a heavy rain event that is more than localized (i.e., radar and observer reports indicate flooding in nearby locations) and poses a threat to life or property.
- Dam break or ice jam causes dangerous out of bank stream flows or inundates normally dry areas creating a hazard to life or property.
- Any amount of water in contact with, flowing into, or causing damage to a residence or public building as a

result of above ground runoff from adjacent areas.

- ≥3 feet of ponded water that poses a threat to life or property.
- Mud or rock slide caused by rainfall.
- Flood waters containing a minimal amount of debris (mud, rock, vegetation) caused by rainfall. This could possibly occur in a burned area with only light to moderate rainfall.

By NWS definition (NWS, 2007a) there are two types of floods distinct from flash flooding. The term river flood applies to any high flow, overflow, or inundation event which is threatening to lives and property and can be quantified or indexed at specific locations (forecast points) along main stem rivers. The term areal flood is applied to any high flow, overflow, or inundation in a defined area such as a group of counties or an area along a river or stream which threaten lives and property that is not covered by flash flooding. Areal floods apply to longer duration precipitation, (greater than six hours), causing slow rises on rivers and streams.

This local flash flood and flood climatological study will provide forecasters with an improved understanding of the frequency, severity and geographical distribution of seasonal and diurnal flood events across the Blacksburg CWA, for improved preparation and anticipation of such events.

2. TOPOGRAPHY AND DEMOGRAPHICS OF THE COUNTY WARNING AREA

The NWS Forecast Office located in Blacksburg, Virginia (RNK) has forecast and warning responsibility across Southeast West Virginia, Southwest Virginia, and Northwest North Carolina (Fig. 1). The WFO Blacksburg CWA includes 40 counties. These counties cover an area from the Appalachians in the west, across the Blue Ridge Mountains, to the Piedmont in the east. The CWA (Fig. 1) is characterized by mountainous terrain over the north and west high elevation valleys (Roanoke and New River) extending through the central CWA and the Blue Ridge mountain range, foothills and piedmont regions over the eastern and southern CWA area. There is a rapid increase in elevation from southeast to northwest, starting from less than 500 feet in the Piedmont, to mountainous terrain of 3200 to 5000 feet in the higher elevations of the Blue Ridge and Appalachian mountains of western Virginia (VA), southeastern West Virginia (WV), and northwestern North Carolina (NC). The Eastern U.S. Continental Divide bisects the CWA, leading to diversity in river flow directions. Close proximity to the Gulf of Mexico and the Atlantic Ocean provides abundant moisture sources for the CWA. A low level flow from the east through the south often produces an efficient moisture flux, and can result in upslope enhancement to precipitation as well.

The WFO Blacksburg CWA is approximately 20,000 square miles and has a population of roughly 1.7 million. A majority of the population (1.1 million) resides in counties along and east of the Blue Ridge in Central Virginia, and Northwest North Carolina. The largest population centers east of the Blue Ridge are the independent cities of Lynchburg (LYH), and Danville (DAN), Virginia, and they are both located along major rivers. Along and west of the Blue Ridge, the majority of the population lives in river valleys, particularly in the Roanoke and New River Valleys of Virginia and the Greenbrier Valley of Southeastern West Virginia.

A majority of the WFO Blacksburg CWA is comprised of rural farmland or is heavily forested, and therefore has a low population density (Fig. 2), with only a few moderately populated cities. However, steep terrain and increasingly populated river valleys contribute to an overall significant flash flood threat over most of the CWA. The majority of homes and populated areas are along rivers and smaller streams, making the threat of damage and loss of life high, particularly in the small basins with steep slopes along and west of the Blue Ridge Mountains. One of the higher population centers, the city of Roanoke and surrounding Roanoke County, has several small stream basins with steep slopes, many of them with a history of flash flooding.

3. DATA

The data included in this study were compiled from 1994 to 2007. The beginning year of the study period corresponds to when WFO Blacksburg first opened. This was part of the NWS modernization, with an increased emphasis on verification and storm data. Data for this study were collected from Local Storm Data publications and the National Climatic Data Center (NCDC) Storm Events database located at [http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms] . Storm Data lists all reports as either flash flooding or flooding, and lists the reports by county, location within the county, date and beginning time. For the purposes of this study an event was defined as each report within a county with a unique time and date, and by the type listed in Storm Data (flash flooding or flooding). Multiple reports with the same date and time were treated as one event. For flood events, the event details page was used to separate the areal small stream floods from floods at river forecast points. This study consists of 1168 documented flash flood or flood events across the WFO Blacksburg's CWA between 1994 and 2007. All of the times are referenced to Local Standard Time (LST).

The NWS uses specialized software to monitor potential flooding called Flash Flood Monitor and Prediction (FFMP). In FFMP, radar estimated rainfall is compared to Flash Flood Guidance (FFG). The FFG is produced by NWS River Forecast Centers, and is an estimate of the amount of rainfall (for given durations, and across small stream watersheds) necessary to produce enough runoff to result in flash flooding. Average Basin Rainfall (ABR) computed from radar estimates for each small stream watershed is then compared to the FFG values in each watershed. In FFMP, one way to estimate the potential flash flood severity is by the Flash Flood Index (FFI), which is the difference in inches between ABR and FFG, (FFI = ABR – FFG) (Davis, 2002). For example, if the ABR for a given duration is 5.0 inches and the corresponding FFG is 2.0 inches, then the Flash Flood Index would be 3.0. Historical data from FFMP were not available for our study. However, since the goal was to classify the severity of floods listed in Storm

Data, a flood severity index was developed based on the impact description for each flood, which often lists monetary damages as well. Table 1 below shows this flood severity index.

4. FLASH FLOOD/FLOOD CLIMATOLOGY (1994-2007)

4.1 ALL FLASH FLOOD EVENTS

a) County Distribution

Flash floods have occurred in every one of the 40 counties in the WFO Blacksburg CWA. There are many factors that would contribute to variability of flash flooding across the WFO Blacksburg CWA, such as steep topography, small drainage basins, land use, soils, and vegetation. Land use, such as in small urban watersheds, can produce a quick flood response from even short duration convective rainfall (Smith et al. 2005). The distribution of flash flood events by county (Fig. 3) in the WFO Blacksburg CWA indicates that population density, which would be associated with more urban or suburban land use, is one of the main factors. Six of the 10 most densely populated counties are also in the top 10 counties for number of flash flood events. In addition, the larger urban areas (all independent cities in Virginia), which cover small portions of counties, have had more events than some of the rural counties. The cities of Roanoke/Salem (14), Danville (11), Lynchburg (7) and Martinsville (7) all had more flash flood events than the counties of Charlotte, Stokes and Yadkin (6 events each).When the severity of the flash flooding is factored in (Fig. 4), topography plays a larger role in the significant flash flood events. Some of the counties with the highest number of significant flash flood events were also counties with lower population density (Tazewell, Giles, Bath, Rockbridge, Franklin and Smyth). What these counties all have in common is small drainage basins in steep terrain.

b) Annual Frequency

There is a wide range in the number of flash flood events each year (Fig. 5) across the WFO Blacksburg CWA. Of the 766 flash floods reported during the 14-year period of this study, (1994 to 2007), the annual totals have ranged from a low of 6 in 1994, to a high of 105 in 2003. There were four drought years, (1999 through 2002), during the period of study. The number of flash flood events in each of the drought years, except for 2002, was above the 14 year median of 47. The 42 flash flood events in 2002 were near the median. In six of the fourteen years of the study, ('94, '95, '96, '03, '04 and '05), tropical storms or their remnants caused flash flooding. The total number of flash flood events in each of those years ranged from the lowest in the study period (six) to the second highest (103).

c) Monthly Frequency

The combination of steep topography and small basins in areas with heavy land use contribute to numerous flash flood events during meteorological conditions of deep moisture and strong forcing across the WFO Blacksburg CWA. Flash flood events can occur in widespread areas in the cool season, (October through March), with synoptic scale lift. Flash flood events occur in both localized and in widespread areas with convection in the warm season, (April through September). Widespread

Table 1: Flood Severity Index (FSI)

Flood severity scale	Flood category	Description
FS1	Nuisance	Few road closures, creeks and streams out of their banks. (Little or no damage)
FS2	Minor	Numerous road closures, numerous creeks and streams flooding, basement flooding, mudslides (Light Damage <$100K)
FS3	Moderate	Some rescues, evacuations, few houses/businesses flooded. (Considerable damage $100K-<$500K).
FS4	Severe	High Threat to Life/Property, several rescues, evacuation of and/or damage to several homes/businesses (Major Damage $500K-<$2M).
FS5	Catastrophic	Very High Threat to Life/Property, numerous rescues, evacuations of and/or damage to homes/businesses, (Catastrophic Damage ≥$2M). *Example: Johnstown, PA (7/20/77); Fort Collins, CO (7/28/97); Madison Co, VA (6/27/95)*

flash flooding may also occur with tropical remnants from July to November. (Hudgins et al. 2005)

Of 1168 documented flood events from 1994 to 2007 in Storm Data, 766 of them were classified as flash flooding. Flash flooding occurred within the WFO Blacksburg CWA in each of the 12 months (Fig. 6), with a maximum in June, and minimums in October and December.
The monthly distribution of events is represented by a slow increase during spring from March through May, a sharp rise from May to June, and then elevated numbers from July through September. In the cool season, the distribution of events is characterized by low numbers from October through December, a peak in January, and then low numbers again in February. The peak in January is attributable to synoptic scale moderate to heavy rain events occurring in conjunction with efficient runoff due to wet antecedent moisture conditions, dormant vegetation, and in some cases frozen ground. Sixty three of the 75 flash floods in January occurred in four synoptic scale events.

June has the highest number of flash flood events, (187), representing nearly 25% of the total, which is also nearly twice the number of the next highest month. The second, third, and fourth highest months are all in the warm season and include July (104), September (93), and August (90). This is consistent with previous studies (i.e., Schumacher and Johnson, 2005a), showing that the southeast U.S. has a peak of flash flooding in the warm season (specifically June and September), but that flash flooding occurred at all times of the year. January had the fifth highest number (75) of flash flood events in the WFO Blacksburg CWA.

Overall, 62% (474) of all flash flood events occurred during the months of June, July, August and September, and over 75% (581) occurred during the warm season from April through September. In the cool season from October through March, January accounted for 41% (75) of the total flash flood events (185).

d) Hourly Distribution

All flash flood events were stratified by their time of occurrence as reported in Storm Data, which is the time that flooding began. Flash flood events occurred at all hours of the day (Fig. 7). The distribution of flash flood events by time, (Local Standard Time, LST), shows a gradual rise from a low point in the early morning (300 am to 600 am), to a peak in the late afternoon and early evening (300 pm to 600 pm), and then a sharp decline after 900 pm. Over a third (290 or 38%) of all events occurred between 300 pm and 900 pm. This covers the time of peak heating for convection (300 pm to 600 pm), and a lag period for runoff (600 pm to 900 pm). Nearly two thirds (486 or 64%) of all events occurred during the 12 hour period from 900 am to 900 pm.
e) Magnitude

All of the flash flood events were classified according the Flood Severity Index (Table 1). Out of the 766 Flash Flood events (Fig. 8), nearly 47% (356) were categorized as FS1. With the addition of all FS2 events (281), the vast majority of flash flood events, over 83%, were either FS1 or FS2. Another 11% (84) of the events were FS3, so a very small number (43 or 6%) of all flash flood events in the WFO Blacksburg CWA from 1994 to 2007 were FS4 or FS5. Although the significant flash flood events (FS3, FS4 and FS5) were relatively rare, they are critical in terms of forecasts and warnings because of their huge impact with hundreds of thousands to millions of dollars in damage and greater potential loss of life. There were seven flood events with one or more fatalities during the period of study, and all but one of the events were FS3 or higher.

Significant flash flood (127) events occurred in every month of the year except December (Fig. 9). Nearly two thirds of them, (81 or 64%), occurred during the following three months: June (32), January (26), and September (23). Three other months had higher totals of ten or more: May (12), November (12), and July (10). It is not surprising that June is the peak for significant flash flooding, as it is also the peak for all flash flooding. A second peak in September could also be expected as this month had the third highest of all flash flood events, and would be heavily influenced by remnants of tropical systems which have historically brought many of the area's significant floods. Twenty of the twenty three significant flash floods in September were associated with two tropical storms or their remnants (Fran, September 4-6, 1996 and Jeanne, September 27-28, 2004). Likewise, the secondary peak for significant flash flooding in January was heavily influenced by just a few synoptic scale storm systems. The twenty six significant flash flood events in January occurred from only four storm systems. One storm on January 18-19, 1996 accounted for 14 of the significant flash flood events. This storm featured rapid snowmelt of a deep snow pack, in addition to the heavy rainfall (Leathers et al. 1998). The three other storms in January that accounted for the rest of the significant flash flood events (12), did not involve significant snowmelt.

During the period of study, there were a total of 17 synoptic scale systems that produced multiple events of significant flash flooding. Ninety seven of the 127 significant flash flood events (76%) occurred in one of these 17 storms, indicating that significant flash flooding is most often widespread enough to occur in multiple counties. A radar study of 116 extreme rainfall events in 1999 to 2001 for the eastern U.S. (rainfall exceeding the 50 year recurrence interval for 24 hour precipitation accumulation) found that 65% of the events were associated with a meso-scale convective system (MCS). (Schumacher and Johnson 2005b) Seven of the 17 storms occurred in the cool season, (October through March), and ten occurred in the warm season, (April through September). Four of the cool season events were in January, and four of the warm season events were in June.

There were two areas, or clusters of counties, (Fig. 10) that emerged in the spatial distribution of significant flash flood events associated with these synoptic scale storm systems. One area (Zone 1) that had several (7) storms in common encompassed the region that extends from the southwest mountains of Virginia, (Smyth and Tazewell counties), northeast into southeast West

Virginia, (Mercer, Summers and Greenbrier counties). The other area (Zone 2) that had several (5) storms in common was in the region that extends along the Blue Ridge in southwest Virginia from Franklin and Roanoke counties, northeast through Bedford, Campbell, Botetourt, Rockbridge and Amherst counties. These areas have topographic similarities, with Zone 1 being predominately western slopes of the Appalachian Mountains, and Zone 2 primarily eastern slopes of the Blue Ridge Mountains.

The lower numbers of significant flash flood events in July and August stand out since they occur during the convective season when the moisture content of the atmosphere is at its climatological peak (precipitable water during these two months averages from 1.25 to 1.50 inches). However, there are several factors that are less conducive to significant flash floods in July and August. Weaker upper level flow tends to produce less organized convection making very heavy downpours more isolated. As noted earlier, significant flash flood events are usually widespread, occurring most often (76%) in multiple counties. There were only two storm systems that produced multiple significant flash flood events in July, and none in August. July and August are also before the tropical season peak of September. Finally, beginning in July, antecedent soil moisture conditions are typically driest as evapotranspiration is at a maximum, and remain near their driest point into November (Climate Prediction Center, 2008).

f) Geospatial Analysis of Flash Flood Prone Stream Basins and Historical Reports

WFO Blacksburg has a local historical database of flash flooding for the years of 1995-2008, which includes a listing of specific locations that have flooded. Many of the flood events listed in Storm Data do not include specific locations, in particular the creeks and roads that were flooded, so the local database has fewer events than Storm Data. However, the local flood database has been useful as another tool for forecasters in warning decision making and also in adding more specificity to the warnings when they are issued.

The Blacksburg NWS has recently begun exploring methods for displaying these historical flash flood reports across the CWA, which includes superimposing with high resolution geospatial information. By entering details of all known flash flood events into a spreadsheet, the data can be imported as an overlay in ArcGIS (ESRI 2009), and ultimately into AWIPS as a shapefile where attributes of each plotted flash flood report can be sampled, and used in future warnings. Within ArcGIS, we are able to overlay historic flash flood locations (if the specific location of an event is known) with a high resolution terrain image (Fig. 11), as well as with physiographic gridded datasets interpolated to small stream basin areas. The method for processing these data, which include land use, slope, forest density, and soil texture, is described in Smith (2003), and includes the development of an experimental "Flash Flood Potential Index" (FFPI) by combining the four layers by initially providing equal weighting to each. An example of the historical flash flood reports overlaid with one of these layers (land use), and also with the combined FFPI image at the resolution of the small stream basins is shown in Figs 12 and 13 respectively. One of the goals of combining these geospatial datasets is to provide forecasters with a high resolution analysis of the most flash flood prone locations across the CWA, down to the individual stream and road crossing by sampling the details of the layer information. Another goal is to integrate this climatological information (past flash flood events and high threat basins) into decision support tools such as the Flash Flood Monitoring and Prediction (FFMP) application, so that precipitation estimates/forecasts and gridded flash flood guidance can all be used together.

4.2 ALL FLOOD EVENTS

According to the NWS Directive 10-922 (NWS, 2007a), watches and warning for floods are required for both areal floods (covering portions of or multiple counties), and floods along rivers at forecast points. Therefore, in this study we separated occurrences of areal flooding from the flooding at forecast points. Overall, there have been 402 documented flood events from 1994 to 2007. Of that total, 277 were flood events at one of the 27 forecast points in the Blacksburg CWA.

4.3 AREAL FLOOD EVENTS

a) County Distribution

There were a total of 125 areal flood events during the period of study. Areal floods were documented in 37 of the 40 counties in the WFO Blacksburg CWA (Fig. 14). Mercer County in WV, Giles and Charlotte Counties in VA, are the only ones where no reports of areal flood events have been documented from 1994 to 2007. This is probably attributable to the shortness of the period of study, (14 years), since there were also several (10) counties with only one event. The factors that would contribute to variability of areal flooding across the WFO Blacksburg CWA are much the same as the factors that contribute to flash flooding, such as land use, soils, and vegetation. The difference would be that topography with a gentler slope would promote a slower response to runoff from heavy rain, and a better chance for areal flooding. As stated earlier, there is a rapid increase in elevation from southeast to northwest across the WFO Blacksburg CWA. Piedmont areas in the east have the gentlest slope, with slopes increasing as you move northwest into the foothills and then the mountains. The distribution of areal flood events by county in the WFO Blacksburg CWA shows higher numbers of areal floods in the Piedmont and foothills. Five counties accounted for a third (33%) of all areal floods. Of those five counties, three (Pittsylvania VA, Caswell and Rockingham NC), are in the Piedmont, and two (Botetourt and Campbell VA) are in the foothills. There does not appear to be any correlation between population density and the number of areal floods. When the severity of areal flooding (Fig. 15) is factored in, topography plays a larger role. There were 17 counties in the WFO Blacksburg CWA that had Moderate (FS3), Severe (FS4), or Catastrophic (FS5) areal flooding. Most (13) of those counties were along the

Blue Ridge Mountains in northwest North Carolina and southwest Virginia where upslope flow often enhances rainfall with tropical remnants and other synoptic systems with a strong southeast flow.

b) Annual Frequency

There is a wide range in the number of areal flood events from year to year (Fig. 16) across the Blacksburg CWA. During the 14 year period of this study, (1994 to 2007), the totals have ranged from a high of 51 in 2003, to several years, (1994, 1995, 1997, 1999, 2000, 2001, 2002), having none. Drought conditions were present from 1999 through 2002, with 1999 and 2002 having severe drought conditions of -3 on the Palmer Drought Severity Index, (NCDC 2008). As has been noted in other studies (D'Odorico and Porporato 2004), land–atmosphere feedback mechanisms may sustain and enhance the effect of initial moisture anomalies occurring at the beginning of the warm season, and because of such feedback, summer soil moisture dynamics evolve toward either a dry or a wet state in which the system may remain locked for the rest of the warm season. Due to the dry state present during drought years, there would be much less widespread heavy rain which produces both areal flooding and river flooding.

c) Monthly Frequency

Areal flood events occurred in every month of the year (Fig. 17). Most months had low numbers (10 or less), but the four month period from May through August stands out as a relative minimum, with only 15 events of the 125 total. This period represents the peak of the convective season when rainfall rates would usually be high enough to produce flooding in less than six hours, so would be frequently classified as flash flooding. The period of May through August also represents the peak of vegetation growth, and when antecedent soil moisture conditions are at their driest. Long duration moderate to heavy rainfall events would not generate as much runoff in May through August as in the cool season. There were two months, February and September, with 42% (53 events) of the areal flooding. February is near the end of the dormant vegetation season, so runoff is still efficient. Runoff from snowmelt did not appear to be a factor in the majority of February areal floods during the period of study. Meanwhile, rainfall producing weather systems are synoptic in scale but with little convection, so may produce prolonged periods of moderate rainfall. The September maximum corresponds to the peak for widespread rainfall associated with the remnants of tropical systems (Hudgins et al. 2005)

d) Hourly Distribution

All areal flood events were stratified by their time of occurrence as reported in Storm Data, which is the time that flooding began. Areal flood events occurred at all hours of the day (Fig. 18). The distribution of areal flood events by time, (Local Standard Time, LST), shows a steep rise from minimums around midnight in two 3-hour periods, (900 pm to midnight, and midnight to 300 am), to a peak in two 3-hour periods around noon, (900 am noon, and noon to 300 pm). Nearly half (45%) of all the areal flood events occurred between 900 am and 300 pm. With the peak frequency occurring before the peak heating of the day, it suggests that areal flooding is most often not a direct result of heavy precipitation from convection. Only 20 of the 125 events (16%) occurred during the 900 pm to 600 am period. One of the reasons for this minimum may be that minor areal flooding is more easily identified during daylight hours.

e) Magnitude

To stratify the severity of the areal flood events (Fig. 19) we also utilized the Flood Severity Index detailed in Section 3, since the descriptions of impact and monetary damages are listed the same way in Storm Data. Over a third of the 125 areal flood events from 1994 to 2007 (38%, or 47), were significant, (FS3 or higher). The majority of significant areal flood events, over 40%, (20), occurred in the month of September (Fig. 20). All but two of the 20 significant areal flood events in September were associated with the remnants of tropical systems (Fran, September 4-6, 1996, Isabel, September 17-19, 2003, Frances, September 5-8, 2004, Ivan, September 15-17, 2004 and Jeanne, September 27-28, 2004). Twenty one of the remaining twenty eight significant areal flood events occurred in the cool season. All of the 21 cool season events were associated with only three synoptic scale storm systems. Each of these storms brought heavy precipitation, producing significant flooding in several counties. In January (8 events) all the flooding resulted from widespread warm heavy rainfall and snowmelt on January 19, 1996. In February (6 events), all the flooding resulted from a deepening low pressure in the southeast U.S. on February 22 to 23, 2003, producing heavy overrunning rainfall. In November (7 events), all the flooding was caused by a heavy upslope rainfall on November 19, 2003. The rest of the significant areal flood events, June (4), March (1) and July (1), all came from less organized systems and were not as widespread.

Ninety five of the 125 areal flood events (76%) were not preceded by flash flooding, which by definition would mean that they were the result of prolonged rainfall of 6 hours or more. Also, over 60% of the significant areal flood events, (29 of 47) were not preceded by flash flooding. It takes high volumes of water to cause considerable damage, and necessitate evacuations and/or rescues, on smaller streams. These significant areal flood events are good examples of the impact that prolonged moderate to heavy rainfall can have in mountainous areas.

A good example of a tropical system bringing significant areal flooding was the remnants of Frances, on September 7-8, 2004. It produced significant areal flooding in seven counties with no flash flooding preceding it. Widespread rainfall amounts over an 8 to 12 hour period ranged from 6 to 8 inches, with hourly rainfall rates seldom greater than 1 inch per hour. A good example of a synoptic scale system that resulted in significant areal flooding occurred on February 22, 2003, in which a deepening low pressure system moved northeast from the Gulf of Mexico and into the Tennessee Valley, bringing widespread 2.5 to 3 inches of rainfall in a 12 hour period, with up to 2 inches in a 6 hour period. Rainfall rates were seldom greater than 0.5 inches per hour. This system produced significant areal flooding in six counties with no flash flooding preceding it.

4.4 RIVER FORECAST POINT FLOOD EVENTS

a) Flood Frequency at Forecast Points

There are 26 river forecast points in the WFO Blacksburg Hydrologic Service Area (HSA), five of which are headwater forecast points (Fig. 21). The number of floods at each forecast point (Figs. 22, 23, and 24) during the 14 years of the study ranged from zero, (Hinton, WV), to 44, (South Boston VA). There are five river forecast points with dams immediately upstream from the gauge, which reduces the flood potential in various amounts. Hinton, WV has never flooded since the Bluestone Dam immediately upstream was built in 1945. Wilkesboro, NC has only flooded five times since the dam was built there in 1962 and only once during the period of study. The other three locations with dams immediately upstream: Covington, VA had two floods during the period of study; Radford, VA had four floods; and Altavista, VA had eight floods. Other than the influence of dams, the other main factor in the number of floods at a particular forecast point was related to location along the river. On each of the six major rivers with more than one forecast point, (James, Roanoke, Dan, Yadkin, New and Greenbrier), headwater points generally had the fewest floods with the number of floods increasing with each forecast point downstream. For example, along the Roanoke River, the city of Roanoke at the headwaters had 11 floods, Altavista downstream had eight floods with some protection from a dam, Brookneal had 14 floods, and Randolph had 27 floods. Three forecast points at the ends of major rivers, (Bremo Bluff on the James, Randolph on the Roanoke, and South Boston on the Dan), accounted for 34 % (95 of 277) of all river floods.

The majority (233 of 277, or 84%) of the river flood events were preceded by either flash flooding or areal flooding. There were two locations that were notable exceptions to this. Of the 13 flood events at Alderson on the Greenbrier River, nearly half (6) were not preceded by flash flooding or areal flooding in the WFO Blacksburg CWA. Three of those six were moderate floods. The high number of river floods at Alderson with no smaller scale flooding preceding them is partially because it is the only river forecast point in the WFO Blacksburg CWA that has its headwaters outside of the CWA. One of the six events not preceded by flash flooding or areal flooding in the WFO Blacksburg CWA was preceded by smaller scale flooding in the headwaters of the Greenbrier River in Pocahontas County. The Greenbrier River has a large drainage area (1,364 square miles) and has no dams to regulate high water flows. Alderson is at the lower end of the river, so there are times that non-flooding heavy rainfall across the drainage area produces river flooding at Alderson. There were 44 flood events at South Boston on the Dan River, and 32% (14) were not preceded by flash flooding or areal flooding. Twelve of those 14 were minor floods, and two were moderate. The Dan River has a very large drainage area (3,300 square miles) and also has few dams to regulate high water flows. South Boston is at the lower end of the river, so there are times that non-flooding heavy rainfall across the drainage area produces river flooding at South Boston.

b) Annual Frequency

There is a great variability in the number of river forecast point flood events each year across the Blacksburg CWA (Fig. 25). During the 14 year period of this study (1994 to 2007) the totals have ranged from lows of one event in both 2000 and 2005, to highs of 59 in 1996, and 55 in 1998. As was noted with areal flooding, there were drought conditions from 1999 to 2002, and there were only 17 river forecast point floods during that four year period. The period from 2005 to 2007 also had a rainfall deficit, with drought conditions developing in 2007. There were only 15 river forecast point floods in that three year period.

c) Monthly Frequency

River floods at forecast points occurred in every month of the year (Fig. 26). There were high numbers in each month in the late cool season from January through March. January had the highest number of flood events for all months, with 61, which is 22% of the total. February had 47 events, or 17% of the total, and March had 37 events, or 13% of the total. The three month period of January through March had over half the river flood events, with a total of 145 events, or 52% of the total. The four month period of January through April accounted for 61% (170) of the river flood events. The high percentage of flood events in the late cool season is likely attributable to efficient runoff due to saturated or frozen soils, dormant vegetation and melting snow cover. There were other peaks in the number of flood events during June and September. The June peak of 26 events corresponds to the peak month for flash floods, and is likely attributable to more widespread flash floods which evolve into river flooding. The September peak of 37 events, which tied for the third highest month, corresponds to the peak in tropical remnant activity across the area from 1994 to 2007; five of the seven tropical related flood events occurred in September.

Overall, 84% (233) of all river forecast point flood events occurred during six months: January, February, March, April, June and September. There were three months with less than 10 events. July, (six events), and August, (eight events), represent the peak of vegetation growth and evapotranspiration, along with less organized convective systems which produce more isolated to scattered heavy rain. October, (six events), is climatologically one of the driest months of the year for the area, with average precipitation of just 3.38 inches (Fig. 27).

d) Hourly Distribution

All river flood events were stratified by their time of occurrence, which is defined in Storm Data as when flooding began at the gage. River forecast flood events occurred at all hours of the day (Fig. 28). The distribution of river flood events by time, (Local Standard Time, LST), shows less of a trend than flash flooding or areal flooding, but has a relative maximum in the morning with a peak from 600 am to 900 am. This is 12 to 15 hours later than the flash flood peak and may represent the lag time for runoff from creeks and small streams to the mainstem rivers.

e) Magnitude

The severity of river flooding is based on three categories: minor, moderate and severe. These categories correspond to pre-defined ranges of levels above flood stage, which varies at each forecast point. Of the 277 events, 95 were classified as moderate, and 25 were classified as major (Fig. 29), the rest (157) were classified as minor.

For the purposes of this paper, we are defining significant river flooding as moderate or major. Impacts to areas around the river gage are much greater beginning at the moderate flood stage. Significant flooding accounted for 43% (120 of 277) of the river flood events in the Blacksburg HSA. Significant river flooding occurred in every month of the year (Fig. 30). January had the highest number of significant river flood events (32), and the three month period of January through March accounted for over 50% (63 of 120) of all significant river flood events. Just as with river flood events in general, the peak in significant flooding from January through March is likely attributable to efficient runoff due to saturated or frozen soils, dormant vegetation and possibly melting snow cover. Average discharge on the rivers is also climatologically higher during this period. September also had a secondary peak of significant river flooding (21), corresponding to the peak for widespread rainfall associated with the remnants of tropical systems. Minimums of significant river flooding occurred in July (1), and August (5), when runoff is least efficient and average discharge on the rivers is climatologically lowest. October (1), November (4) and December (3) also had minimums of significant river flooding. These months have three of the lowest average monthly precipitation amounts for the area, and average discharge on the rivers is also climatologically lower.

There is no discernable pattern to the distribution of the severity of river flooding by locations of the forecast points on the rivers. This is likely because the severity of the flooding is largely determined by the impacts of certain water levels to homes, businesses and other structures near the forecast point. Thus the severity categories are unique for each forecast point.

4.5 FLOOD AND FLASH FLOOD EVENTS ASSOCIATED WITH TROPICAL SYSTEMS

There were eight tropical systems during the period of study (1994 to 2007) that caused flooding or flash flooding in the WFO Blacksburg CWA. All of the flood events from these tropical systems occurred along and east of the Blue Ridge Mountains (Fig. 31). Of the eight tropical systems, one had minimal impact, causing nuisance or minor flooding. Cindy, in July of 2005, brought nuisance flooding to Halifax and Pittsylvania counties. The other seven tropical systems brought at least moderate areal or flash flooding (FS3) to one or more counties in the Blacksburg CWA. There were two groupings of counties that had more than one significant flood event associated with a tropical system (Fig. 31). The northern mountains of North Carolina (Zone 1) would have strong upslope enhancement from south-southeast winds, due to the orientation of the Blue Ridge, and a steep escarpment. Tropical systems bringing significant flooding to Zone 1 include Opal, Frances and Ivan, and they all had tracks either along the spine of the Appalachians, or west of the mountains. The area along the Blue Ridge in southwest Virginia (Zone 2) would have upslope enhancement from southeast winds, and these counties are also more heavily populated. Tropical systems bringing significant flooding to Zone 2 include Beryl, Fran, Isabel, Frances and Jeanne, and they all had tracks either along the spine of the Appalachians, or east of the mountains.

Impacts from individual storms include the following: Beryl, in August 1994 brought moderate flooding to Rockbridge County, and minor flooding to Amherst and Bedford Counties in Virginia. Opal, in October, 1995, impacted only six counties, but brought moderate flooding to four of them. Fran, in September, 1996, had the greatest impact in terms of severity, with 17 of the 40 counties in the WFO Blacksburg CWA affected. Fifteen of the 17 counties affected had moderate flooding or worse, with six counties reporting severe (FS4) flooding, and three catastrophic (FS5) flooding. Isabel, in September of 2003, caused flooding in eight counties, with only nuisance to minor flooding in seven of those eight counties. However, one county (Rockbridge) had catastrophic (FS5) flooding. Frances, in early September of 2004, had a widespread impact, with 14 counties affected, and seven of those 14 reporting moderate flooding. Another tropical remnant, Ivan, in mid September, brought flooding to only Watauga County North Carolina, but it was severe. Finally, a third tropical system in late September of 2004, Jeanne, affected portions of the area. Jeanne had a widespread impact, affecting 18 counties, but 14 of them had only nuisance or minor flooding. However, two counties reported moderate flooding, and Roanoke and Botetourt counties had severe flooding.

All of the storms listed above brought excessive rainfall of 6 inches or more to portions of the WFO Blacksburg CWA (Hudgins et al. 2005). Other factors, such as antecedent conditions and rainfall rates, play a role in determining the severity of the flooding experienced.

5. CONCLUSIONS

This local flash flood and flood climatological study provides forecasters an improved understanding of the frequency, severity and geographical distribution of seasonal and diurnal flood events across the Blacksburg CWA, and will improve situational awareness and help enhance flash flood and flood warning decisions for the protection of life and property.

Following is a summary of the key findings:

- There is a wide range in the annual variability of flood events each year across the Blacksburg CWA. During the 14 year period of this study (1994 to 2007), the flash flood totals have ranged from a low of 13 in 2005, to a high of 105 in 2003. The flood totals, (areal and river), have ranged from a low of 0 in 2002, to a high of 113 in 2003.

- Flash flooding and areal/river flooding occurred in every month of the year.
- 25% of all flash flood events occurred in June.
- Overall, nearly 62% of all flash flood events occurred during the months of June, July, August and September, and over 75% occurred during the warm season from April through September.
- Flash flood events occurred at all hours of the day.
- The distribution of flash flood events by time shows a gradual rise from a low point in the early morning (300 am to 600 am), to a peak in the late afternoon and early evening (300 pm to 600 pm), and then a sharp decline after 900 pm.
- The vast majority of flash flood events, nearly 83%, were classified as either FS1 (nuisance) or FS2 (minor).
- Significant flash flood events (FS3, FS4 and FS5) occurred in every month of the year except December.
- 17 % of all flash floods were significant (FS3, FS4 or FS5). Only 6% were severe or catastrophic (FS4 or FS5).
- June was the peak for significant flash flooding, with 25% (32) of the total (127). There were also peaks of significant flash flooding in January (efficient runoff and possible snowmelt), and September (tropical), both around 20% of the total.
- The majority (76%) of significant flash floods occur in multiple county events.
- Areal flood events occurred in every month of the year except for July.
- Only 12% of the total areal flood events occurred in the four month period from May through August.
- Over 40% of the areal flooding occurred in February and September.
- Over a third of the areal flood events (38%), were classified as significant flooding (FS3 or higher).
- The vast majority (87%) of significant areal floods occur from either tropical remnants, (42%), or large scale synoptic storms in the cool season (45%).
- River forecast point floods occurred in every month of the year.
- January had the highest number of river flood events for all months with 22% of the total.
- January through March accounted for over half (52%) of the river forecast point flood events.
- September (tropical peak) had a secondary maximum of river forecast point floods with 37 events.
- Nearly a half (46%) of the river floods at Alderson on the Greenbrier River, and nearly a third (32%) of the river floods at South Boston on the Dan River, were not preceded by flash flooding or areal flooding in the WFO Blacksburg CWA.
- June (flash flood peak month) had a tertiary peak of river forecast point floods with 26 events.

- Eight tropical systems caused flooding or flash flooding during the period of study (1994 to 2007). Seven of those caused significant flooding.
- Fran, in September, 1996, had the greatest impact in severity. 17 of the 40 counties in the WFO Blacksburg CWA were affected. Fifteen of the 17 counties affected had moderate flooding (FS3) or worse, with six counties reporting severe (FS4) flooding, and three catastrophic (FS5) flooding

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Reference to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its, or favoring by the United States Government or NOAA/National Weather Service**.** Use of information from this publication shall not be used for advertising or product endorsement purposes.

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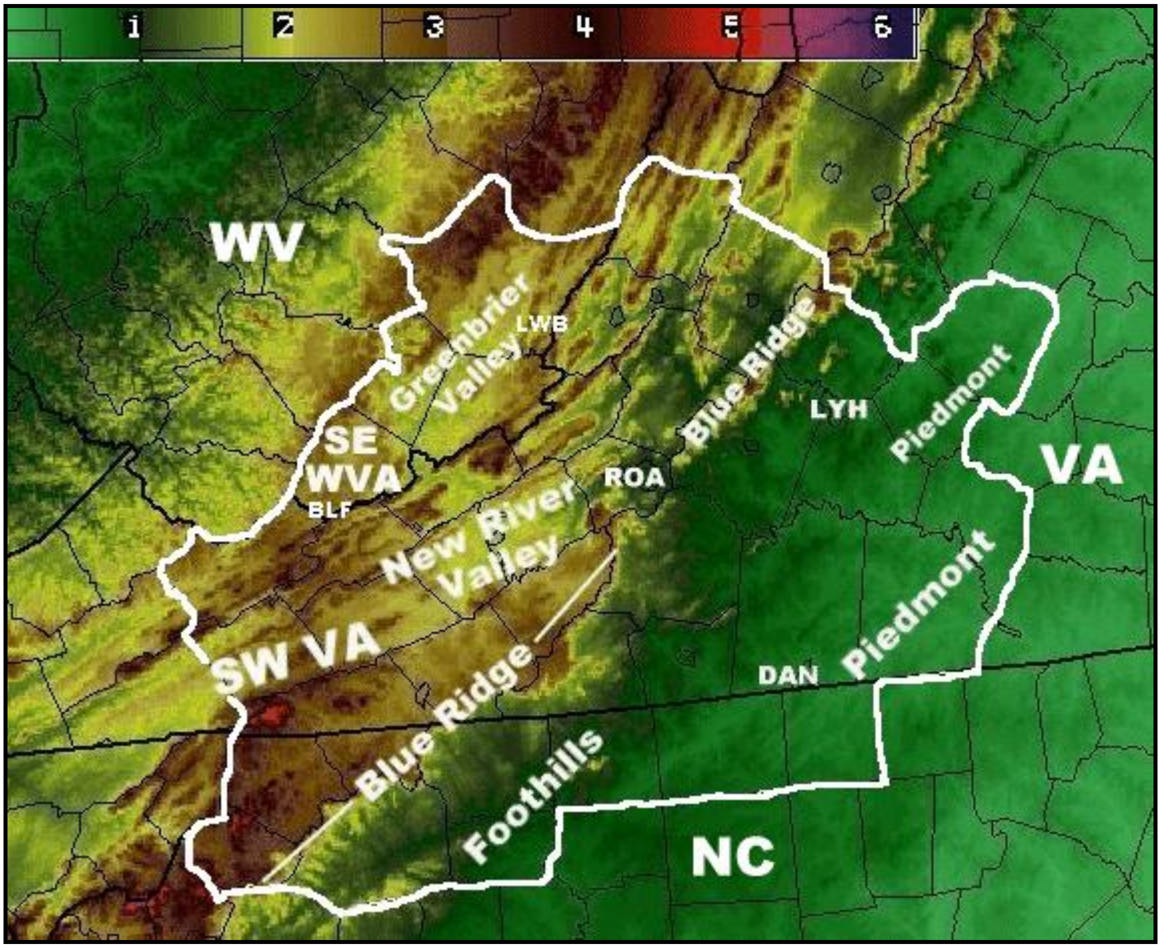

Figure 1. WFO Blacksburg, VA, (RNK) County Warning Area (white border) and regional/topographical map indicating geographical areas (scale in thousands of feet).

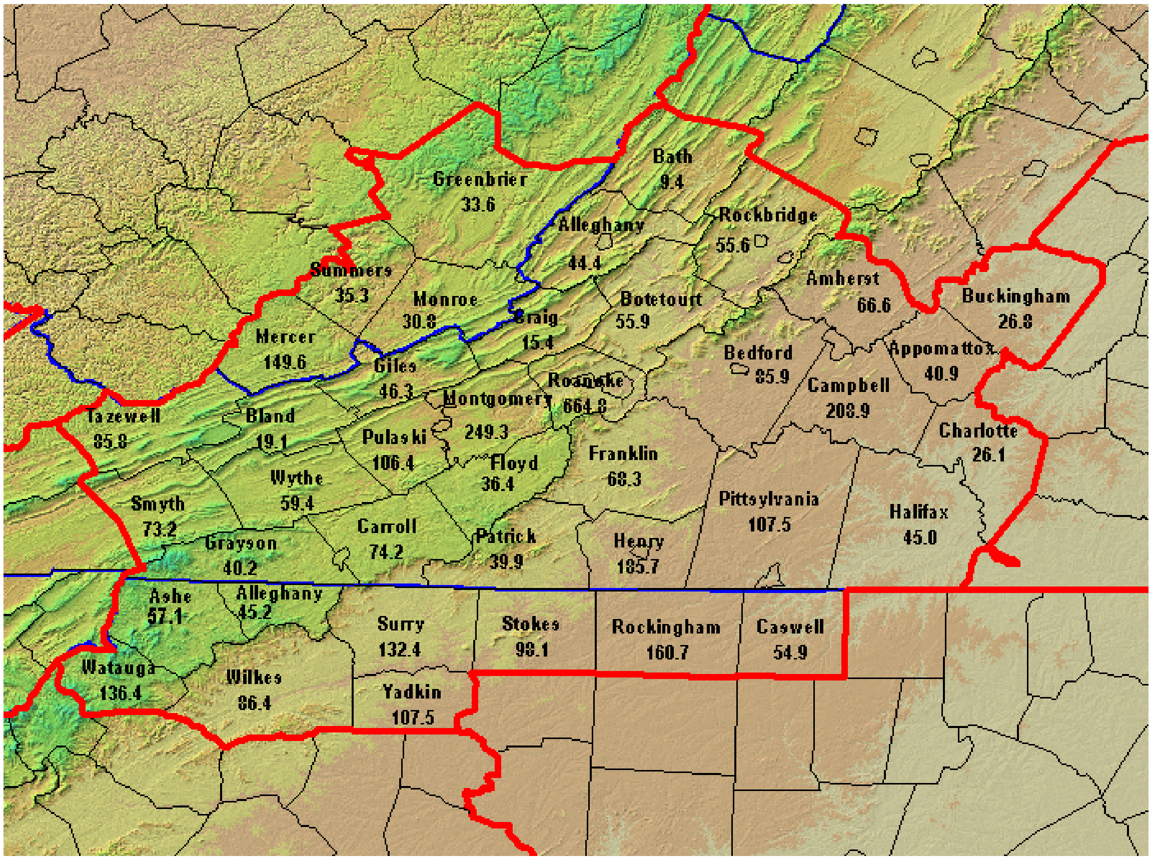

Figure 2. Population density (persons per square mile by county) based on 2000 Census Data.

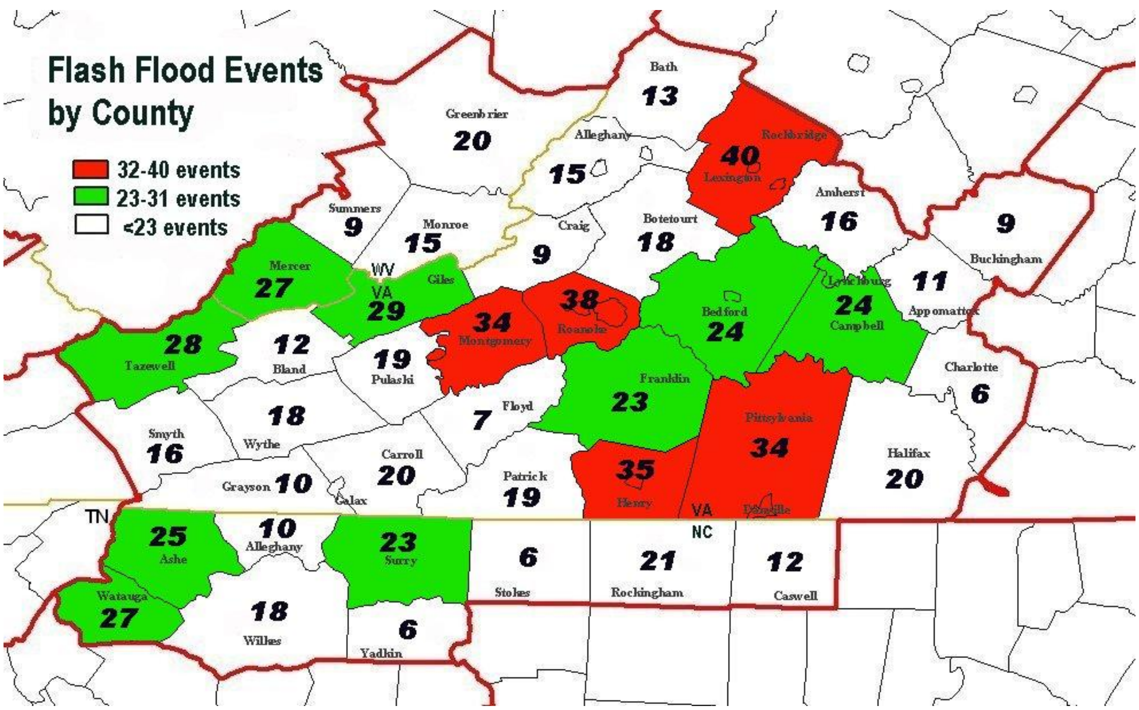

Figure 3. Flash flood events by county (1994-2007).

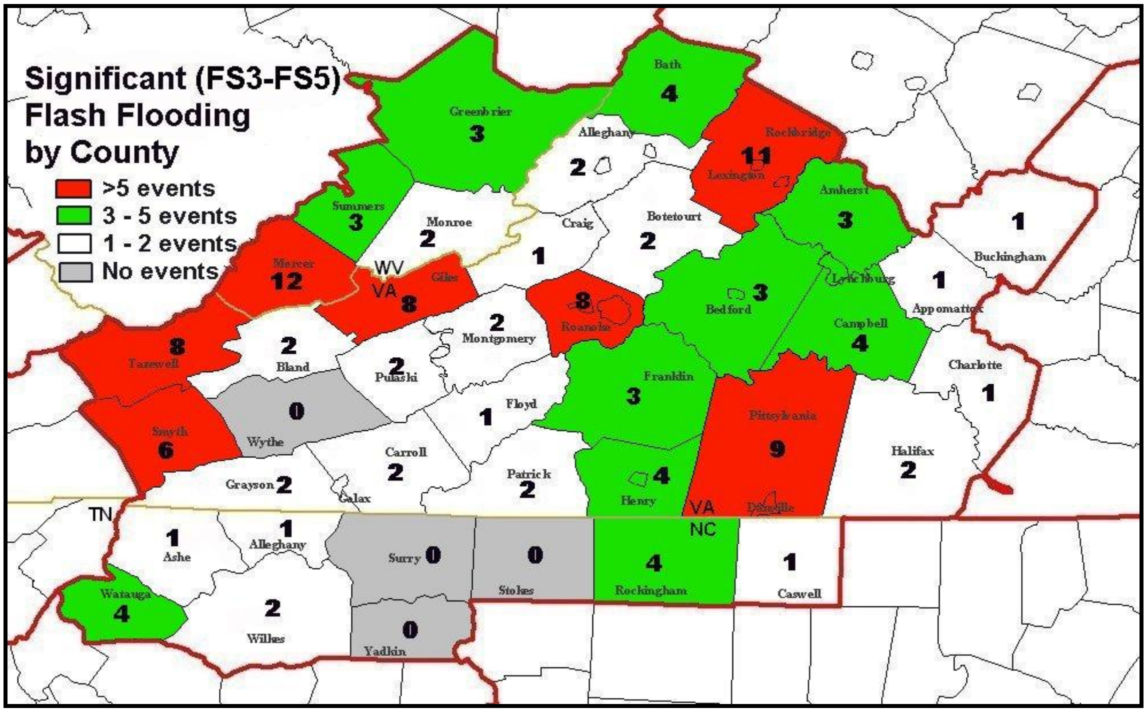

Figure 4. Significant (FS3-FS5) flash flood events by county (1994-2007).

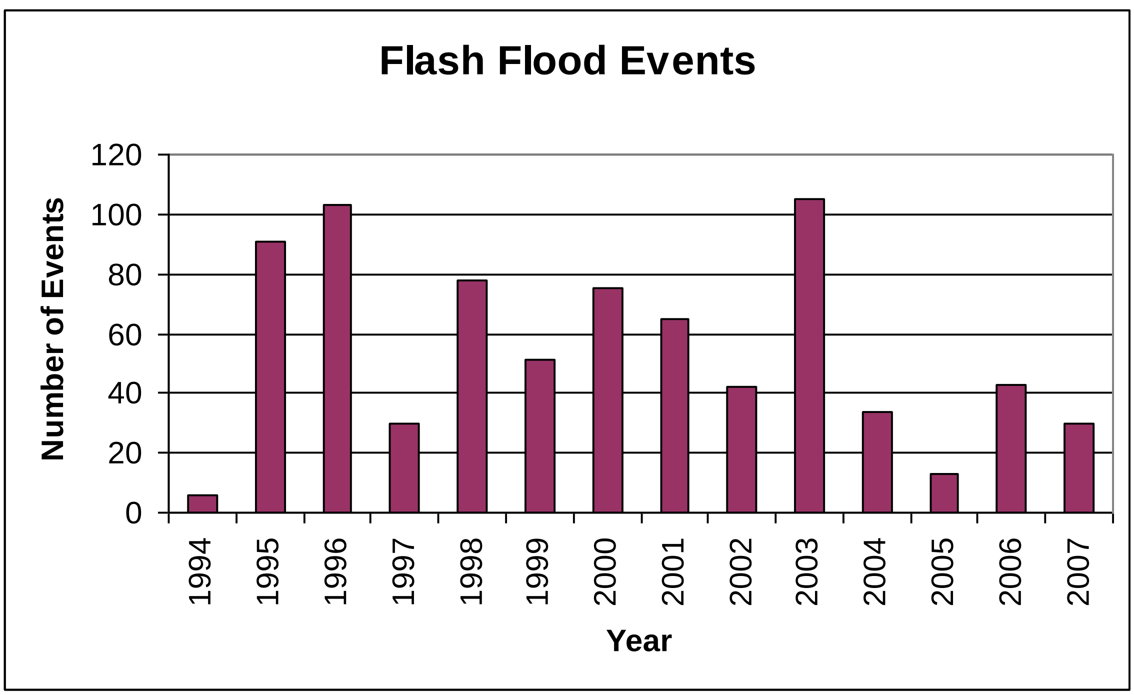

Figure 5. Flash flood events by year (1994-2007).

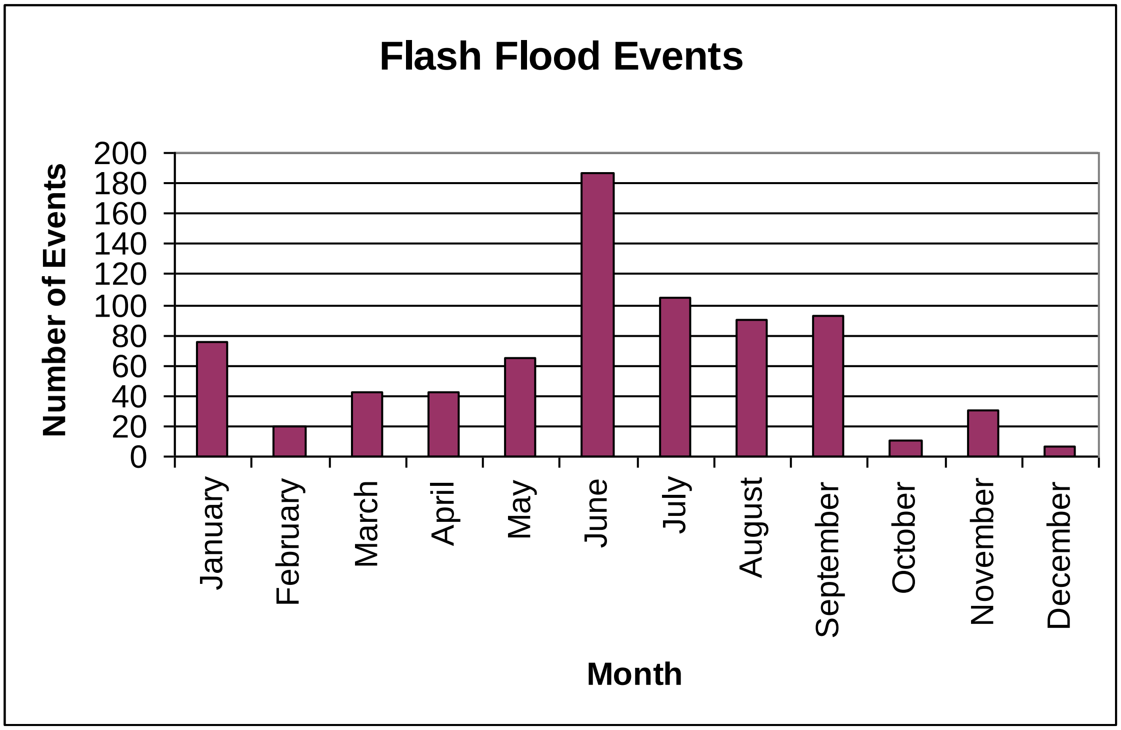

Figure 6. Flash flood events by month (1994-2007).

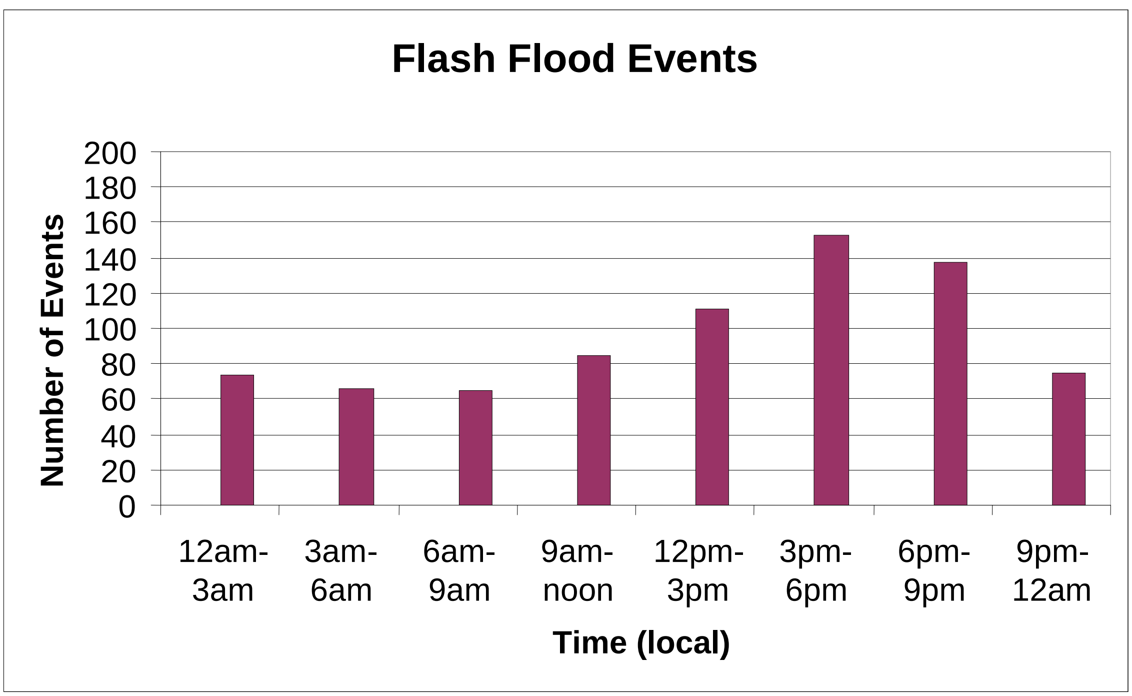

Figure 7. Flash flood events by time (1994-2007).

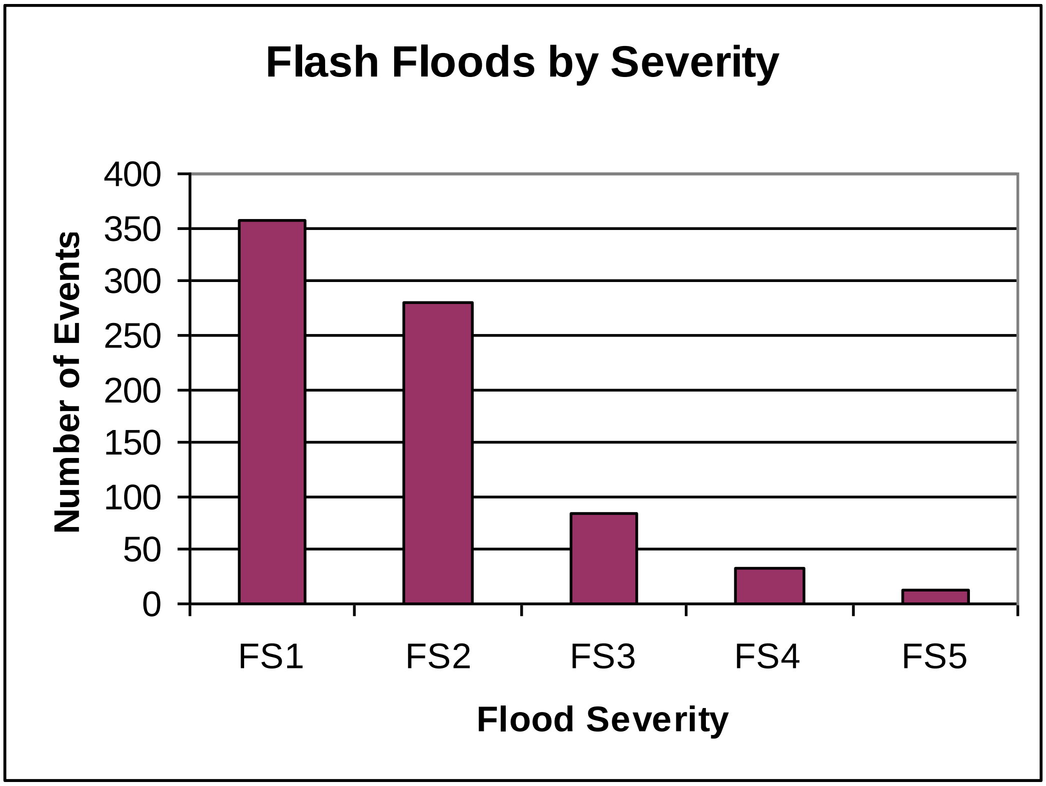

Figure 8. Flash flood events by Flood Severity Index (1994-2007).

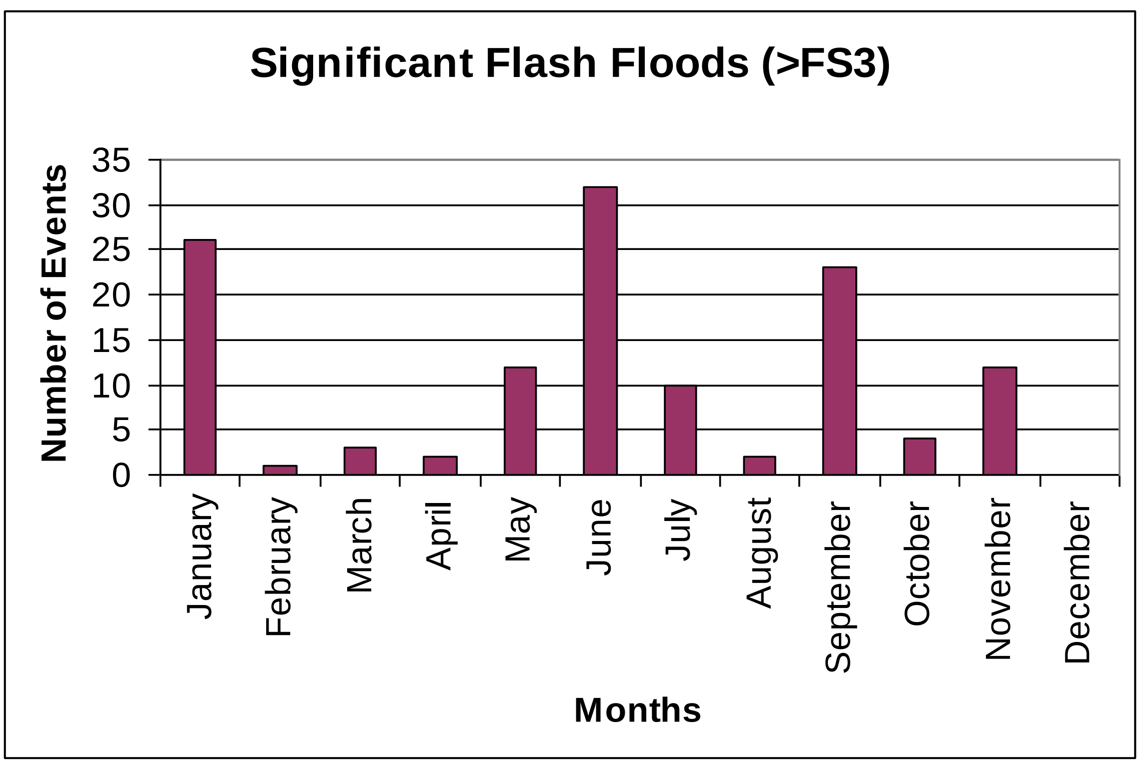

Figure 9. Significant (FS3-FS5) flash flood events by month (1994-2007).

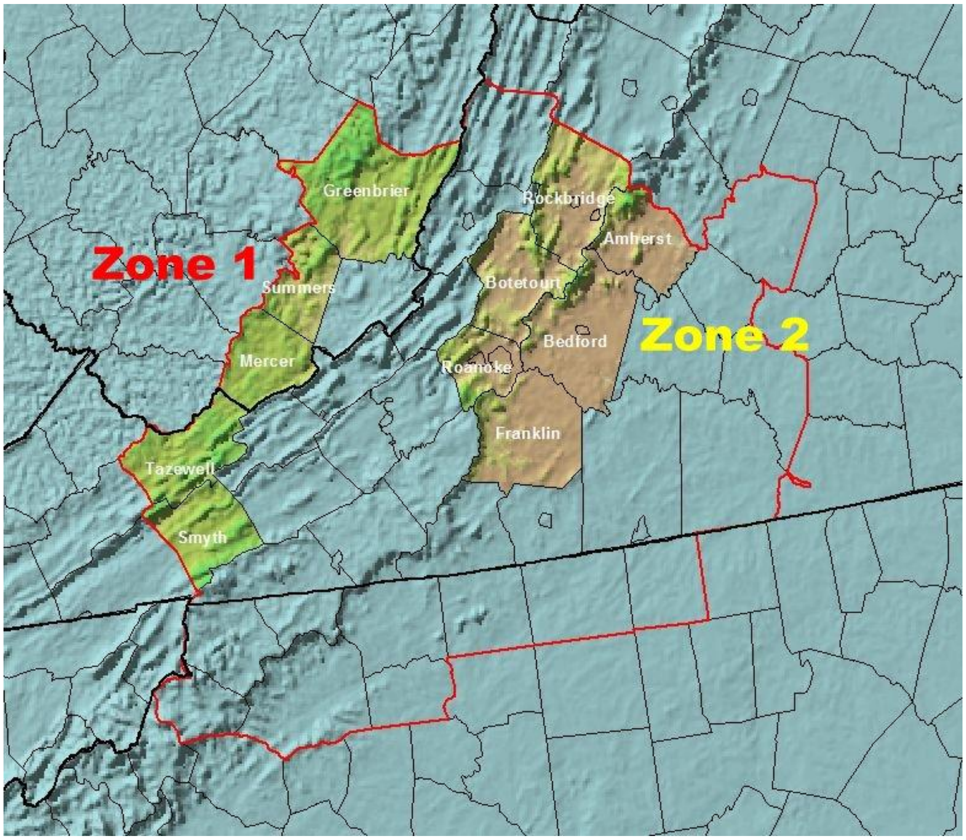

Figure 10. Synoptic scale significant flash flood event zones.

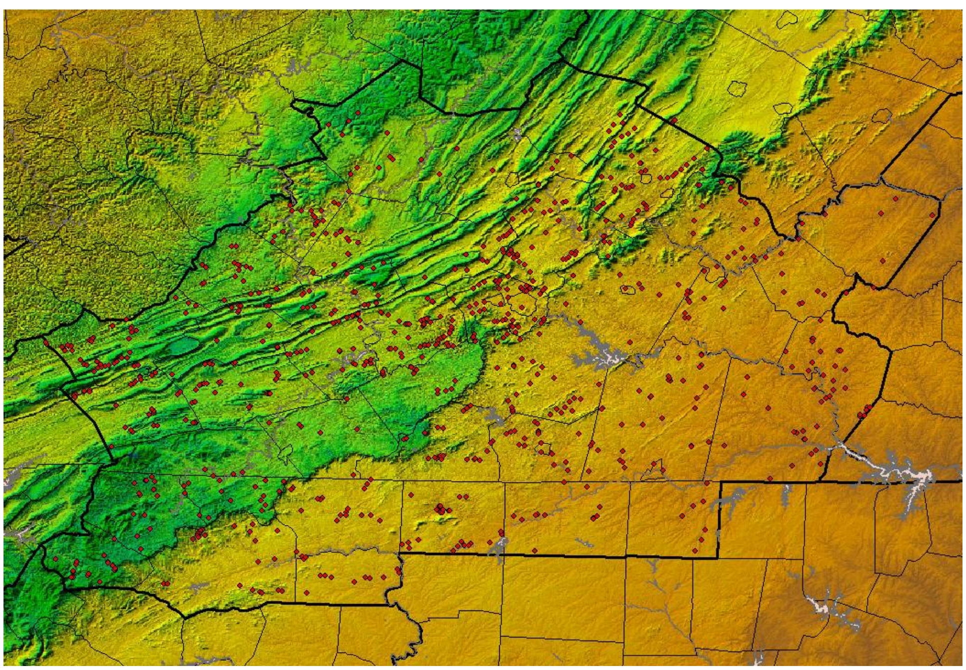
Figure 11. Flash flood locations from a local database of events (1995-2008) where the specific locations are known, and time period is similar to that used in the study.

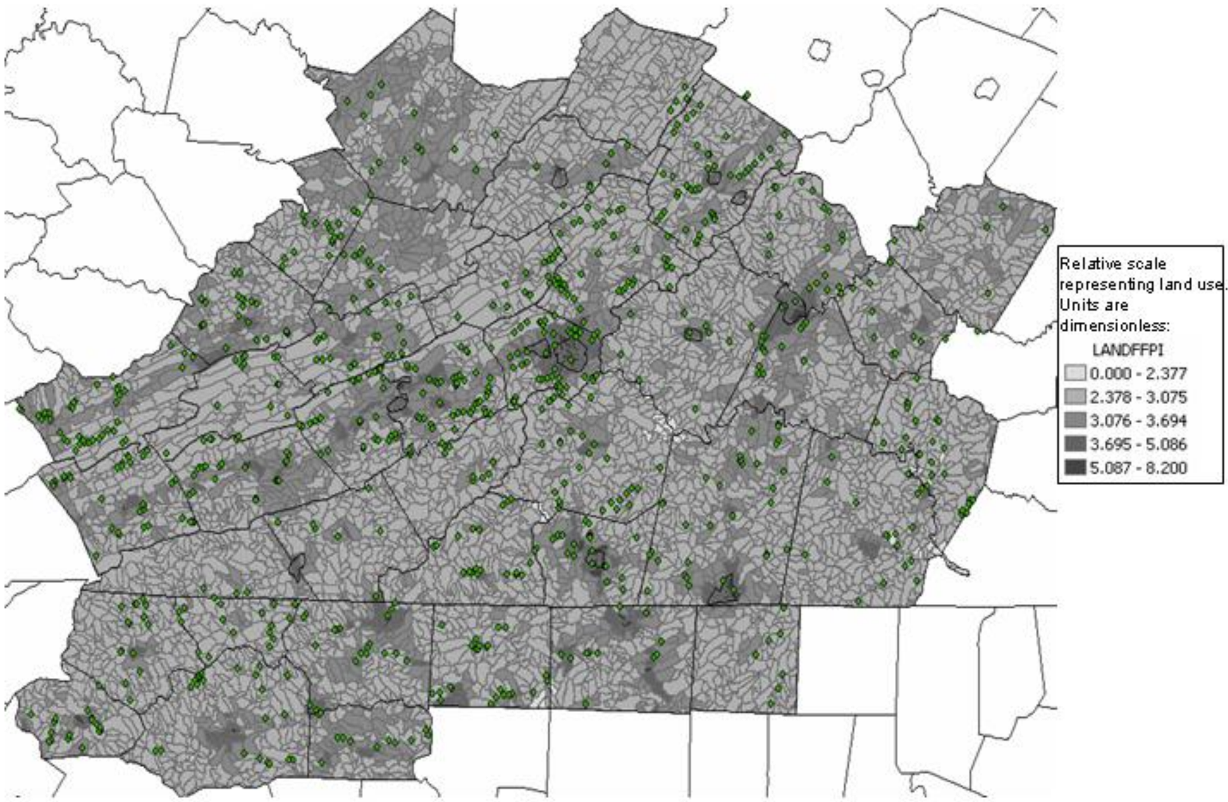

Figure 12. As in Figure 11, except flash flood locations overlaid with a relative-scale for land use percentage, interpolated to small stream basin regions. Darker colors represent more urbanized land use. See Smith (2003) for explanation of the datasets used to develop this relative scale.

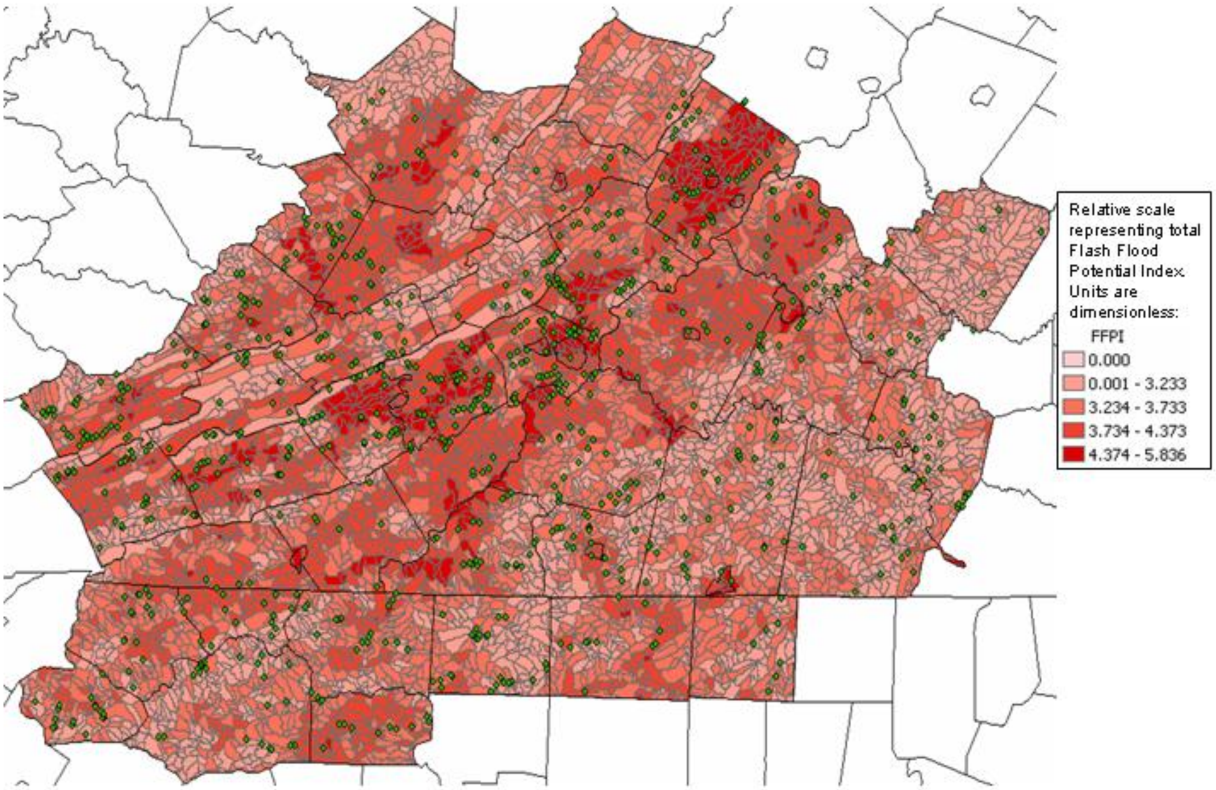

Figure 13. As in Figure 11, except flash flood locations overlaid with a relative scale for the "Flash Flood Potential Index" (FFPI), which is created from equal weighting of four physiographic layers: land use, slope, forest density, and soil texture. Darker reds indicate greater flash flood potential due to a combination of the four factors. See Smith (2003) for further details on the methodology for developing the FFPI relative scale.

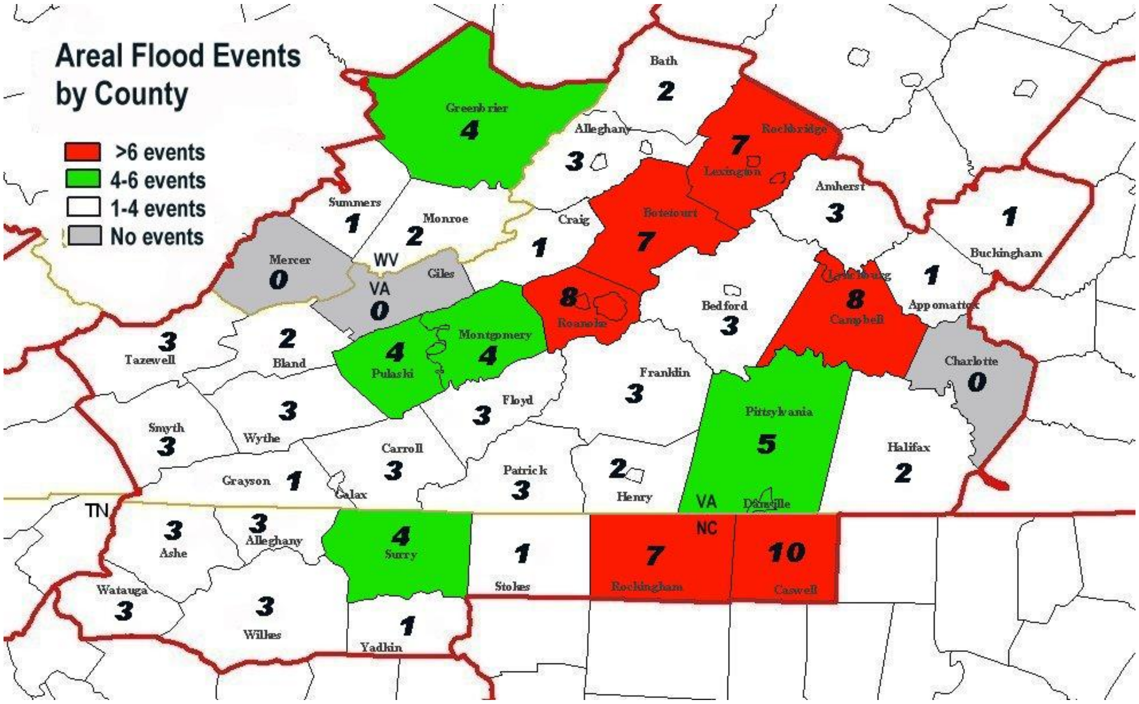

Figure 14. The total number of areal flood events by county (1994-2007).

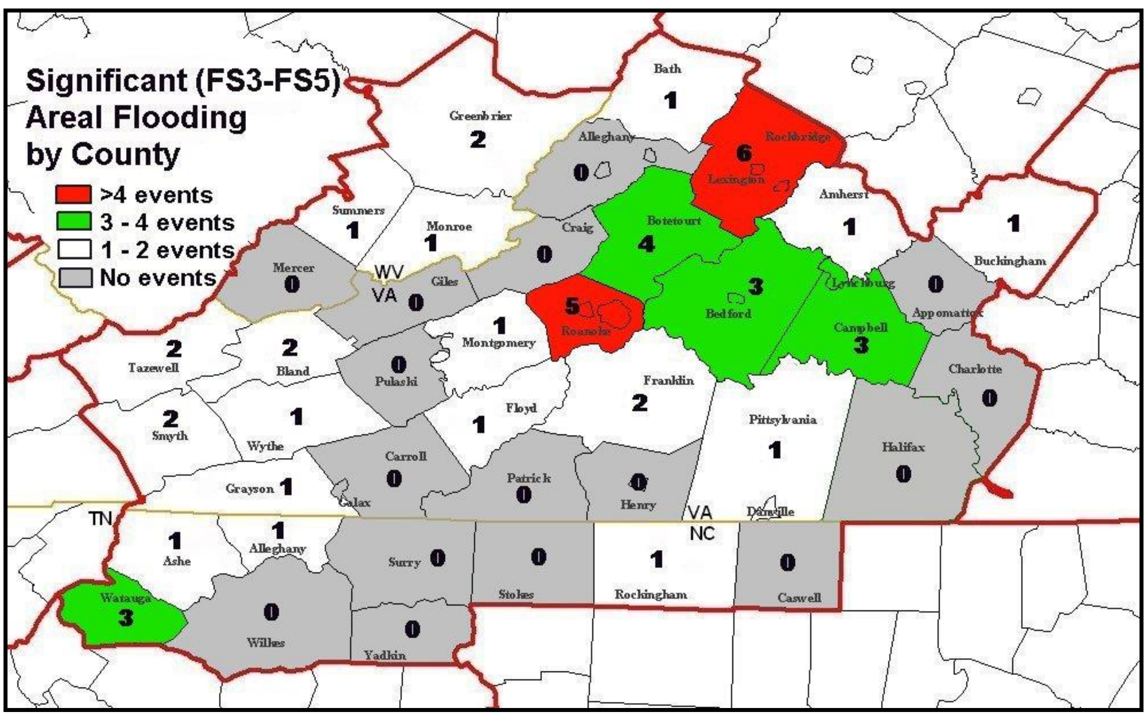

Figure 15. Significant (FF3-FF5) areal flood events by county (1994-2007).

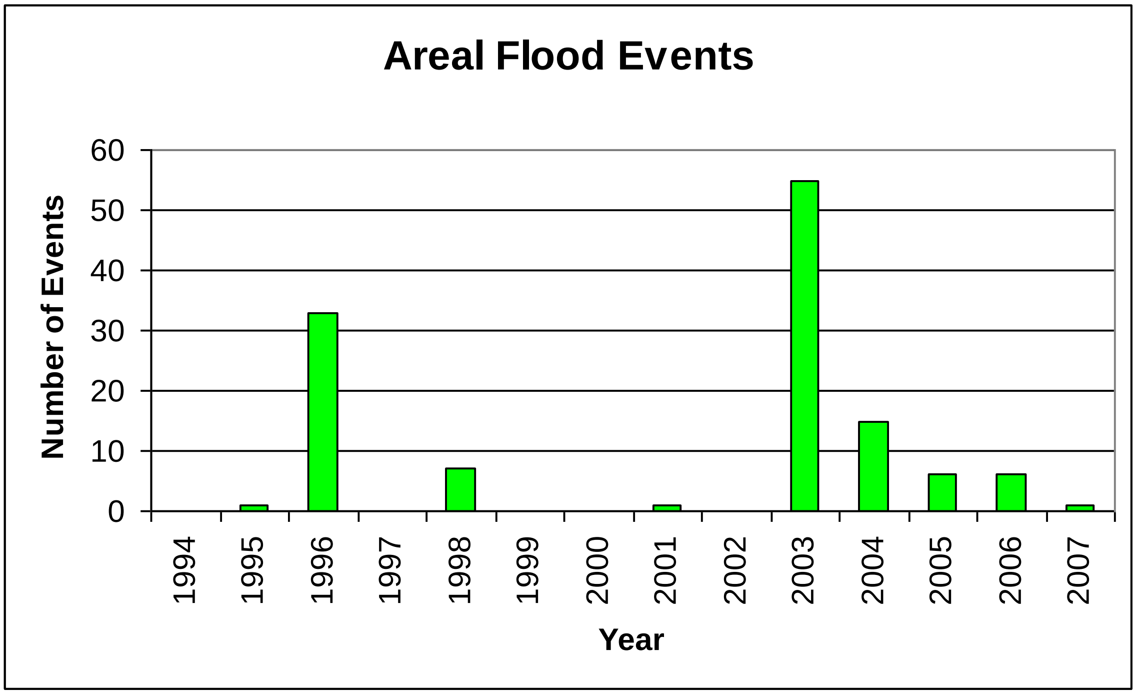

Figure 16. Areal flood events by year (1994-2007).

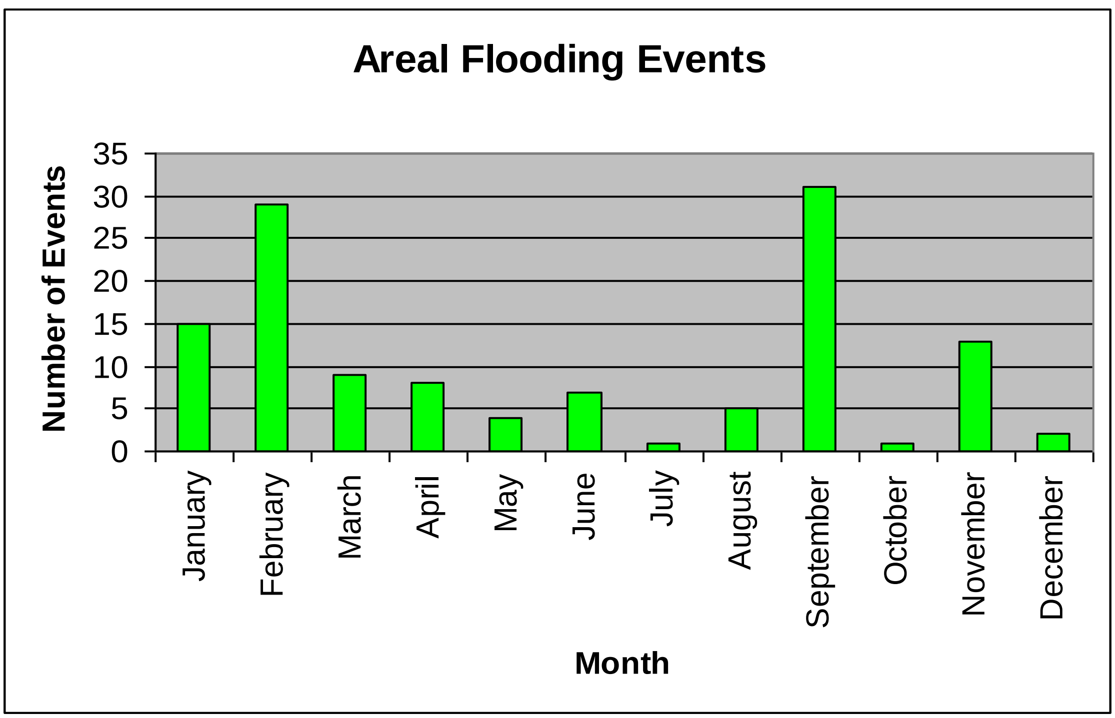

Figure 17. Areal flood events by month (1994-2007).

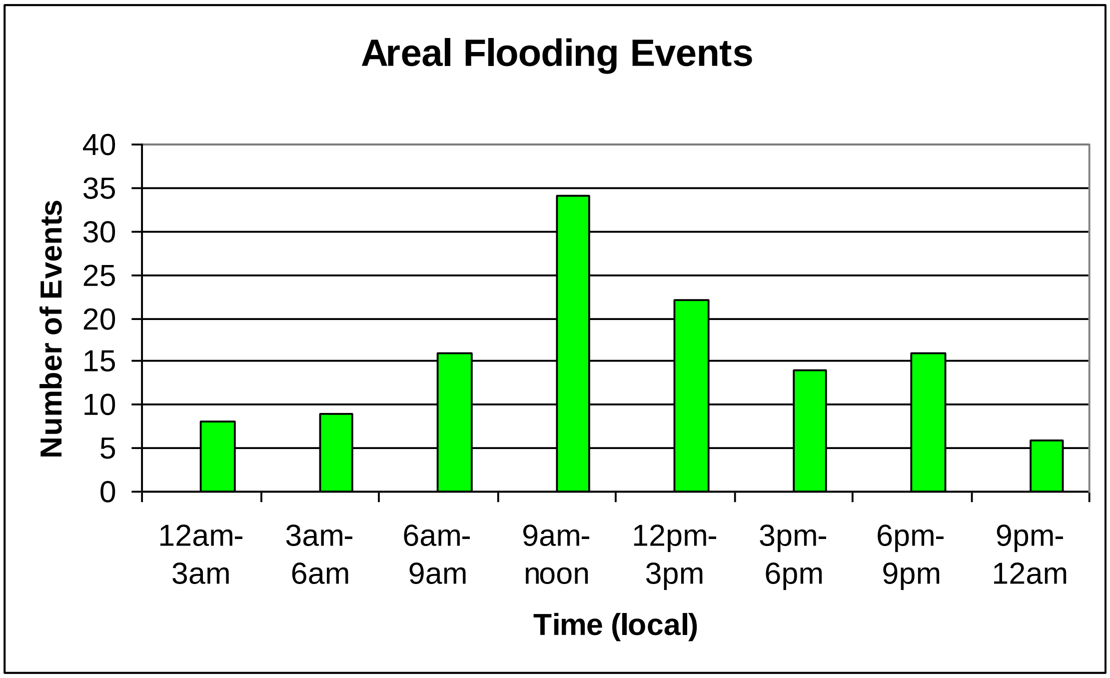

Figure 18. Areal flood events by time (1994-2007).

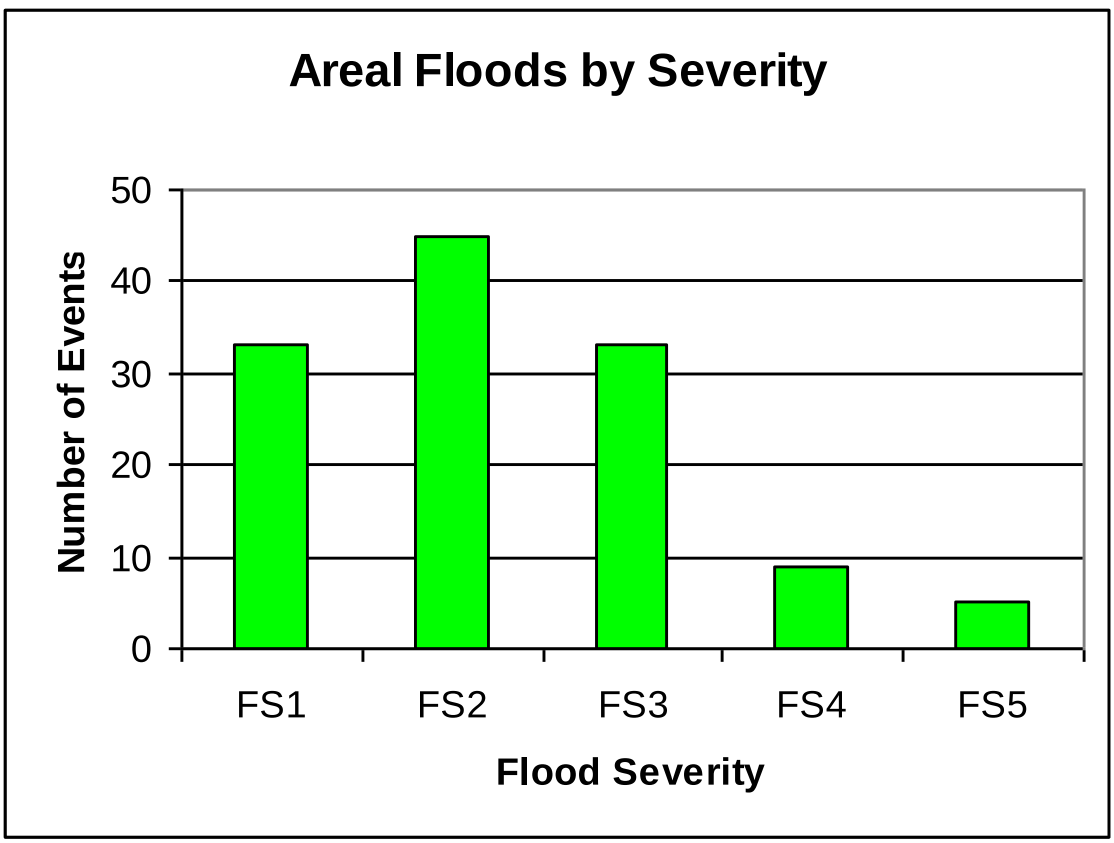

Figure 19. Areal flood events by Flood Severity Index (1994-2007).

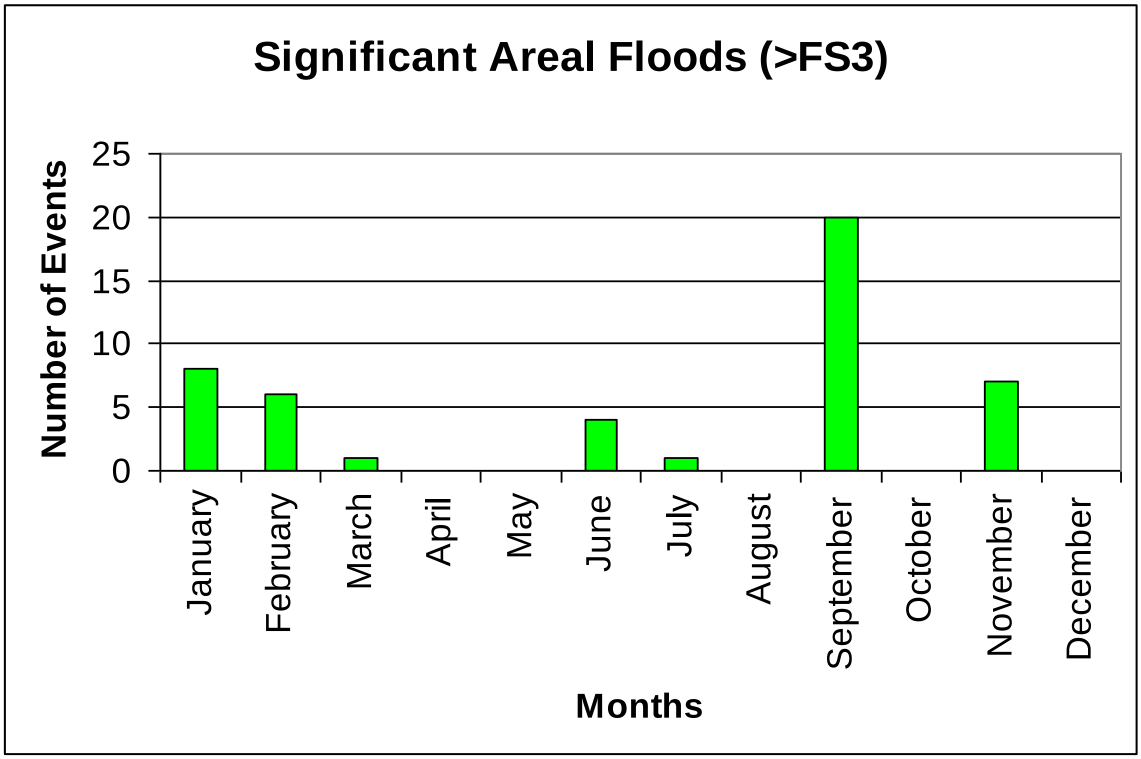

Figure 20. Significant (FS3-FS5) areal flood events by month (1994-2007).

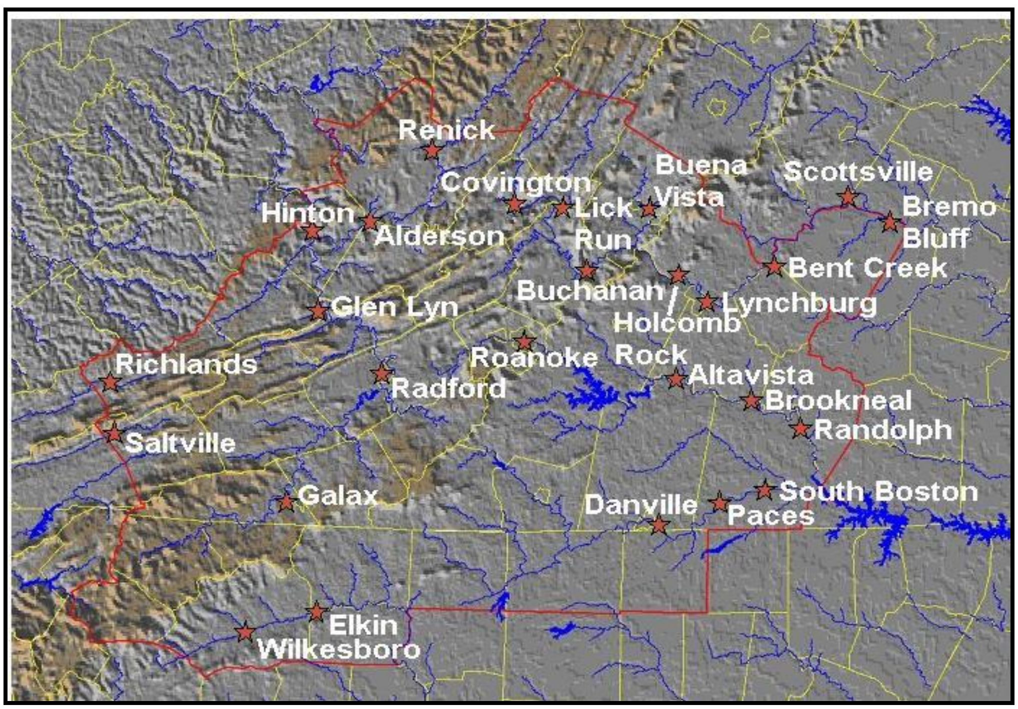

Figure 21. WFO Blacksburg, VA, (RNK) Hydrologic Service Area (HSA) and river forecast points.

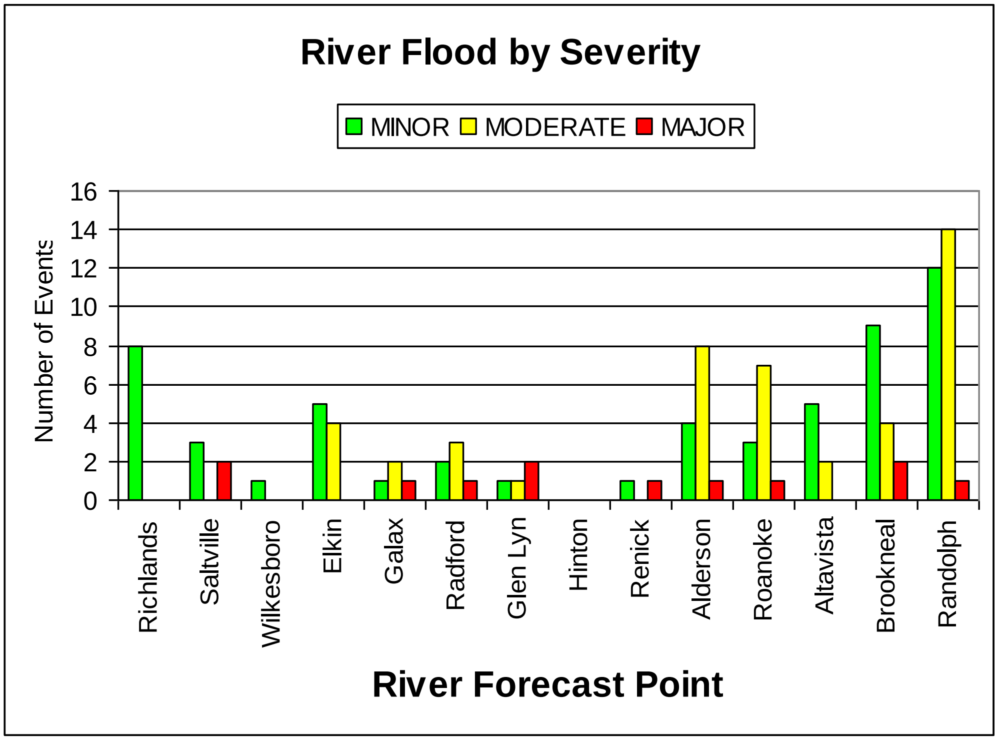

Figure 22. River flood by severity for forecast points along the Clinch, Holston, New, Greenbrier and Roanoke Rivers (1994-2007).

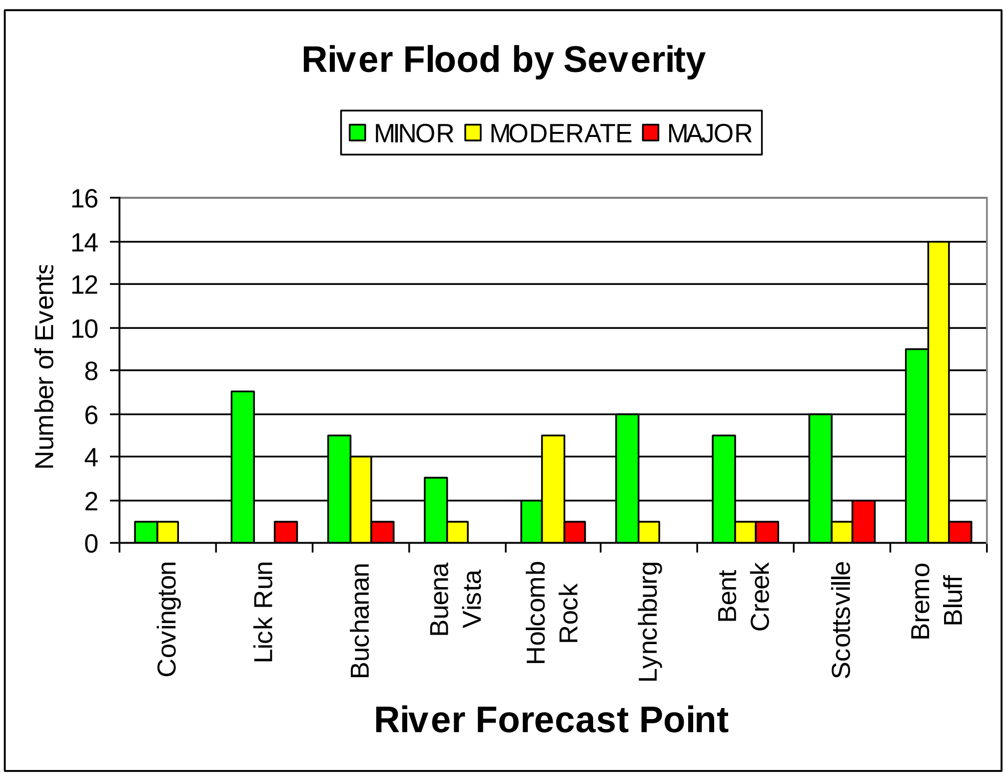

Figure 23. River flood by severity for forecast points along the Maury and James Rivers (1994-2007).

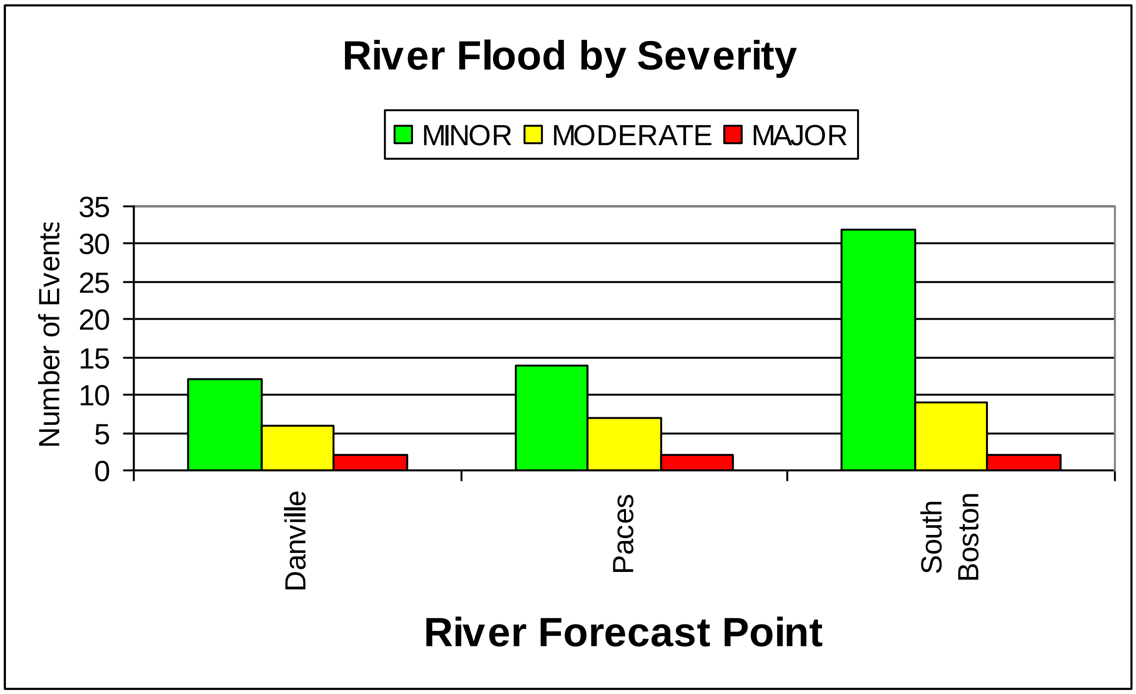

Figure 24. River flood by severity for forecast points along the Dan River (1994-2007).

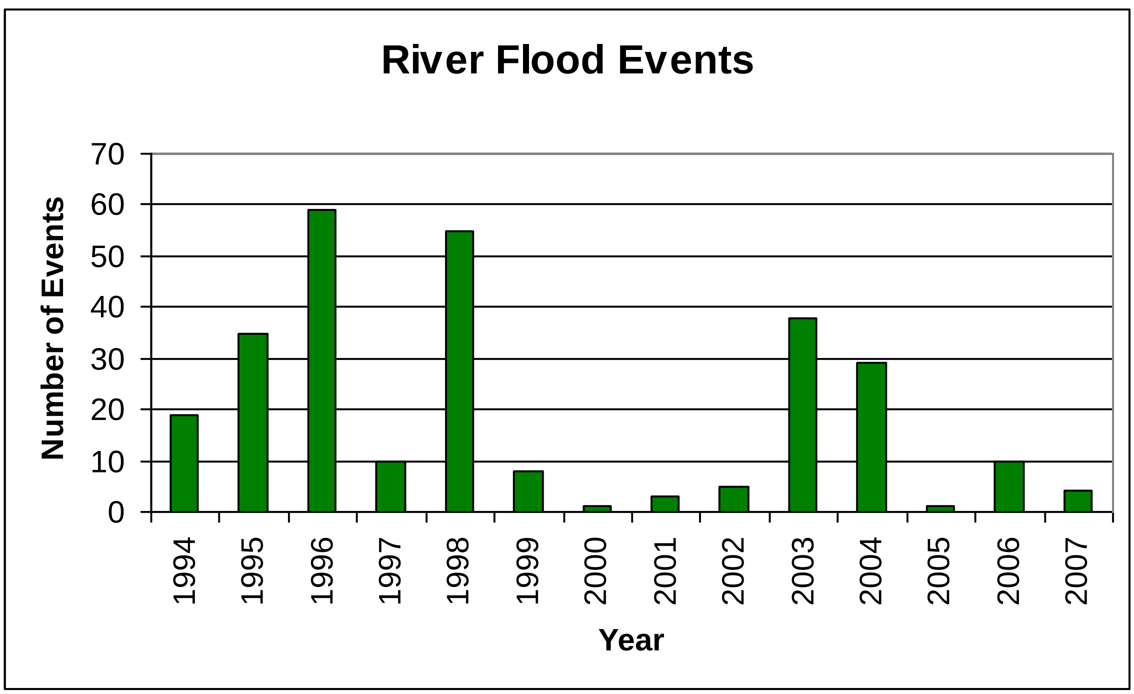

Figure 25. River flood events by year (1994-2007).

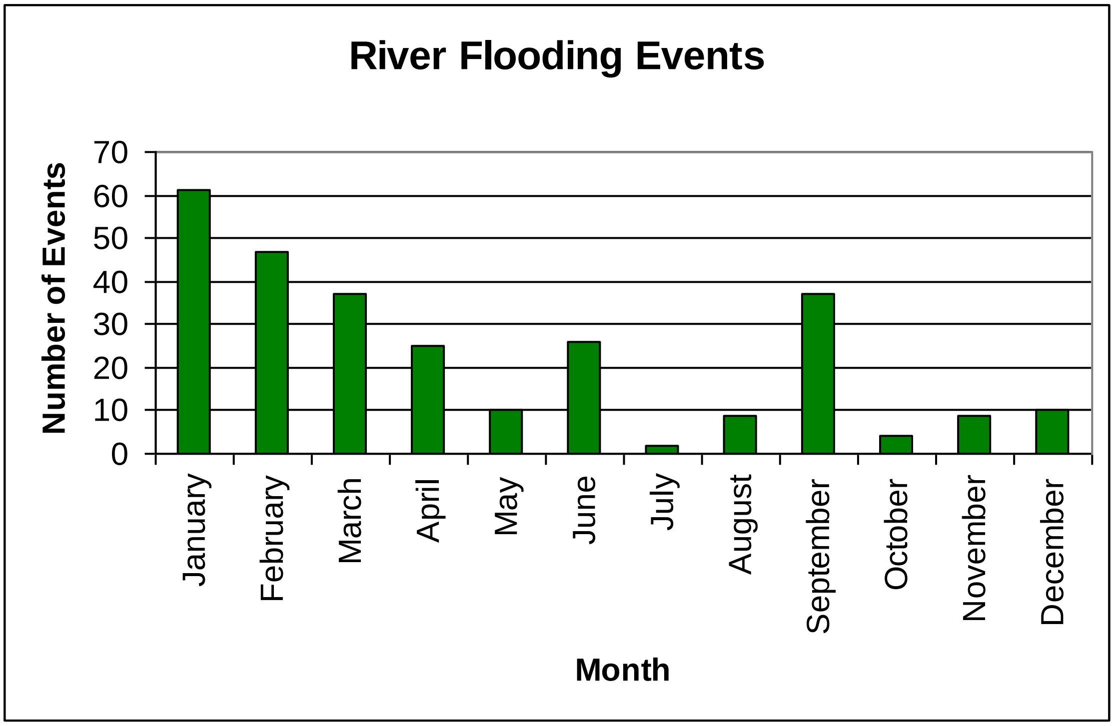

Figure 26. River flood events by month (1994-2007).

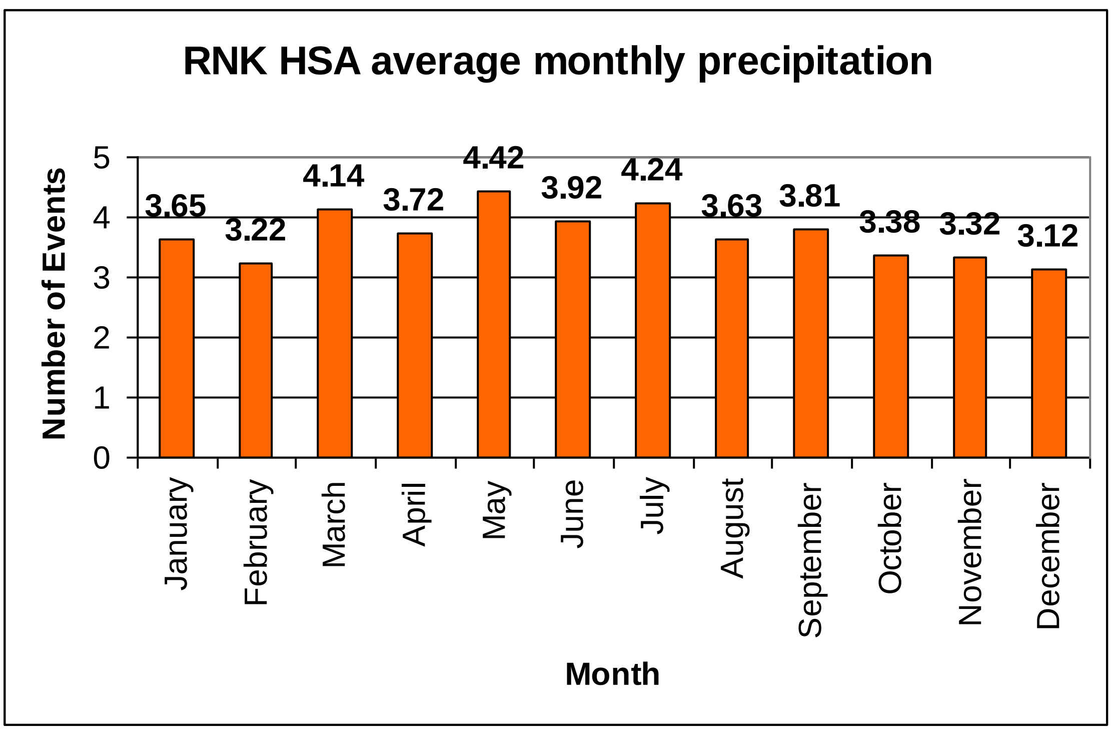

Figure 27. WFO Blacksburg, VA, (RNK) Hydrologic Service Area (HSA) average monthly precipitation from 1970 – 1999.

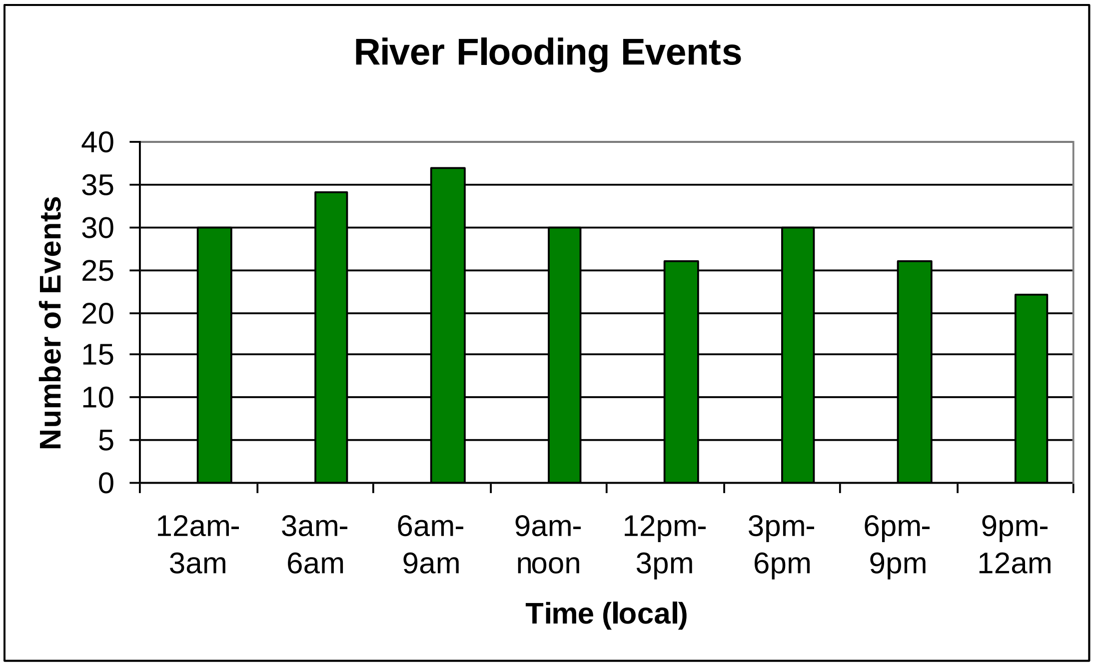

Figure 28. River flood events by time (1994-2007).

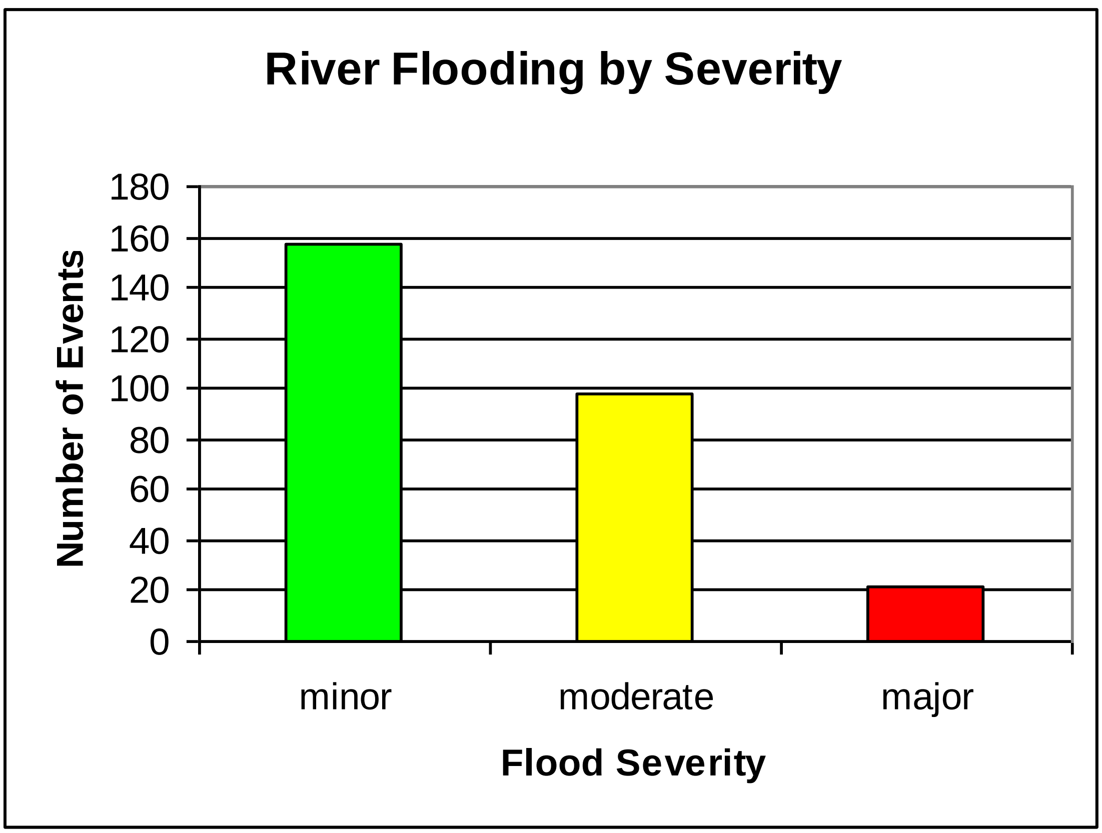

Figure 29. River flood events by severity (1994-2007).

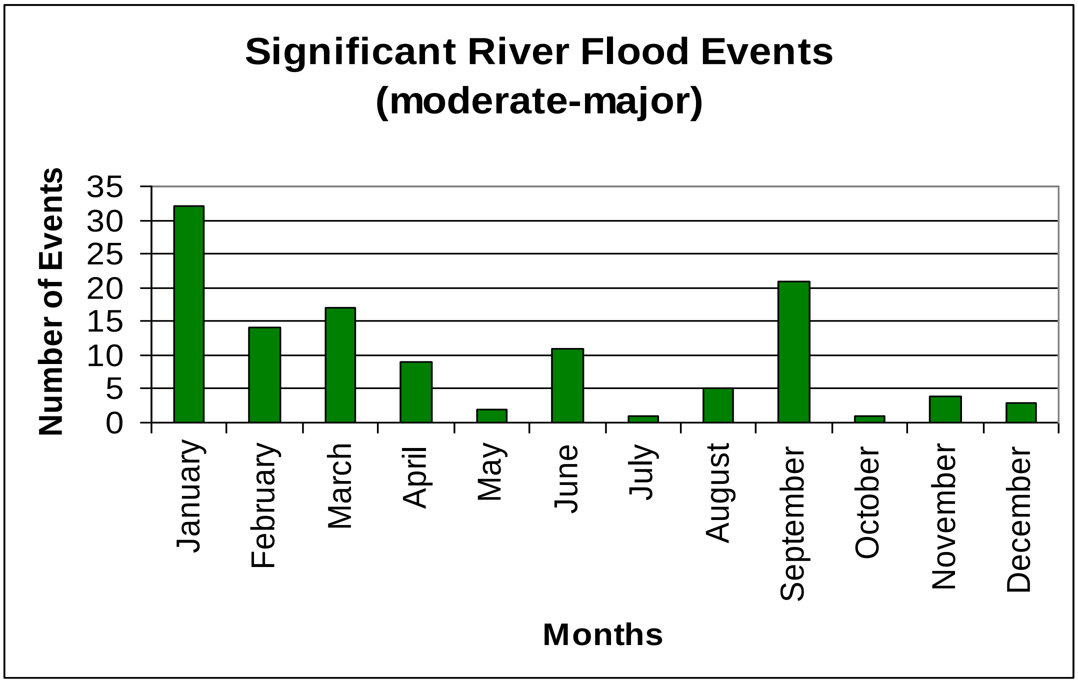

Figure 30. Significant (moderate and major) river flood events by month (1994-2007).

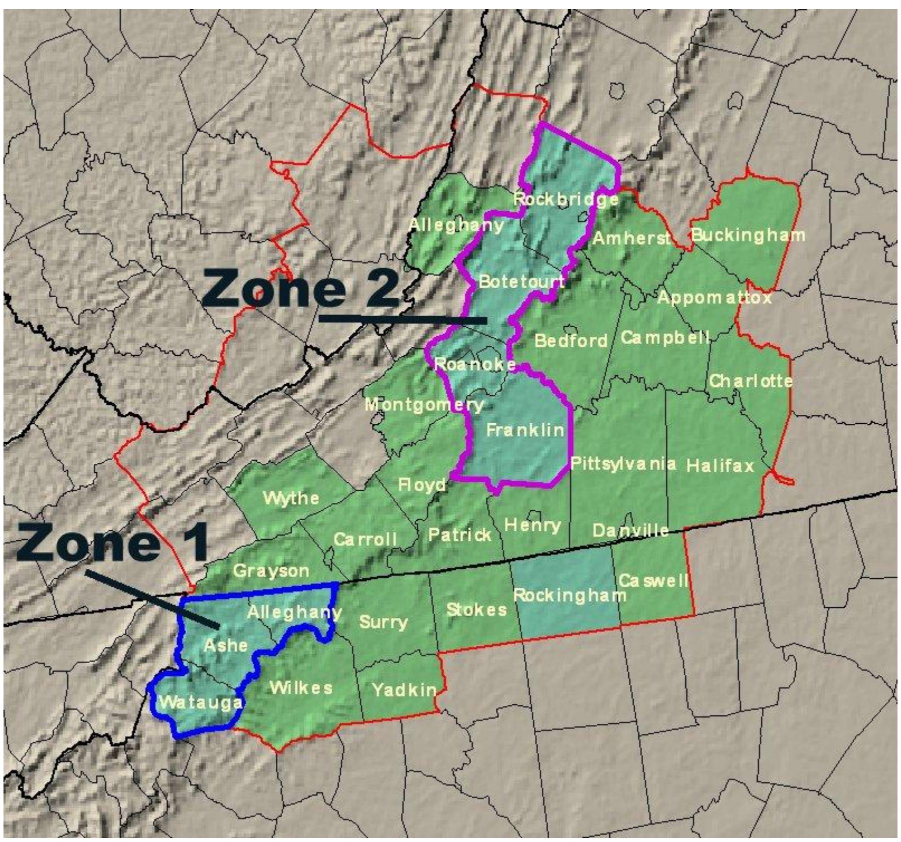

Figure 31. Counties with flood events from tropical systems (green shade) and significant flood events (turquoise shade). Two distinct zones experiencing multiple significant floods from tropical systems are outlined in blue and purple.

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