ABSTRACT

Title of Document: FLOODS, HURRICANES AND CLIMATE: INFLUENCES ON THE POTOMAC RIVER BASIN

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The suggestion from preliminary analysis of data derived from stream gauges in the Potomac River Basin is that tropical storm types generate many of the high magnitude flood events in the Potomac River Basin. The goals of this study are to 1) determine whether or not tropical storms are, in fact the primary cause of extreme floods, 2) determine whether tropical-storm characteristics, e.g., landfall location and wind speed, or climatic conditions can be used to predict extreme floods in the Potomac River Basin; and 3) evaluate the flood potential of sequential tropical storms by comparing the flood response to a single September tropical storm event (Isabel, 2003) with the flood response to a series of four September tropical storm events in 2004. All assessments utilized thirty-seven stream gauge discharge records and archival data on named tropical storm characteristics for the period 1950 to 2004. The data were used in logistical regression to establish the importance of tropical storms in flood generation. Models of the relationship between tropical storm characteristics, climatic factors, including the

Atlantic Multi-decadal Oscillation and Pacific Decadal Oscillation; and annual peak discharge were developed using generalized linear modeling. Western Potomac River Basin flood responses to Hurricanes Isabel (2003), Ivan and Jeanne (all in 2004) were evaluated based on hydrograph and runoff characteristics. Antecedent moisture and soil moisture storage capacity, during the four storms, were also assessed using discharge data.

Tropical storms and frontal storms generate most of the floods in the upper 10% of flood distributions for study. Generalized linear modeling indicates the Pacific Oscillation Index and atmospheric pressure associated with the tropical storm play a key role in the storm's ability to generate a flood. It was also determined that a single intense storm, such as Hurricane Isabel (2003), is a better flood generator than a series of closely spaced storms, such as the series of tropical storms in 2004.

FLOODS, HURRICANES AND CLIMATE: INFLUENCES ON THE POTOMAC RIVER BASIN

By

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Dedication

To my ancestors on whose backs I ride. To my descendants - this is my legacy to you.

Acknowledgements

When I started this journey the universe just opened up and put all of these beautiful people on my path. Along the way they provided encouragement, technical advice, financial assistance, employment, housing, took care of my house and my daughter, coached me through the writing process, stood up for me when I couldn't do it myself and just listened. The following family members aided me: Dr. Arthenia J. Millican, Ms. Catherine Alia, Ms. Amanda L. Robinson, Mr. Gregory H. Neverson, Jr., Ms.Valerie J. Neverson and Ms. Kiana A. Neverson. My friends aided me: Ms. Mamie S. Dent, Mr. D. Spencer Neale and Ms. Maryanna Smith. The University of Maryland (UM) PROMISE Program aided me, including Dr. Wendy Carter, Dr. Johnetta G. Davis, Dr. Renetta Tull, Mr. John A. Jones and fellow students particularly Dr. Angela Grant and Dr. Michele Harris. I'm especially grateful for the following silent supporters; Dr. Earlene Armstrong; members of the UM College Park (CP) Academic Achievement Programs: Dr. Jerry Lewis, Dr. Alice Murray and Ms. Lisa Gill and the US Geological Survey, Office of Surface Water particularly Robert Mason and D. Phillip Turnipseed. A special thanks goes to Dr. Harry Lins for jobs to keep me afloat, books, compassion, encouragement and laughs. In the UMCP Geology Department, I am thankful for Dr. Karen Prestegaard for sticking with me and making me admit to and communicate what I knew, Ms. Dorothy Brown, Ms. Jeanne Martin, Dr. Phil Piccoli, Ms. Ginnette Villeneuve and Dr. E-an Zen. So many people aided me in my efforts, if I don't have your name listed; know that your efforts on my behalf were recognized and appreciated.

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Chapter 1: Introduction

Flood magnitude and frequency have traditionally been thought of as being generated by random hydrological processes. Thus, the occurrence of flood events is considered to be independent and random in time (e.g., Dunne and Leopold, 1978). Flood frequency analyses based on these assumptions provides estimates of the frequency and magnitude of floods (e.g., Benson, 1968; US Water Resources Council, 1981; Turcott and Greene, 1993). Recent advances in hydrometeorology indicate that floods are not necessarily generated by homogeneous sets of similar events. Furthermore, the timing of flood events may be tied to specific conditions in ocean-atmospheric interactions.

After the extreme floods in the northeastern United States in 1936, Jahns (1947) suggested evaluating atmospheric conditions to aid in the understanding of flood characteristics. Later, Kilmatrin noted the increased accuracy in flood frequency and magnitude estimation gained by analysis of floods a function of storm type. Hirschboeck (1988) sorted the flood events in an Arizona watershed based on flood frequency and meteorological causes, to show that different storm types generate different magnitudes and frequencies of floods. Hirschboeck (1988) also showed that invoking the concept that there are external causes at play when extreme floods occur enhanced the understanding of floods provided by stochastic analysis. It is well understood that streamflow is dependent upon precipitation intensity, duration and repetitiveness and that precipitation intensity, duration and repetitiveness is dependent upon climatic factors, such as El Nino/Southern Oscillation (ENSO). The challenge is to identify these relationships and evaluate their effects on flood magnitude. In northern California for example, flash floods are due to weak middle-level troughs (Aguado *et al*., 1992). Also, streamflow magnitude may be higher during El Nino years than non-El Nino years (Reynolds *et al*., 1997). Thus, flood frequency prediction in California might be improved when the probabilities of occurrence are estimated base on ENSO phase.

Flooding in the Potomac River Basin might also be better predicted if ENSO or other climate factor phases are considered. Along the eastern coast of the United States and in the Potomac River Basin, moisture derived from hurricanes and tropical storms is responsible for the generation of some of the highest magnitude flood events (Paulson, *et al*, 1991, Perry *et al*., 2001). ENSO and other climate factors are known to influence tropical storm track and development (Bossak, 2004). Further, the observational record of named Atlantic tropical storms suggests a recent increase in Atlantic hurricane activity (Goldenberg *et al*., 2000). There is considerable debate as to whether the increase in hurricane activity is due to an improvement in the tropical storm detection (Landsea, 2007; Nyberg *et al*., 2007; Neu, 2008), due to multidecadal climate cycles (Goldenberg *et al*., 2000), or an increase in sea surface temperatures (Knutson and Tuleya *et al.*, 2007). Regardless, alteration in the timing and number of tropical storms that track across the Potomac River Basin may require new flood frequency and magnitude estimates.

Global climate modeling can also benefit from detailing the relationship between climate, tropical storms and flood response. Tuleya *et al*. (2007) provided a statistical model to estimate the intensity and distribution of precipitation after a tropical storm or a hurricane made landfall using Hurricane Fran 1996. This storm impacted the Potomac River Basin. The statistical model, however, did not predict flood response based on the intensity and distribution of tropical storm/hurricane related precipitation. Information provided by models of flood response due to tropical storms and how climate patterns alter tropical storm intensity in the face of a changing climate is a critical need for natural hazard early warning system design and water resource management (Helweg *et al.*, 2006; Olsen, 2006). In order to meet that critical need, realistic models must be developed, and that requires detailed knowledge of associations between climate patterns, tropical storms, and the flood response to storms on a basin scale (Gleick *et al.*, 2000). The purpose of this work is to provide information that may be used in global climate modeling by proving that the primary meteorological cause of extreme floods in the Potomac River Basin is tropical storms, linking tropical storm related floods in the basin to climate patterns and evaluating the flood response to tropical storms with different delivery mechanisms and under different soil moisture conditions.

OUTLINE OF THESIS

This thesis is composed of this introductory chapter, three chapters that present the results of three different investigations into the linkages between hurricane activity and floods in the Potomac River Basin and a chapter that summarizes and discusses the importance of the three investigations. Chapter 1 contains a discussion of the state of knowledge regarding the pertinent relationships among climate patterns, hurricanes and floods. In it I provide a brief review of the literature and a discussion of Potomac River Basin physiography including climate and seasonal variations in streamflow. Chapters 2, 3 and 4 are independent and each contains an abstract, an introduction, methods, results, discussions and conclusions. Chapter 2 is a formal evaluation of the suggestion from previous works that the primary cause of extreme floods in the Potomac River Basin is tropical storms. In Chapter 3, I derive a model that predicts the likelihood of annual peak discharge based on atmospheric pressure and the Pacific Decadal Oscillation index. Assessment of several proposed statistical models based upon tropical storm status, climate factors and their relationship to annual peak discharge generation (storm effectiveness) is also discussed. In Chapter 4 I present the results of an examination of hurricane-related storm events during the month of September in the years 2003 and 2004 with an emphasis on surface moisture and its influence on flood response. Finally, in Chapter 5, the text ends with a discussion of major findings and their implications. The remainder of this introduction immediately follows.

POTOMAC RIVER BASIN PHYSIOGRAPHY

The 38,000 km^2 Potomac River Basin includes portions of the District of Columbia, Maryland, Pennsylvania, West Virginia, and Virginia (Figure. 1). The Potomac River Basin contains portions of five physiographic provinces, each of which has distinctive bedrock geology and topography (Trapp and Horn, 1997: Figure 1). The Coastal Plain is a seaward-sloping lowland underlain by Jurassic to Holocene aged sediments. The boundary between the Coastal Plain and Piedmont Province is called the fall line due to waterfalls located along the boundary. The Piedmont Province is composed of Pre-Cambrian to Paleozoic age folded metamorphic and igneous rocks as well as Mesozoic sedimentary basins comprised of shale, sandstone, and conglomerate. The Blue Ridge Province is a mountainous area that forms the northwestern margin of the Piedmont and is composed primarily of igneous and medium-grade metamorphic rocks. West of the Blue Ridge, there are variably resistant, folded sedimentary rocks that form the Valley and Ridge Province. Portions of the Appalachian Plateau, a province underlain by flat sedimentary sequences of similar composition to the Valley and Ridge Province also occur in the watershed (Trapp and Horn, 1997).

Climate

The watershed topography and vegetation influence temperature and precipitation regimes. In general, about 58% of the basin is covered with evergreen forests. Evergreen forests are primarily in the west. Other land uses include agriculture (~32%), mining, recreation and residential occupation (Interstate Commission on the Potomac River Basin, 2008). Mean annual temperature ranges from about 8°C in mountainous areas of West Virginia to 14°C in the lower Chesapeake Bay area. Average January temperatures are around -0.4°C and July temperatures average 24°C. The average length of the freeze-free season based on a minimum temperature higher than 0° C ranges from more than 230 days in lower portions of the basin to fewer than 130 days on the Allegheny Plateau (Hayden and Michaels, 2004). Variation in the length and location of the freeze-free season indicates places where snowfall can accumulate and where snowmelt or rain on snow can be the cause of floods.

Precipitation amounts are not strongly seasonal but average precipitation is higher and more variable during the summer months (Figure 2a). February is the driest month, which is when the average depth of precipitation is 76 mm and July is the wettest month, which is when the average depth of precipitation is 114 mm (Hayden and Michaels, 2004; West Virginia Climate Center, 2005). With regard to the timing of specific precipitation types, throughout the basin snowfall has been recorded in all months except July and August. Average monthly snowfall amounts in January have been at a maximum

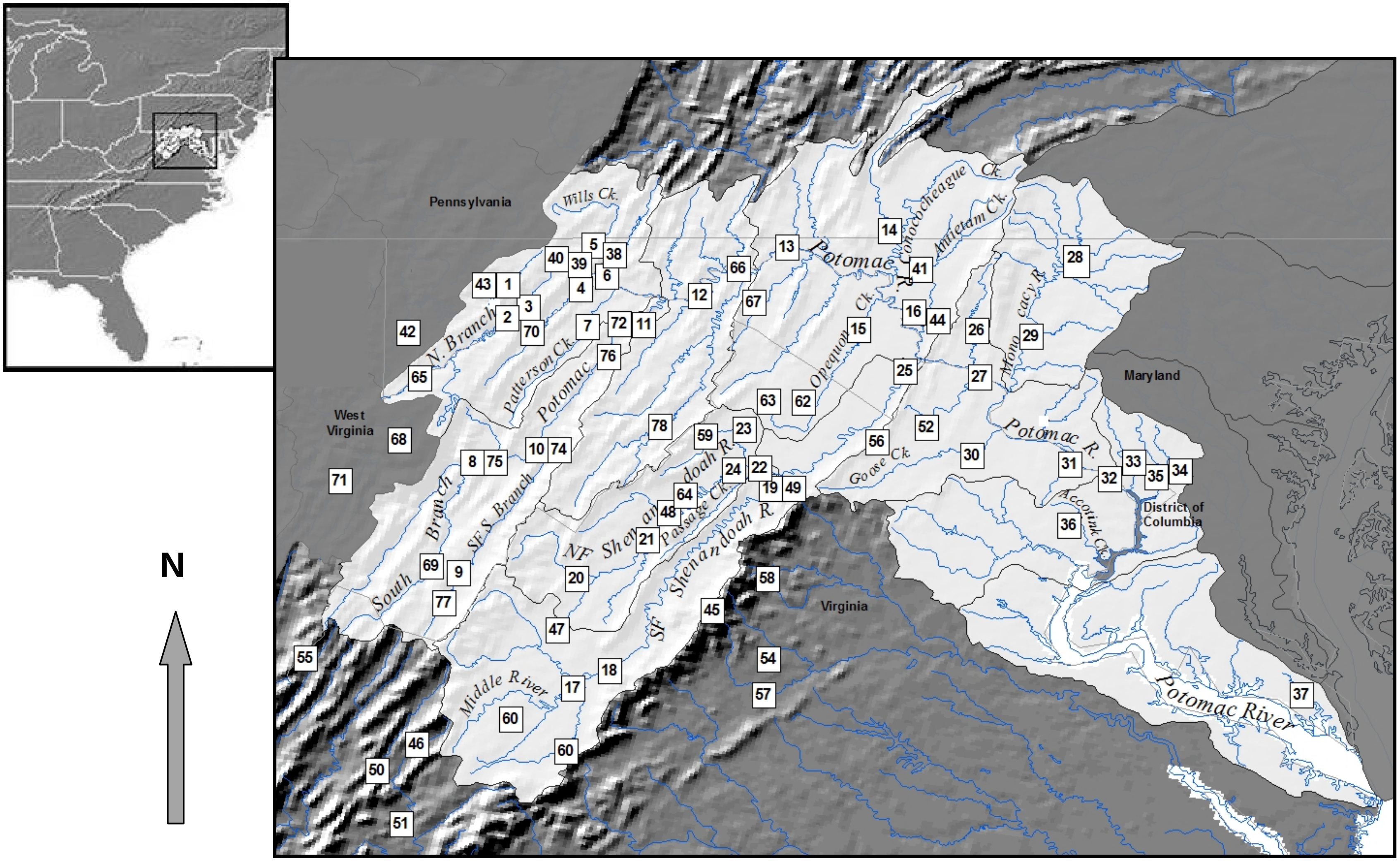


Figure 1. Potomac River Basin (white area). The basin encompasses four states and the District of Columbia. The Potomac River is a tributary of Chesapeake Bay. Red circles = streamflow gauges, blue circles = precipitation gauges, blue lines = streams, black lines = sub-basin boundaries. Numbers in squares locate streamflow gauges (1 to 37) and precipitation gauges (38 to 78). See Appendix Tables 12 and 13 for gauge descriptions.

(275 mm) in the mountainous western Potomac River Basin. Throughout the basin, rainfall can occur in any month. Annual average rainfall ranges from a maximum of approximately 1,143 mm at extreme east/west ends of the basin, to a minimum of 762 mm in areas where there is a rain shadow effect. From June to November tropical storms contribute to summer rainfall variability. Thunderstorms also contribute to summer rainfall, and usually occur in July or August as independent storms or in association with tropical storms.

a) Average monthly precipitation pattern based on the gauge record at Hagerstown, MD.

b) Average monthly discharge pattern based on the gauge record at Little Falls near Washington, DC.

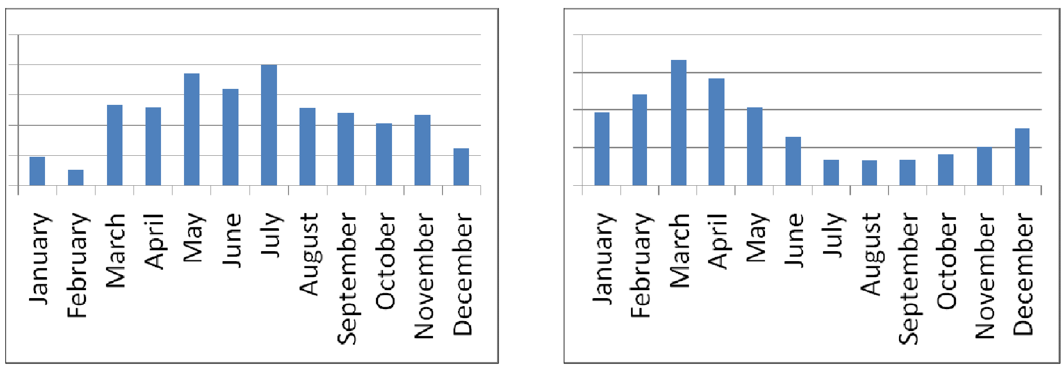


Figure 2. Representative patterns of average monthly precipitation (left) and discharge (right) throughout the Potomac River Basin. On average, streamflow is highest in March and lowest in July. The precipitation pattern is nearly opposite with highs occurring from late spring through summer.

Streamflow

On average, streamflow is highest in early spring and decreases to a low during summer months (Figure 2b). This pattern is due to the seasonal patterns in precipitation and evapotranspiration. Fall and winter precipitation recharges groundwater, which translates into higher base flows, evapotranspiration is highest in summer and rainfall is slightly less, thus leading to lower base flows. Annual peak discharges are usually recorded in late winter to early spring. However, more of the annual peak discharges that make up the upper tail of the flood distribution curve have occurred between the beginning of June and the end of November (Paulson *et al.*, 1991). Due to the orographic controls on temperature and evapotranspiration, there is also a strong relationship between stream base flow and elevation (Gurtz *et al.*, 2003)

Chapter 2: The Timing, Meteorological Causes, and Spatial Response of Potomac River Basin Floods

ABSTRACT

Several studies suggest but none specifically identify tropical storms as the primary meteorological cause of extreme floods in the Potomac River Basin. Studies also imply El Nino/Southern Oscillation (ENSO) modifies precipitation enhancement, timing and spatial extent. This study used annual maximum series and partial duration series data for 37 gauges in the Potomac River Basin to determine the storm type, timing and spatial variability associated with extreme floods in Potomac River Sub-basins. Exploratory data analysis was also undertaken to examine the possible sensitivity of annual peak discharge to ENSO phase variation. Twenty-four flood events occurred over the course of 114 years. Fifty percent of the events were generated by tropical storms, approximately 33 percent were generated by frontal storms and the remaining 16 percent were generated by either thunderstorms or Nor'easters. Discharges associated with tropical storms populate the upper tail of flood discharge distributions regardless of gauge location. Frontal cyclones that produce either rain-on-snow or heavy rainfall have generated the largest floods at some of the North Branch Potomac River sub-basin gauge locations. Flood responses to frontal storms show power-function (discharge versus drainage area) exponents closer to 1.0 with less scatter (higher R^2 values) than the basin response to tropical storms. Exploratory data analysis revealed sub-basin scale sensitivity to ENSO

phase variability. ENSO also influences precipitation in the western basin, therefore the possibility exists that ENSO phase leads to alteration of flood regression equations.

INTRODUCTION

The Potomac River Basin is the subject of several studies that mention the relationship between floods and meteorological/climatic causal mechanisms but none that evaluate the influence of meteorological cause on flood regression equations. Studies have examined the flood response to a single storm event (Bogart, 1960; Bailey, *et al.,* 1975; Carpenter, 1988; Sturtevant-Rees *et al.,* 2001) others have focused on spatial scaling of flood peaks (Smith *et al.,* 1992) and provided data regarding the timing, spatial distribution and magnitude of floods in the upper 5 to 10% of the discharge distribution on active gauges (Paulson *et al.,* 1991 and Perry *et al.,* 2001). A summary of the timing, magnitude and areal extent of floods deemed significant by various authors are listed in Table 1. The variety of the results of these previous studies of floods within the Potomac River Basin suggests that flood response may vary due to the location of storm activity, the areal extent of storm coverage and the type of storm. Researchers also developed regional flood regression equations that note the influence of sub-basin characteristics on streamflow variability in different portions of the Potomac River basin (Jennings *et al.,* 1994; U.S. Water Resources Council, 1981). In this method of flood frequency analysis, floods that are generated from different storm types are often treated as part of the same flood data series to create a flood flow probability distribution. Therefore, the separation of flood response by sub-basin does not answer the question as to whether or not the regression curve is influenced by a prevailing storm type that varies depending upon which Potomac River sub-basin is under consideration.

Table 1. Summary of USGS Reports of Significant Potomac River Floods

Date	Affected area	R. I.	Stated Causes and Comments
June 1889	Potomac River basin.	Unk.	Largest flood on record prior to the flood of 1936.
Mar. 1913	Shenandoah River basin	>100	Regional flooding
Mar. 28-30, 1924	Potomac River basin.	20 to >100	Snowmelt and intense rainfall.
Aug. 23-24, 1933	Potomac River basin	10 to >100	Hurricane.
Mar. 17-19, 1936	Potomac River basin.	20 to >100	Thick ice, snowmelt, and intense rainfall runoff.
Oct. 15-16, 1942	Shenandoah River basin	10 to >100	Hurricane
June 10, 1949	Potomac River basin	>50	Flash flooding on SB Potomac River
Oct. 14-16, 1954	North Branch Potomac	25 to >100	Hurricane Hazel.
Aug. 12-13, 1955	Monocacy River, Rock Creek, Anacostia River basins	5 to 10	Hurricane Connie.
June 21-23, 1972	Central Maryland, District of Columbia,	50 to >100	Hurricane Agnes.
Sept. 23-26, 1975	Monocacy River basin	10 to > 100	Hurricane Eloise.
Sept. 5-6, 1979	Rock Creek	50 to >100	Hurricane David.
Nov. 4-7, 1985	Potomac River basin.	2 to >100	Hurricane Juan combined with stationary front.
Jan. 19-20, 1996	Potomac River basin	2 to >100	Rain on snow
Sept. 6-8, 1996	Potomac River basin	4 to >100	Hurricane Fran
Note: Table constructed from data provided by Paulson et al. (1991); Doheny (1997) Perry et al. (2001) and Sturdevant-Rees et al. (2001). Unk. = unknown			

The influence ENSO on precipitation is described in general terms by the US Climate Prediction Center (2008). Namais (1973) notes the enhancement of tropical storm precipitation due to ENSO phase in the assessment of climatic conditions related to Hurricane Agnes 1972. In my preliminary evaluation of the Potomac River Basin flood response to Agnes 1972, it was found that the storm generated record floods at 22 % of the Potomac River gauges examined. Therefore, Namias (1973) hints at a relationship between ENSO and tropical-storm generated extreme floods in the Potomac River Basin.

Meteorological Conditions That Can Lead to Floods in the Potomac River Basin

In general, there are three main sources of moisture delivered to the Potomac River Basin: Maritime tropical moisture from the Gulf of Mexico, maritime tropical moisture from the Atlantic Ocean, and recycled continental moisture (Paulson *et al.,* 1991; Doheny, 1997; and Perry *et al.,* 2001). Moisture that is delivered to the basin can interact with several meso- to synoptic-scale phenomena that can lead to flood-generating storm events. These processes are reviewed in the following paragraphs.

Uplift and cooling of warm air masses is an essential part of cloud formation and precipitation. Local convective lifting, convergence and orographic uplift mechanisms are associated with storms that generate precipitation. These lifting mechanisms can work together within one storm system or individually to produce precipitation.

Convective lifting - Localized convective lifting is due to a high contrast in surface temperatures. When the warmer of two air pockets rises above the condensation level, clouds can form and generate thunderstorms (Barry and Chorley, 1998). Convective lifting usually occurs over the Potomac River basin in summer. Thunderstorms generate precipitation of short duration (30 minutes to 1 hour) and local areal extent. Therefore, extreme floods due to convective storms are usually limited to small drainage basins. The average number of days during which localized convective thunderstorms happen over the Potomac River Basin ranges from less than one day in winter to ten days in summer (Hayden and Michaels, 2004).

Convergence - Convergence is the meeting of two near-surface air masses either flowing horizontally at unequal speed or in different directions in an area of low pressure. The warm moist air masses (from the Gulf of Mexico or Atlantic in the case of the Potomac River Basin) rise to adjust to air accumulation, which can lead to cloud formation and storms. Convergence is the key component in cyclone development and sustainability and it is a mechanism that operates in concert with orographic uplift to produce precipitation in mountainous or coastal regions.

Orographic lifting – Orographic lifting can generate precipitation or enhance the effect of a precipitation event generated from other processes. In the case of orographic lifting, air is forced to 'climb' over topographic barriers. Adiabatic cooling takes place in the process and this cooling, the slowing down of air flow due to energy loss and convergence leads to precipitation. The effect of orographic lifting can be local or regional in scale. This mechanism is responsible for the rain shadow effect and, because of repeated episodes of precipitation, snow accumulation in mountainous regions during cooler periods. Orographic lifting enhances streamflow magnitude when spring floods occur, in rain on snow events, and when hurricane-related storms are the cause of flooding. (Hirshboeck, 1988) Peaks in rainfall accumulation in the Shenandoah River basin during Tropical Storm Fran in September, 1996 are attributed to orographic enhancement (Sturdevant-Rees *et al.*, 2001).

Frontal cyclones - Regardless of location, mid-latitude cyclones or frontal convergence storms are one of the main causes of floods in the continental United States. Mid-latitude cyclones develop when two air masses of different temperatures and densities are moving nearly parallel to a front. Under the right circumstances, a wave with an alternating cold and warm front develops and a circular atmospheric pressure system with lowest pressure at the center forms at the apex of the wave. Convergence produces strong uplift and the storm rotates counterclockwise. In general, mid-latitude cyclones have a central area of convergence, a ‘leading’ warm front and a ‘trailing’ cold front. The warm front is associated with low to moderate continuous precipitation that can last over a broad area for 6 to 12 hours. The cold front is associated with more intense but shorter duration precipitation. As the storm matures, occlusion can produce continuous and intense precipitation over a broad area (Barry and Chorley, 1998). In most instances, these systems originate in the west and travel east with the jet stream. Frontal convergence is listed as the cause of the 1936 floods in the Potomac River Basin (Paulson *et al.*, 1991). This was the flood of record at the downstream, mainstem gages.

Nor’easters – Cyclonic fronts can also originate in the east and travel west. The systems that travel to the Potomac basin from the northeast (instead of from the eastern tropics) are called Nor’easters. Strong easterly winds along with heavy regional-scale precipitation are generally associated with these hurricane-like storms.

Tropical storm/cyclones -- Another type of cyclone that introduces moisture into the Potomac River Basin is the Atlantic tropical cyclone. Although the generation of Atlantic named storms is unclear the following set of conditions occurs about 60% of the time: Remnants of a pre-existing tropical disturbance, most often off the coast of western Africa, is present in the Atlantic Ocean; the disturbance is far enough north of the equator for the Corioles Force to be effective; the disturbance has a weak (rather than strong) wind shear and a slight circular rotation; and ocean temperatures are 27°C or higher to a depth of 50 meters (Barry and Chorley, 1998, Fitzpatrick, 2006).

A tropical disturbance develops into a tropical depression, then a tropical storm. In the process, what were once disorganized convective cells becomes an organized system of convective cells with convergence aiding the rapid, forceful upward movement of warm moist surface air and divergence aiding outflow near the tropopause (Barry and Chorley, 1998). Latent heat from warm moist air provides energy for the storm as it moves in a pole ward direction at speeds between 16 and 24 kmh. The tropical storm can become a hurricane as latent heat is supplied to the system and the cold center of the tropical storm becomes a warm center hurricane. Hurricanes are different from other cyclones because of this warm center and the presence of relatively calm conditions at their centers. Hurricane centers are surrounded by a band of intense wind and rain, called the eyewall, and outer bands of convective clouds and rain. In general, tropical storms last for four to five days and hurricanes last for two days (Barry and Chorley, 1998).

Statement of the Problem

In most studies of the Potomac River basin, high magnitude floods are assumed to be part of the same data series regardless of meteorological causal mechanisms. Possible problems with analyzing flood series data without considering the meteorological or climatic circumstances at play when the data were recorded are the inability to project changes in flood frequency and magnitude due to changes in frequency of moisture delivery from a specific storm type, changes in the prevailing storm type that generates extreme floods and/or changes with a change in the status of climatic driving forces. Evaluation of the causal mechanisms responsible for extreme floods in various regions might be the best approach to predicting the effects of climatic change.

Research Objectives

My research objectives are as follows:

1. To determine when ≥ 10-yr. recurrence interval discharge (extreme flood) events occurred at each of the 37 selected gauges and determine which types of storm events generated these floods.
2. To determine the relative magnitude of extreme floods versus the 1.5-yr. recurrence interval discharge (high frequency reference flood) events at each study gauge.
3. To determine whether or not the same storm type generated extreme floods at all study gauges in all Potomac River sub-basins.
4. To determine the spatial extent of the extreme floods in the Potomac River basin based on study gauge response and the relationship between maximum discharge due to a specific storm event (Qmax) and drainage area above the gauging station (DA).
5. To determine whether or not study gauges recorded sensitivity to ENSO by noting variations in flood frequency and magnitude with variations in ENSO phase.

Statement of the Hypotheses

Given the findings from previous work, discussed above, on the meteorologic and climatic causes of extreme floods in the Potomac River Basin, I have developed the following hypotheses that will be tested in this chapter.

1. Tropical storms are the primary cause of extreme floods within most of the Potomac River Basin.

2. Extreme discharge recurrence interval as a function of drainage area varies with storm type
3. Extreme floods in the Potomac River Basin are due to variations in ENSO phase.

DATA SOURCES AND METHODOLOGY

A master list of one-hundred and ninety active gauges in the Potomac River Basin was acquired by accessing the US Geological Survey (USGS), National Water Information System (NWIS): Web Interface at http://waterdata.usgs.gov/nwis and requesting a list of sites and descriptions based on the Potomac River Basin six-digit Hydrologic Unit Code (20700). Gauges were selected for inclusion in this study because continuous records of peak discharge series (Qpeak) and partial duration series (Qpd) data were available for years between 1950 and 2000. Thirty-seven gauges met the selection criteria. Although the criteria required records beginning in 1950, select gauges began continuous recordings prior to then. The earliest recording of discharge was in 1878 at Petersburg, WV. The longest continuous recordings began in 1895 on the gauge at Point of Rocks, MD (Appendix Table 12). Selected gauges have drainage basins that range in area between 150 km^2 and 7,000 km^2. Data for gauges on the North Branch Potomac River near Cumberland, MD and the North Fork Shenandoah River at Cootes Store, VA were used to illustrate differences in the timing and causal mechanisms that generated floods in the Potomac River Basin overall. These two gauges were chosen for their similar drainage basin areas and were called index gauges in this study. All 37 select gauges however, were utilized in all evaluations made in this study.

Qpeak data is considered valuable to this study because it lists the highest instantaneous discharge recorded in a given year. Instantaneous discharge is a measure of discharge rate recorded in the study area at 15- to 30-minute intervals depending on the gauge location. Qpd data is also valuable because it includes all discharges above a base discharge. The base discharge is determined by the USGS and assigned discharge values are always ones that are well above bankfull discharge but lower than the extreme maximum recorded by the gauge of interest. As a result, Qpd data includes multiple overbank discharges that have occurred in a single year rather than a single maximum for the year. Both records are useful. The Qpeak data is useful for flood frequency estimation. The Qpd provides a more robust estimate of flood frequency because of the abundance of data; and when Qpd data points are matched with the type of storm that generated the point, more is understood about the relationship between to two. Since the Qpd data points can be matched with storm type and it reports overbank discharges other than extremes, use of the data set can better delineate the areal extent of discharge due to a given storm event.

The monthly Multivariate ENSO Index (MEI) rank acquired at http://www.cdc.noaa.gov/people/klaus.wolter/MEI/mei.html was used to determine ENSO status. The MEI was used because it is updated monthly, gives the status of all processes that relate to ENSO cycle and it undergoes robust statistical analyses to derive an index value and rank (Wolter and Timlin, 1993).

Determining the Timing, Causes and Spatial Scaling of Floods

To test the hypothesis that extreme floods are primarily generated by tropical storms, the discharge exceedence probability (P) and recurrence interval (1/P) for flood events at each of the gauge sites had to be established by statistical analysis of Qpeak data for each of the 37 gauges. Recurrence interval estimation is a non-parametric statistical technique that is insensitive to outliers and therefore, more robust than methods based on parametric estimation (Devore, 2000). Data were first ranked from the largest event to the smallest event. The largest flood in each series was given a rank (m) of 1. The ranked data were then used to determine an observed probability distribution, in which the exceedence probability of each flood event could be determined using Equation 1 below (Gumbel, 1958).

$$P = m/ (n+1), \tag{1}$$

where m is the rank of the event, and n is the number of years of record.

For purposes of this study, a flood event is the date when discharges are reported to be in the upper tail of the discharge distribution at a selected gauge site. To determine the primary cause of extreme floods, flood events were selected if a record flood was reported by at least one study gauge on a given day and that date corresponded with the date of a storm (+/- 1 day) event. In all cases, more than one gauge responded to the same event. The selection criteria yielded a list of 24 flood events (Appendix Table 13).

Establishing Spatial Relationships

The spatial extent of a storm event and of the area receiving moisture from the storm has an influence on flood response (Smith, 1992 and Solyom and Tucker, 2004). To estimate the spatial extent of the listed 24 record-setting flood events derived from the previous step Qpd data for each of the 37 study gauges was examined. The same causal mechanism was considered responsible for any floods that were listed in the Qpd record as occurring on the same date (+/- two days) as any one of the 24 record-setting flood events. Results were then tabulated to note the number and location of responding gauges (Appendix Table 13).

The spatial response of the floods based on causal mechanism (frontal system or tropical storm) and as a function of drainage basin area (scaling relationships) was also evaluated as a part of this study. Discharges and drainage areas were transformed using the power function to determine scaling relationships. The spatial scaling of peak discharges within the Potomac River Basin was expressed as:

$$Q = b*DA^{m}, \tag{2}$$

where Q is either Qpeak or Qpd, b is a coefficient, DA is drainage area and m is both slope and the exponent in the power transformation that describes the relationship between drainage basin area and Qpeak. Log-log plots were constructed illustrate the results regression analyses. Slopes in the range between 0.90 and 1.0 indicated a linear relationship between the floods and drainage basin area. Exponent values that were < 0.9 indicated flood peaks that were not as strongly related to basin area. The coefficient of determination (R^2) indicated the strength of correlation between drainage area and discharge. R^2 was also used as an indicator of the heterogeneity in discharge response within a given basin. Scaling relationships were also evaluated by contrasting study gauge discharges that had the same recurrence intervals. All models underwent analysis of variance and model critique.

Extreme Flood Normalization

To compare the magnitude of Qpeak and Qpd data points that resulted from the same storm events and to compare Qpeak and Qpd data at different gauge stations within the Potomac River watershed, Qpeak and Qpd discharges were normalized by dividing the discharges of interest by the 1.5-year recurrence interval (R.I.) discharge. Each gauge was considered an independent point with a corresponding watershed area in this analysis, even though all of the gauges are in part of a stream channel network that feeds into the most downstream mainstem gauge. The use of a dimensioned variable, such as discharge cannot be used to compare flood magnitude among variously-sized watersheds. The 1.5-year recurrence interval (R.I.) discharge was chosen as a reference flood because it is well-constrained by statistical analysis, it serves as a high frequency reference flood that is also tied closely to watershed area and; in many watersheds, it approximates the bankfull flood (Langbein and Leopold *et al.*, 1964). Thus, the normalized flood frequency curve derived from the above technique gives information as to the amount of overbank flooding under non-constrained conditions and likely caused by the storm event.

Extreme Flood - ENSO Cycle Relationship Assessment

Three techniques were employed to explore the possibility of a relationship between Potomac River Basin extreme floods and ENSO cycle status. In the first technique, Qpeak data was sorted by the timing of events and the coincidence with ENSO phase and gauge location to develop a frequency curve. In the second technique, the top three discharges were extracted from each gauge record and sorted by ENSO status. Then statistical summaries were generated and tabulated to detect differences in mean, median, quantiles, inter-quartile ranges and standard deviations with differences in ENSO status. Tables are presented in the Results section below. In the final technique, a regression analysis of Qpeak data sorted by ENSO phase was undertaken. MEI ranks that ranged from 1 to 11 were considered La Nina status, ranks that ranged from 12 to 36 were considered normal status and ranks that ranged from 37 to 55 were considered El Nino status. The period of observation was from 1950 to 2000. Gauges, along with the results of each analysis and ENSO status, were sorted into North Branch Potomac River, South

Branch Potomac River, Shenandoah River, Potomac River mainstem. In the final technique, the assumption was that the discharge probabilities conformed to a Weibull distribution and graphs were reconstructed to illustrate the difference in slope with the difference in ENSO status. A rank of 1 was assigned to the rarest discharge for the period of observation. The rank order of Qpeak was used in graph construction in this step as well. The advantage of using the rank order of Qpeak, rather than the Qpeak value itself, is that it is robust, quick to calculate and allows for comparison between basins without normalization by drainage area or some other factor.

RESULTS

Timing and Causes of Floods in the Potomac River Basin

Overall, annual peak discharges in the Potomac River Basin can occur at any time throughout the year. When the dates of annual maxima are classified by month, however, regardless of sub-basin, spring months have the greatest number of annual peak events (Figure 3).

In general, the frequency of Qpeak shows a pattern of seasonality similar to that of the mean monthly discharge series that was shown in Chapter 1(Figure 3 inset). The one exception to this pattern is the peak flows that occur in August through September, when the mean monthly discharge show minima. Overall, Qpeak events occur most frequently in March, which is also the time of year when mean monthly discharge is highest. As the year progresses, there is a gradual decline in mean monthly discharge. There is also a decline in the number of Qpeak events, particularly for gauges in the North Branch Potomac River Basin. Minimums for both mean monthly and the number of Qpeak events are reached in July or August. After that, mean monthly discharge and the number

a) $Qpeak_s$ by month recorded at the North Branch Potomac River near Cumberland MD gauge.

b) $Qpeak_s$ by month recorded at the North Fork Shenandoah River gauge near Cootes Store, VA.

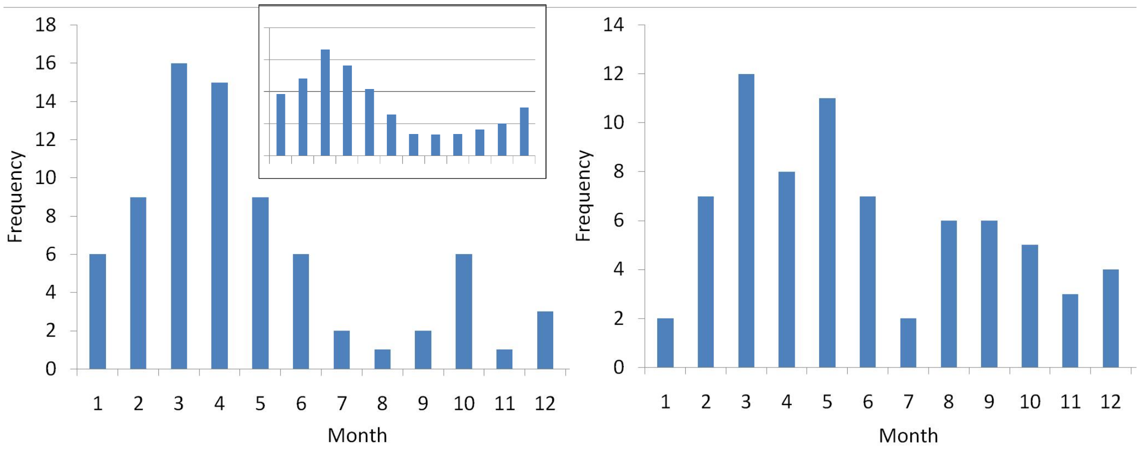
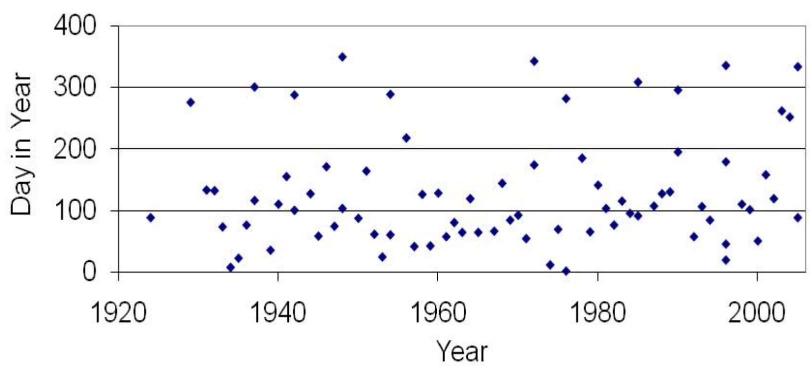


Figure 3. Number of times Qpeak occurred in a given month based on the gauge record at the two index gauge stations. Average monthly precipitation trend based on the gauge record at Hagerstown, MD (inset). Frequency maximums do not equal.

of Qpeak events are no longer synchronous. North Branch Potomac River sub-basin gauges show a small peak in the number of Qpeak events in October and the rest of the Potomac River watershed shows a secondary peak in the number of Qpeak events in August and September. Study gauges report these conditions in spite of the fact that mean monthly discharge is at its lowest from August to September. During August and September tropical storms are most abundant in the Atlantic Ocean Basin (Landsea, 2007) and these storms frequently deliver moisture into the Potomac River Basin. Therefore, the behavior of the Qpeak data series also implies that North Branch Potomac River sub-basin gauges were not as heavily influenced by tropical storms in August and September as the rest of the sub-basins (Figures 4 and 5).

Closer inspection of the timing of Qpeak events, with an emphasis on events in the upper 10% of the annual peak discharge distribution, revealed the fact that most extreme floods occur at two distinct times of year: during the spring (February, March and April) and during August and September; which is the heart of hurricane season (Figure 5, Appendix Table 13). Although some extreme floods occurred on the same day, gauges located in the North Branch Potomac River were more likely to record extreme floods in winter or spring (December to April) and further downstream, gauges recorded extreme floods almost exclusively in late summer or early fall (August to October; Figure 5).

a) Qpeak for the gauge on the North Branch Potomac River near Cumberland, MD.



b) Qpeak for the gauge on the North Fork Shenandoah River at Cootes Store, VA

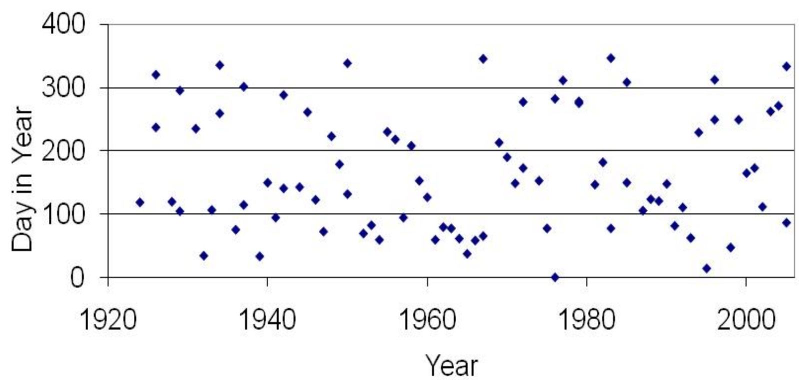


Figure 4. Qpeak data plotted by the day of occurrenceusing data from the two index gauges. Graph is constructed based on the gauge record from 1924 to 2005.

Previous studies that list the timing and cause of flood events that were of high magnitude and extensive areal coverage were presented in Chapter 1 (Table 1). As suggested by the literature, tropical storm moisture is the leading cause of floods in the

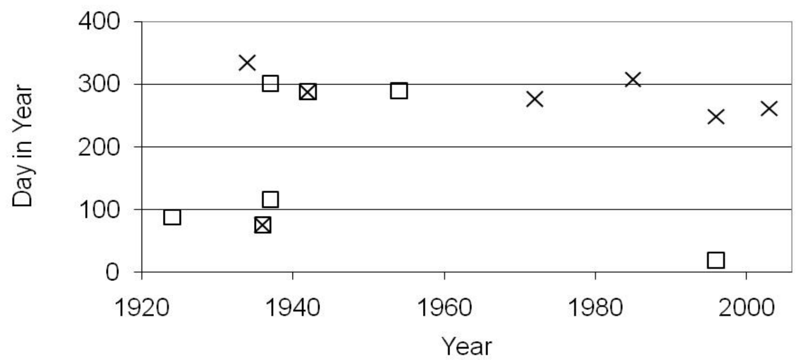
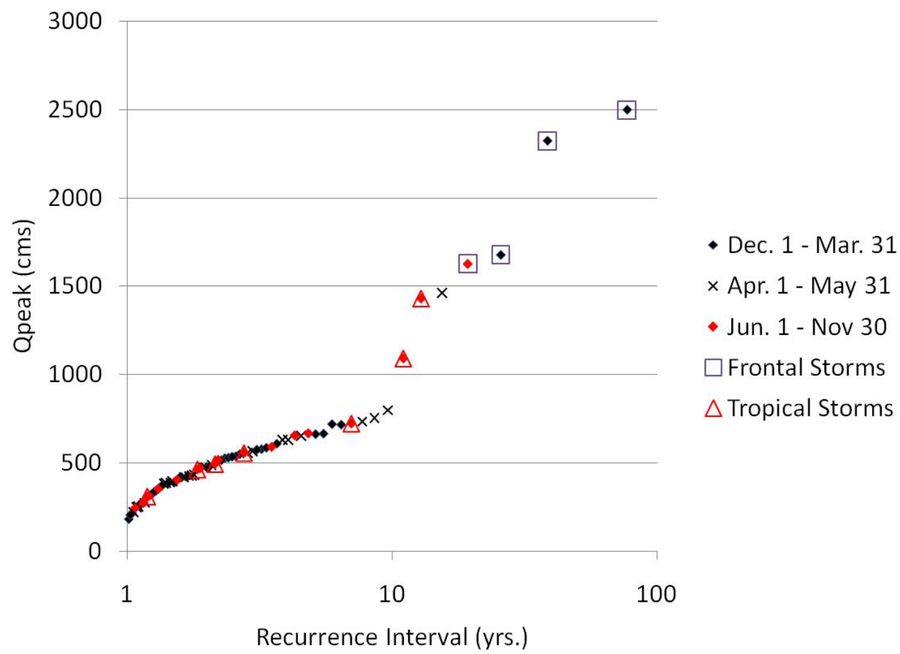


Figure 5. Qpeaks in the upper 10% of the distribution for the gauges on the North Branch Potomac River near Cumberland, MD (squares) and on the North Fork Shenandoah River at Cootes Store, VA (Xs).

Potomac River Basin followed by frontal cyclonic storms that lead to rain-on-snow events or intense rainfall (Figure 6, Appendix Table 13). Tropical storm moisture is the terminology used here because in some cases, only remnants of moisture from the original tropical storm remained. These remnants then interacted with other meteorological conditions that led to excessive rainfall and extreme floods. From now on, these events will be referred to only as tropical storms.

The results of this analysis revealed that the timing of extremes is bi-modal. For the most part, frontal cyclones generate floods in winter (December through March) and tropical storms generate floods during summer and early fall (June through November). Both of these two main storm types were effective at generating floods over large portions of the basin as well as generating extreme discharges. Less frequently, Nor’easters and convective thunderstorms have been the cause of extreme floods. Nor'easters and convective thunderstorms generally occur from spring to fall. In all cases, extreme flood events far exceed annual flood averages for the period of record (, Figure 6, Appendix Table 13)

a) Qpeak discharge distribution by season and with known meteorological causal mechanisms identified - North Branch Potomac River near Cumberland, MD gauge.



b) Qpeak discharge distribution by season and with known meteorological causal mechanisms identified -North Fork Shenandoah River at Cootes Store, VA gauge.

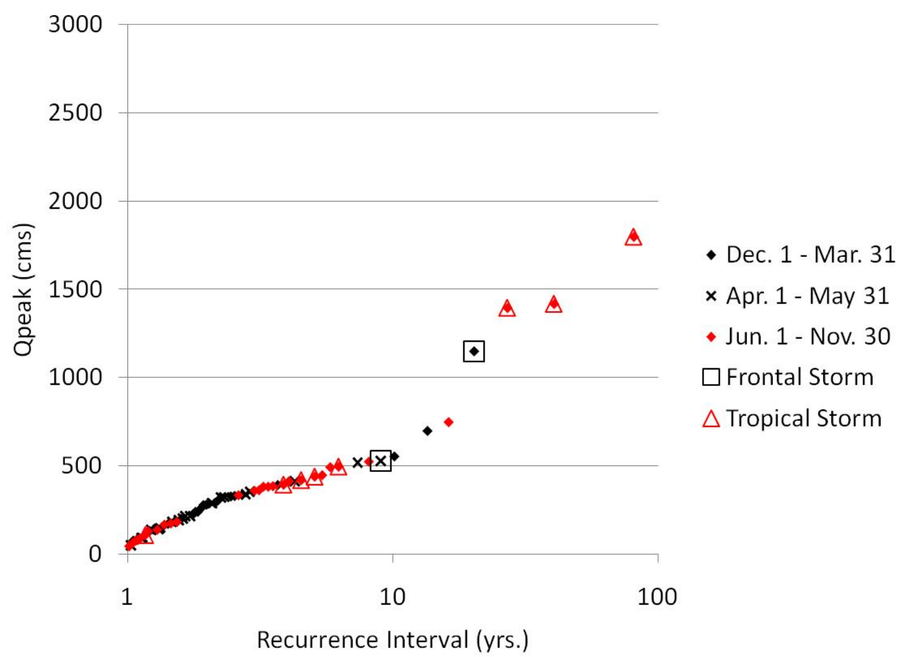


Figure 6. Contrast in Qpeak R.I., event related storm type and timing. The leading cause of extreme floods in the North Branch Potomac River basin is more likely to be due to frontal storms. Extreme floods in other Potomac River sub-basins are more frequently generated by tropical storms.

It was expected that frontal cyclones would be the leading generators of floods regardless of location because frontal storms are the leading generators of precipitation throughout the United States. In addition, frontal systems have no seasonal dependence and, when aided by orographic lifting, precipitation is enhanced. Extreme floods in the Potomac River watershed, however, are primarily generated by tropical storms. Frontal cyclones are the leading cause of extreme floods only in the North Branch Potomac River sub-basin. Not only are frontal cyclones less important than tropical storms for record-flood generation, Qpeak events associated with frontal cyclones were closer to the 1.5-yr R.I. than Qpeak events associated with tropical storms (Table 2, Figure 7). For example, the largest frontal cyclones generated record floods that averaged ~6 times the 1.5-yr. R.I. (bankfull) flood in all basins, while the record discharges related to tropical storm occurrence are ~10 times the bankfull flood. The maximum tropical storm flood magnitude for the North Branch Potomac River is less significant and ~5 times the bankfull flood (Figure 7).

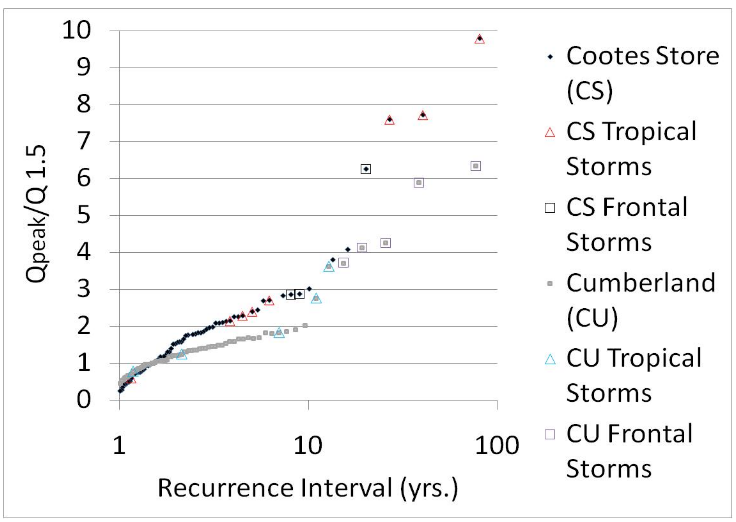


Figure 7. Dimensionless flood frequency diagrams for the North Fork Shenandoah River Cootes Store, VA and the North Branch Potomac River at Cumberland, MD. In the Shenandoah Basin, tropical storms generate the largest magnitude floods, frontal storms create maximum peaks in the North Branch Potomac River Basin.

Table 2. Regression Parameters for Floods

Flood Description	Coefficient (b)	Exponent (P)
1.5-year flood†	9.8	1.00
Record peak discharge* Potomac River Basin	10.6	0.72
Record peak discharge* Shenandoah River Basin	23.2	0.63
Frontal cyclone induced record floods§ Potomac River Basin	1.5	0.92
Tropical storm induced record floods§ Potomac River Basin	15.7	0.68
Note: #Listed flow statistics were plotted as functions of drainage area. †Parameter values provided by K. Prestegaard. *Data extracted from Qpeak data. §Data extracted from Qpd.		

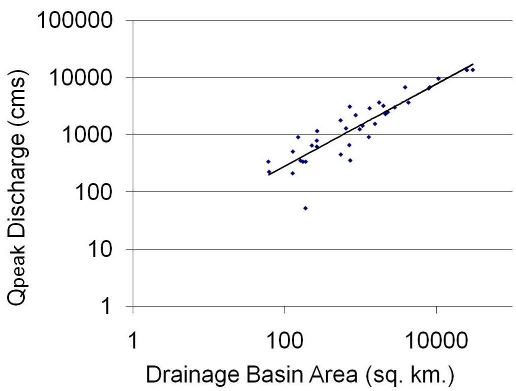
Scaling Floods by Storm Type

The purpose of this section is to determine whether or not Qpeak varies as a function of drainage basin area (D.A.), causal mechanisms and/or location. Different storm scenarios were considered to make a determination. The results are reported in the following paragraphs.

The linear relationship between Q1.5 and drainage area is reported in Table 2. Record Qpeak, regardless of storm type, did not have a linear relationship to drainage area, whether all study gauges were used or only gauges in the Shenandoah River Basin (Table 2 and Figure 8). Recall the fact that record floods in the basin, as a whole, include both frontal storms and tropical storms as causal mechanisms, while record floods in the Shenandoah River Basin were due to tropical storms almost exclusively.

The exponent (P) derived from regression analysis of gauges that responded to frontal storms is more linear than P derived from regression analysis of gauges that responded to tropical storms (Table 2 and Figure 9). Even though the exponent (0.92) related to frontal storms suggested D.A. was responsible for most of the variability in Qpeak, the model

a) Maximum Qpeak discharge for all study gauges.



b) Maximum Qpeak for all study gauges in the Shenandoah River Sub-basin.

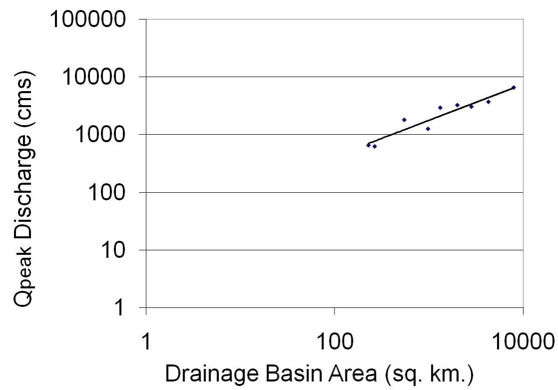


Figure 8. Record Qpeak as a function of drainage basin area for the entire watershed and for the largest contributing sub-basin. Regression parameters are listed in Table 2. There are thirty-seven study gauges and eight study gauges in the Shenandoah River Sub-basin. All maximums are based on the period of record for each gauge.

failed the critique phase. Floods due to tropical storms had a smaller exponent (0.68), which indicates Qpeak is less a function of drainage area when tropical storms are the cause of floods. For purposes of this study, this is also an indication that the gauge response to tropical storm precipitation varies from one gauge to another (is heterogeneous). The thought was that the difference in the number of gauges used in the two regressions influenced the results. So, new regression analyses were undertaken after all Qpeaks associated with frontal storms and tropical storms were sorted, re-plotted and transformed. The results were the same (Table 2),

The next consideration was the fact that frontal storms include as a sub-set rain-on-snow and excessive rainfall events. Since the flood response to the events can vary, it was decided that scaling relationships that resulted from each of these storm types should be compared to scaling relationships that resulted from tropical storms. It was further decided that individual storm events with near-equal impact in terms of discharge recurrence intervals and areal extents of coverage should also be compared.

a) Frontal storm-generated maximum $Q_{peak.}$ b) Tropical storm-generated maximum Q_{peak}

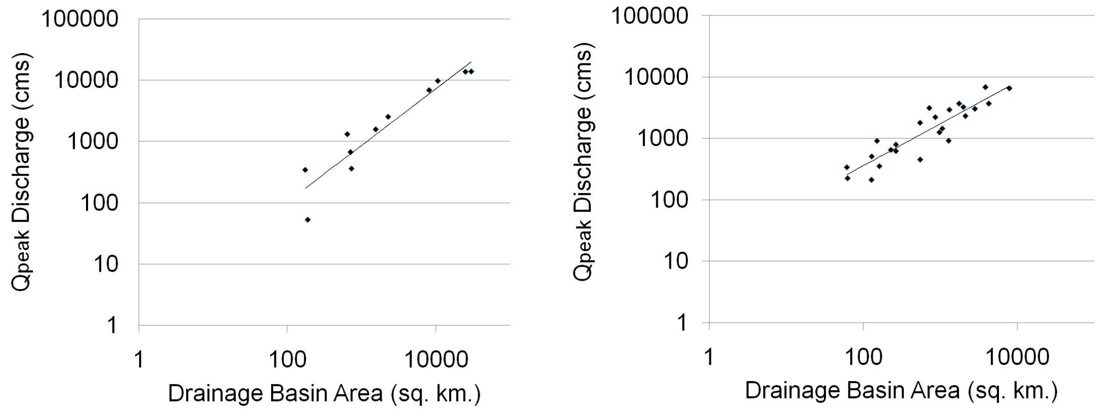


Figure 9. Record Q_{peak} as a function of drainage basin area for the two primary storm types. Regression parameters are listed in Table 2. Eleven gauges reported maximum discharges due to frontal storms. The remaining 26 gauges reported maximum discharges as a result of hurricanes. All maximums are based on the period of record for each study gauge.

The scaling relationships based on discharges recorded around March 17, 1936 (a rain on snow event) and June 22, 1972 (a tropical storm event) were therefore contrasted and again, scaling was closer to linear when the March 17 event response was plotted than when the June 22 event response was plotted. (Table 3, Figure 10). This is to be expected because there was a large blanket of snow covering the area prior to the rainfall event of March 1936. The March 1936 rainfall event covered the same broad region of snow cover, thus resulting in discharge recurrence intervals that did not decrease with increasing basin areas. In the case of Agnes, the storm was centered in the east and the impact was greatest close to the storm's center with a diminishing effect grading toward the west. Therefore, while the areal extent of coverage was nearly equal for the two events, the overall impact of precipitation on discharge recurrence interval was not the same throughout the basin.

Table 3. Regression Parameters for floods generated by different mechanisms

Flood Dates	Storm type	Coefficient(b)	Exponent (P)
March 17-19, 1936	Frontal cyclone	2.95	0.83
June 22-24, 1972	Hurricane Agnes	7.16	0.65
March 27-30, 1994	Frontal cyclone	0.59	0.82
September 19-23, 2003	Hurricane Isabel	2.22	0.75

a) Q_{pd} due to a frontal storm on March 17, 1936.   b) Q_{pd} due to a hurricane on June 22, 1972.

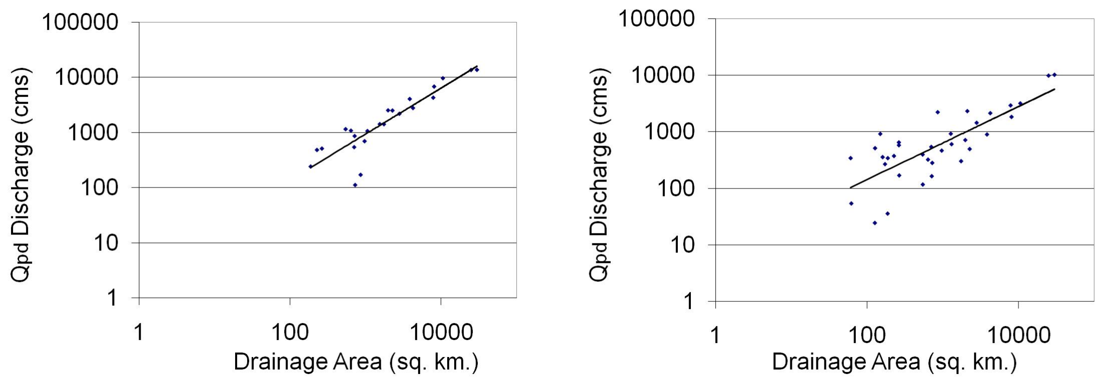


Figure 10. Qpd as a function of drainage basin area due to two different storm types. Regression parameters are listed in Table 3. Twenty-three gauges responded to the storm in March 1936 and 37 gauges responded to the storm in June 1972.

Two excessive rainfall events with different causal mechanisms were also contrasted (Figure 11). It was thought that if storms covered the same general area and had a similar path; regression equations would be similar, regardless of storm type. For this part of the evaluation, the representative frontal cyclone-induced storm was the March 29, 1994 event and the representative tropical storm was the September 19, 2003 event.

Exponents and R^2 values related to the frontal cyclone generated discharges on March 27-30, 1994 were similar to those for the March 17, 1936-related event. The exponents and R^2 values associated with the September 19-23, 2003 (Hurricane Isabel) discharges indicated more homogeneity in discharge response than previous scaling efforts, but values were still not as high as those related to the two frontal storms. The consideration when evaluating discharge response induced by Hurricane Isabel was the fact that it crossed the Potomac River Basin in a path nearly parallel to that of many frontal storms and in spite of that, the flood response was still less homogeneous than that of the response to frontal systems (Figure 11).

a) Q_{pd} due to a frontal storm on March 27, 1994   b) Q_{pd} due to a hurricane on September 19, 2003

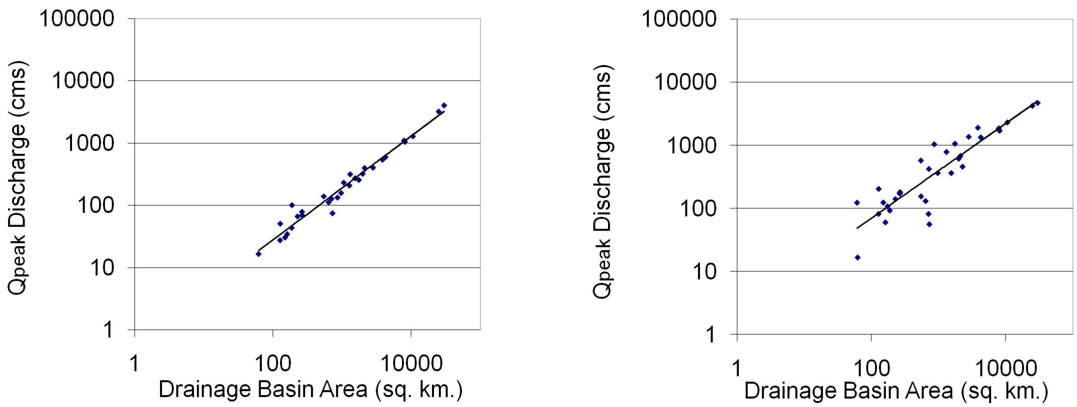


Figure 11. Partial duration discharges as a function of drainage basin area due to two different storm types. Regression parameters are listed in Table 3. Thirty gauges responded to the storm in March 1994 and 34 gauges responded to the storm in September 2003.

Flood Discharge/Drainage Area Relationships

All mainstem gauges report a single event (March, 1936) as the cause of record discharge. At the same time, based on determination of Qpd/Q1.5 ratios associated with frontal systems and tropical storms, frontal systems should have less of an impact on mainstem extreme discharge than tropical storms, particularly in the downstream reaches of the Potomac River Basin where basin areas are largest. Preliminary evaluation of Qpd data at all study gauges in operation during notable storm events (see Appendix Table 13) suggested that there was a difference in the areal extent of responding gauges based on storm type. During the course of this analysis, I found frontal storm events that generated extreme floods also generated nominal to moderate floods over a broader region than most tropical storm events. If frontal storms, in general, produce nominal to moderate floods over broad regions and tropical storms are generally more local, then that may be the reason record Qpeaks due the storm of March 17, 1936 have not been broken on mainstem gauges. Another reason is flood hazard mitigation efforts along the mainstem.

Extreme Floods and ENSO Cycle

Extreme floods in the Potomac River Basin are sensitive to geographic position and the status of ENSO. (Figure 12, Table 4). In the North Branch Potomac River sub-basin, gauges reported extreme flood events most frequently during La Niña (MEI rank $\leq$ 11). Gauges in the downstream portion of the basin, particularly in the Piedmont and Coastal Plains regions, reported extreme floods during El Nino (MEI rank $\geq$ 45). Sub-basin gauges in the middle reach of the Potomac River Basin reported extremes when conditions were normal ($>$ 11 and $<$ 44).

The above analysis suggests the differences in flood response among some of the sub-basins of the Potomac River Basin may be due to differences in the sensitivity to ENSO phase. In the previous section, it was established that the Shenandoah River sub-basin is more likely to be affected by hurricanes than the North Branch sub-basin, Given the fact that the study gauges show a sensitivity to ENSO and the primary cause of floods is tropical storms, is useful to examine further the relationship between tropical storms, floods in the Potomac River Basin and ENSO. This will be the subject of a subsequent chapter.

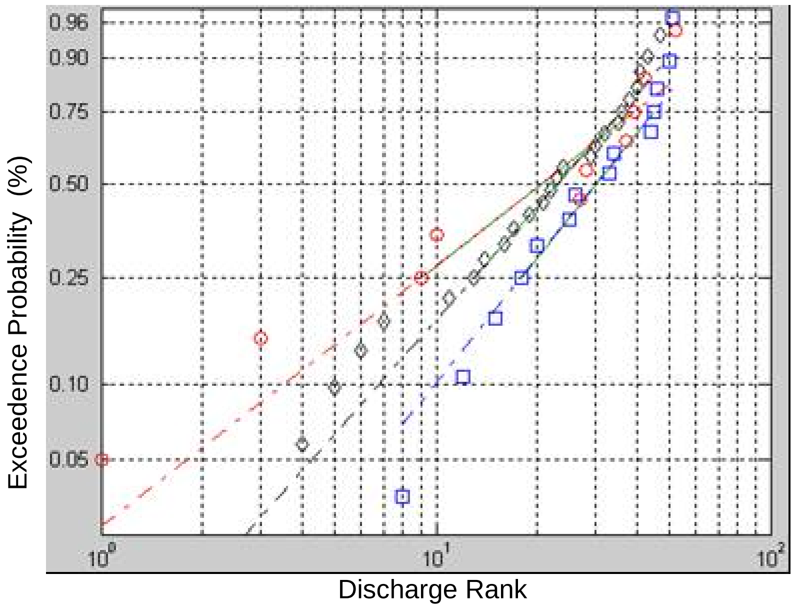


Figure 12. Composite graph of exceedence probability versus Qpeak rank based on the gauge record at Wills Creek MD. Discharges are sorted by ENSO phase. Red circles = El Nino, black diamonds = normal, blue squares = La Nina. Dashed lines = regression lines for each phase. A rank of one is record discharge.

Table 4.Select MEI Values#

ENSO phase*		North Branch Potomac R.	South Branch Potomac R.	Shenandoah River	Potomac R.
Median	El Nino	**29.1 ± 3.6**	25.5 + 3.0	**17.7 + 4.0**	23.9 + 5.9
	La Nina	31.0 ± 6.0	25.8+ 7.2	27.4 + 6.1	27.7 + 5.5
	Normal	**22.4 ± 4.0**	27.8 + 3.8	**30.0 + 4.3**	27.0 + 4.8
10^{th} %ile	El Nino	9.9 + 3.4	6.2 + 2.1	5.2 + 0.5	6.5 + 3.0
	La Nina	6.7 + 5.4	5.3 + 1.7	7.8 + 4.0	6.6 +3.7
	Normal	5.0 + 1.1	5.3 + 0.5	6.8 + 2.8	6.0 + 1.9
Mean D.A.(km^2)		889	1,646	2, 243	3.011
No. of gauges in the basin		4	5	4	37
Note: #MEI averages taken when gauges reported maximum Qpeaks between 1950 and 2000. *El Nino, La Nina and Normal phases are based on MEI values. See Data and Methodology for details. Values in bold plot outside of other ranges and are considered significant.					

DISCUSSION AND CONCLUSIONS

This study identifies tropical storms as the primary cause of extreme floods in the Potomac River Basin. Even though these storms occur during the time of year when temperature and therefore, evapotranspiration rates are high, they still manage to generate the bulk of floods in the upper 10% of gauge Qpeak distributions in the basin. Exceptions are some of the gauges in the North Branch Potomac River sub-basin and the gauge on Opequon Creek at Martinsburg, WV. Tropical storms are not strongly related to drainage basin area even when the storm has the same general track as a frontal storm. One reason this may be the case is orographic enhancement. Sturdevant-Rees et al. (2001) indicate orographic enhancement is an important factor in rainfall distribution and runoff generation. The importance of orographic enhancement holds even though, in many instances, tropical storms have a trajectory that is near parallel to the Appalachian Mountain ranges (Klein *et al.,* 2007). If only meteorologic dynamics and their interaction with surface topography are considered, Barros and Kuligowski (1998) offer an explanation for extreme flood responses in the case of tropical storms by pointing out the fact that shallow relief can influence precipitation and meso-scale leeward effects are important in the development of localized precipitation enhancement.

The scaling properties of flood responses due to frontal systems were more homogeneous than that for tropical storms whether by basin or storm type. Barros and Kuligowski (1998) observed windward effects and leeward effects were important at different scales in the January 19, 1996 storm event and that the leeward effect generated extreme floods in small watersheds in the Susquehanna River Basin while orographic enhancement of a different type led to higher rainfall on the windward side of the

Allegheny Front. The same processes could be at play when frontal storms generate floods in the Potomac River Basin. The combined windward and leeward orographic effects would account for the near-linear scaling properties of frontal cyclone induced flood responses.

1) Floods generated by tropical storms are an important part of the extreme flood distribution for gauges in the Potomac River Basin.

2) The possibility that ocean warming may result in an increase in either the frequency or magnitude of tropical storms means we should investigate the conditions under which tropical storms generate floods in the Potomac River Basin.

3) The non-linear and heterogeneous flood responses to tropical storm events in the Potomac River Basin implies rainfall/runoff characteristics for tropical storms may be heterogeneous and sensitive to antecedent moisture conditions, these should be investigated.

Tropical storms will be the focus of the remainder of this study because they generate more extreme floods than frontal storms, comprise portions of the Qpeak record, regardless of frequency and magnitude, and are more easily identified in archival storm records and discharge records. The next chapter is devoted to understanding when these storms are effective flood generators and what climatic processes are influencing their effectiveness.

Chapter 3: Floods, Hurricanes and Climate Factors

ABSTRACT

Tropical storms generate many of the high magnitude flood events in the Potomac River Basin. Climatic factors can enhance precipitation (Elsner and Bossak, 2004) and tropical storm development and track (Bossak, 2004). This suggests the status of a tropical storm at landfall or on arrival in the basin as well as certain climatic factors control how effective a tropical-storm can be at producing floods. This chapter examines the hypothesis that the combined status of the storm at landfall, the status of the storm on arrival in the basin and the status of climate factors one month prior to a storm event are predictors of storm effectiveness. This hypothesis was tested by first modeling effective tropical storms as a function of storm status and climate factors using the logit link testing model fit. Two parameters are the best predictors of tropical storm effectiveness. One is the Pacific Decadal Oscillation Index and the other is the surface pressure associated with the storm when it arrives in the basin.

INTRODUCTION

In the Potomac River Basin, the peak discharge for the year is often due to the delivery of moisture from tropical storms (Bailey *et al.,* 1975; Carpenter, 1988; Perry *et al.,* 2001; Sturdevant-Rees *et al.,* 2001; Rhodes, this study). In some cases, storm track is directly responsible for the pattern of precipitation (e.g., Hurricane Fran 1996, discussed by Tuleya *et al.*, 2007) that leads to annual peak discharges. In other cases, the storm is distal and the precipitation event and floods in the basin results from the interaction between remnants of moisture from the tropical storm and a complex set of meteorological circumstances that enhance precipitation intensity or duration. For example, total rainfall depth due to Hurricane Agnes 1972, was influenced by (Namias, 1973 and Bailey *et al.,* 1975). What is not understood is the strength of tropical storms and/or the status of climatic factor/s needed to increase the likelihood that a storm is effective (able to generate annual peak discharge) in the Potomac River basin.

The purpose of this study is to evaluate relationships between the occurrence of tropical storms, floods and climatic precursors to suggest a model that predicts when a tropical storm will induce Qpeak. The terms 'annual peak discharge' and 'floods' are used interchangeably in this study.

Hurricane-Flood Response Studies

Bailey et al. (1975) and Carpenter (1988) suggest that storms with low wind speeds at landfall and that enter the United States distal to the Potomac River Basin (LA and FL landfalls) are more capable of generating extreme annual peak floods. Sturdevant-Rees et al. (2001) however, suggests annual peak discharges are due to storms that have high wind speeds at landfall, enter the United States proximal to the basin (North Carolina landfalls) and cross the basin with low wind speeds and high pressure. Also, models of tropical-storm induced rainfall distribution suggest an exponential decrease in rainfall with distance from the point of landfall (Tuleya et al, 2007). These results contradict one another, and suggest that a more detailed study of floods generated by tropical storms is required.

Climatic Factors That Influence Moisture Delivery to the Potomac River Basin

Climatologists have identified several climate factors that contribute to either eastern US summer precipitation or tropical storm development and track. The Madden-Julian Oscillation (MJO) westerly phase is linked to increased hurricane activity in the Gulf of Mexico (Maloney and Hartmann, 2000). Sahelian Rainfall (SR) moving out over the Atlantic Ocean off the coast of West Africa is significantly correlated with intense hurricanes that make US landfall (Landsea *et al.*, 1992). Other climate factors that influence hurricanes and precipitation are described in the paragraphs that follow.

The Atlantic Multi-decadal Oscillation (AMO) is a global scale pattern of low temporal frequency (20 to 40 years) sea-surface temperature and sea-level pressure anomalies that may have a connection to the thermohaline circulation (Delworth and Mann, 2000). The AMO index (AI) is described based on Atlantic Ocean average surface temperature shifts of approximately 0.6°C (1°F). Temperature is observed between 75°W and 7.5°W longitude and from the equator to 60°N. This climate phenomenon influences US rainfall, temperature and possibly the intensity and abundance of Atlantic Ocean hurricanes (McCabe *et al.,* 2004; Enfield *et al.,* 2001 and Goldenberg *et al.,* 2000). The Atlantic Multi-decadal Oscillation index (AI) is correlated to rainfall over North America and to changes in the frequency of droughts and severe hurricanes (Enfield *et al.,* 2001; McCabe *et al*., 2004).

El Nino/Southern Oscillation (ENSO) refers to coupled equatorial sea surface temperature and atmospheric pressure anomalies that are related to trade wind intensity (Figure 13). Trade wind strength alters sea surface height and the zonal and depth distribution of ocean temperatures. Under normal conditions, sea surface temperatures are

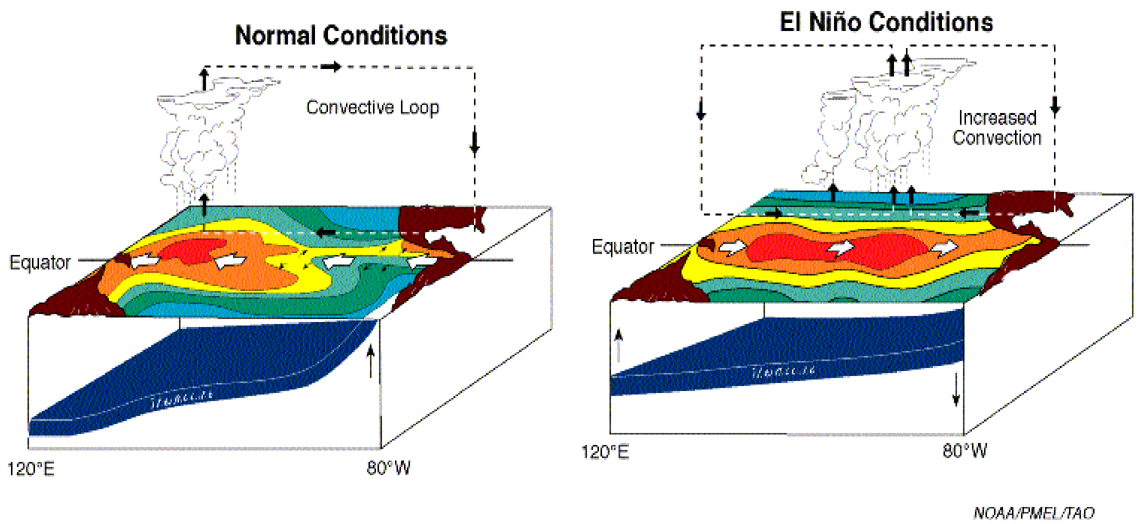


Figure 13. ENSO warm phase (left) and cold phase (right) conditions. El Nino is represented by the spreading of warm (warm colors) sea surface temperatures across the equator toward Peru and a shallow uniform slope in the thermocline. The Southern Oscillation is centered more to the east during El Nino. Image downloaded from El Nino Theme page at http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html

warmer in the western Pacific Ocean (Figure 13; NOAA, 2005). These normally warmer sea surface temperatures lead to abundant rainfall in the western Pacific Ocean. The rainfall is due to convective uplift of the warm moist air. This is the atmospheric component of the system and is referred to as the Southern Oscillation (NOAA/PMEL/TAO, 2005). El Nino is identified by anomalies in sea-level pressure, zonal and meridional surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky over the tropical Pacific (Rasmusson and Carpenter, 1982). A periodic warming in sea surface temperature and accompanying heavy rainfall has been known to people in Peru since at least the 1800s (National Academy of Science, 2000). Walker (1928) first described the Southern Oscillation, and then Bjerknes (1969) related the Southern Oscillation to El Nino. During ENSO negative phases (La Nina) the probability of a wetter than normal summer and early fall (July, August, September and October) increases in the upstream portion of the Potomac River Basin (NOAA, 2007).

La Nina is also associated with an increased number of Atlantic hurricanes (Bossak, 2004).

The climate pattern later named El Nino is held responsible for the circumstances that led to the track of Hurricane Agnes 1972 and extreme precipitation associated with that storm (Namias, 1973). Extreme precipitation due to Hurricane Agnes (1972) led to the most severe flooding on record for a large portion of the Potomac River Basin.

The North Atlantic Oscillation (NAO) is a pattern of atmospheric circulation and geopotential height anomalies that are bi-modal and persist for a month to several years near Greenland at approximately 55°N latitude and the North Atlantic between 35°N and 40°N latitude (Barnston and Livesey, 1987). The NAO is present during all months and considered to be in positive phase when the readings are lower than average near Greenland with corresponding higher than average readings in the mid-latitudes (Figure 14; Barnston and Livesey, 1987). The NAO was first described by Walker and Bliss (1932), its effect on temperature variation was later noted by Bjerknes (1969) and later, Wallace and Gutzler (1981) assigned the name North Atlantic Oscillation to this phenomenon. The NAO modifies the position of the Bermuda High, thus altering hurricane track. When the NAO is strong, the Bermuda High shifts eastward and storms are less likely to strike the northeastern United States.

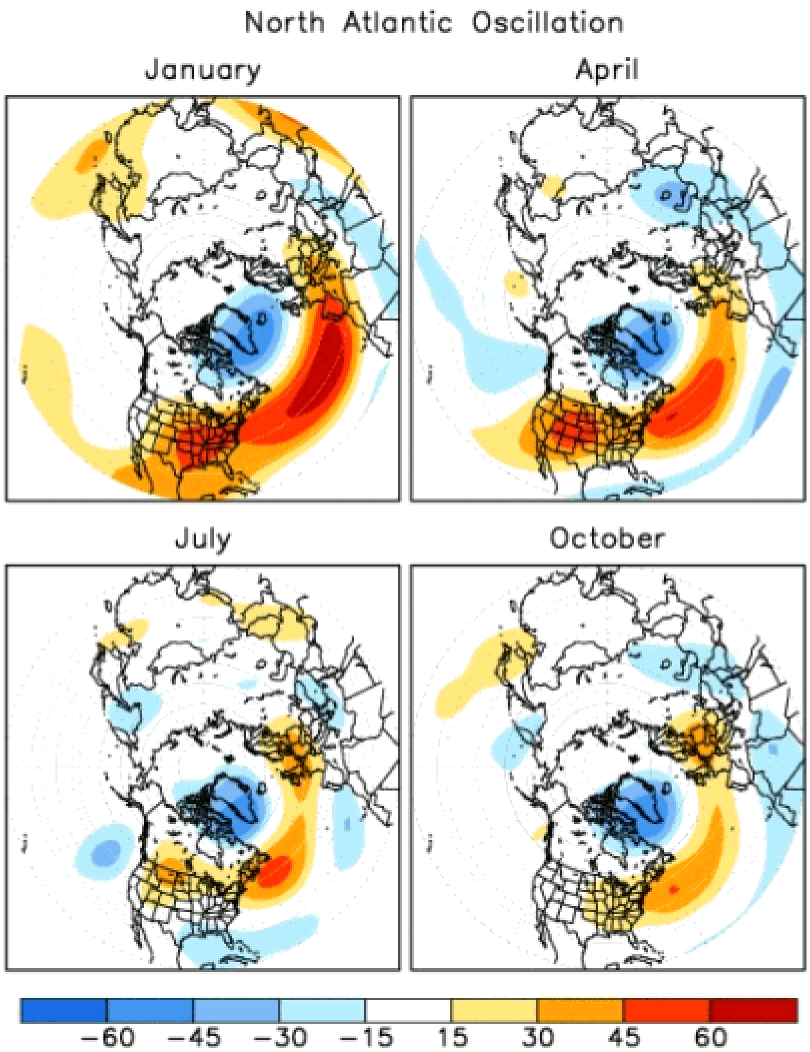


Figure 14. North Atlantic Oscillation - positive phase. Colors represent the temporal correlation between standardized geopotential height anomalies and the North Atlantic Oscillation time series during the month shown. Map acquired on 5/31/2008 from the NOAA, Climate Prediction Center, at http://www.cpc.noaa.gov/data/teledoc/nao_map.shtml.

The PDO is often described as an ENSO-like climate phenomenon because it occurs in the Pacific Ocean in the same location as El Nino/Southern Oscillation (ENSO) and there is a combined sea surface temperature, sea level pressure and wind pattern relationship (Figure 15; Zhang *et al*., 1997). The Pacific Decadal Oscillation, however, shows a stronger signal in the northern Pacific while the ENSO signal is strongest near the equator (Zhang *et al*., 1997). In general, the PDO is identified by statistical analysis

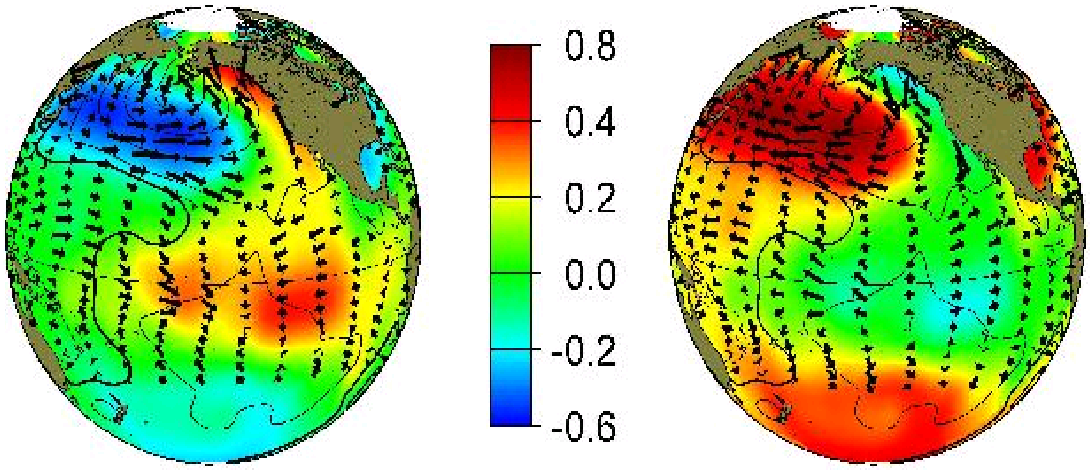


Figure 15. Pacific Decadal Oscillation warm phase (left) and cold phase (right). Sea surface temperature (colors) and sea level pressure (contours) anomalies are the leading indicators of PDO variability. Wind stress (arrows) varies with changes in SST and SLP Mantua (1997). Color bar = temperature departure. Downloaded March 9, 2008 from http://jisao.washington.edu/pdo/.

of mapped sea surface temperature and sea level pressure anomaly patterns in the Northern Pacific Ocean north of 20°N latitude. The indicators of a warm phase are cold sea surface temperatures and low sea level pressure anomalies near the Aleutian Islands and the Gulf of Alaska and warm sea surface temperatures near the western coast of the Americas. This pattern was first noticed by Hare (1996) and Zhang et al. (1997) and later described by Mantua *et al*. (1997). The Pacific Decadal Oscillation (PDO) influences July and August precipitation in the US Mid-Atlantic Region (Barlow *et al.*, 2001).

The Quasi-biennial Oscillation is the dominant direction (easterly or westerly) of zonal equatorial winds in the lower stratosphere. These winds persist for approximately two years as they move toward the tropopause and weaken (Reed *et al*. 1961, Baldwin *et al*., 2001). Reed *et al*. (1961) gives credit to Von Berson [sic] for discovering this "thread of steady west winds encircling the globe . . ." near the equator and to Palmer (1954) for characterizing stratospheric zonal flow near the equator while suggesting a cyclic nature to the downward movement of the winds. Later, Lindzen and Holton (1968) would model the QBO (Figure 16). The westerly phase of the Quasi-biennial Oscillation (QBO) enhances hurricane activity (Bossak, 2004).

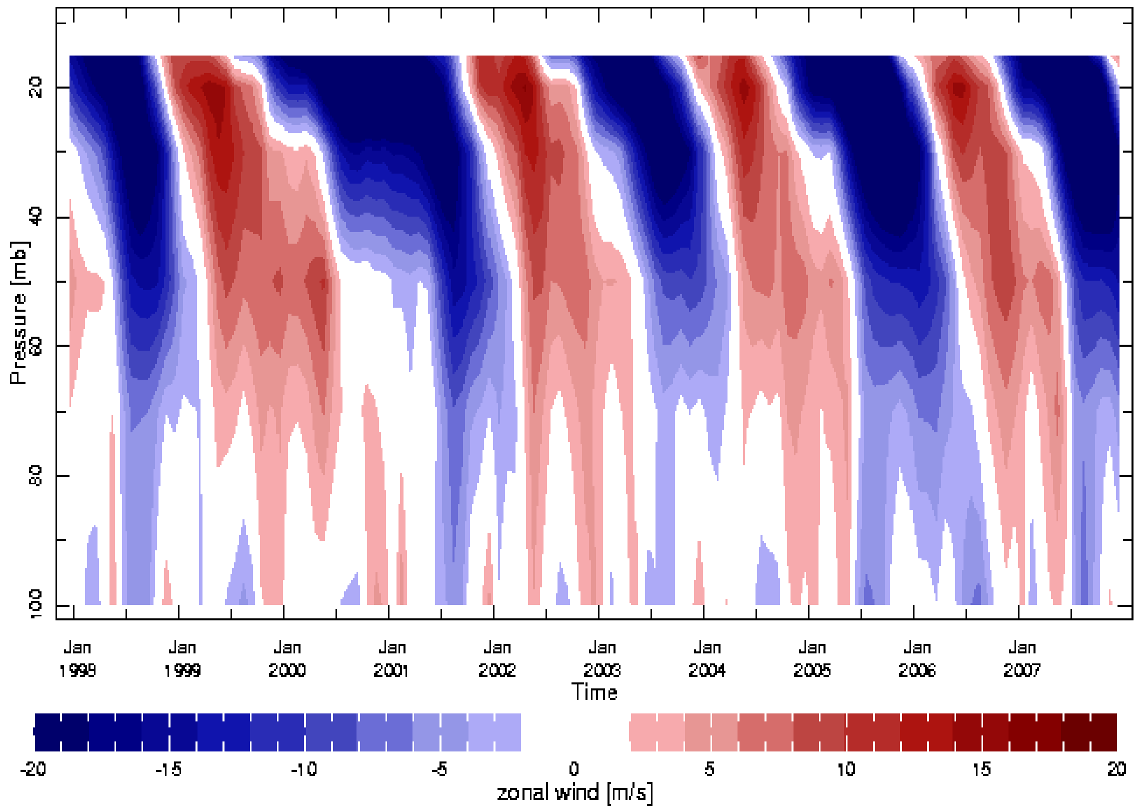


Figure 16. Illustration of the Quasi-biennial Oscillation. Cross-sectional pattern of average zonal wind speed in the stratosphere with respect to time (1998 to 2007). Measurements were taken between 5°S to 5°N latitude. Red indicates west winds, blue indicates east winds Data for the plot provided by the US NOAA, NCEP-NCAR Reanalysis Program. Image acquired from The International Research Institute for Climate and Society http://ingrid.ldeo.columbia.edu/maproom/.Global/.Atm_Circulation/QBO.html on March 9, 2008

Statement of the Hypothesis

Given the previous work on Atlantic hurricanes and climate and the flood response to hurricanes in the Potomac River Basin, I have developed the following hypotheses that will be tested in this chapter. In the presence of tropical storm moisture in the Potomac

River Basin, annual peak discharges are a response to the following explanatory variables:

1. Storm landfall location,
2. Storm center atmospheric pressure and wind speed at landfall,
3. Storm center atmospheric pressure and wind speed on arrival in the Potomac River Basin,
4. climate precursors that influence eastern US summer precipitation, landfall location and tropical storm development, or
5. A combination of items 1 to 4.

DATA SOURCES AND METHODOLOGY

Moisture abundance in hurricanes is related to the storm's central atmospheric pressure and wind speed. Hurricanes have steep pressure gradients. And, as tropical storm intensity increases atmospheric central pressure decreases and the amount of moisture taken up into the storm cell also increases. Intense wind speeds and low atmospheric pressures indicate moisture production. As a result, it was decided that tropical storm landfall location, storm status at landfall and storm status on arrival in the basin would be examined to determine their importance in storm effectiveness. The role of climate precursors and their underlying influence on tropical storm development and track will also be addressed.

In brief, the following steps were taken to determine whether or not tropical storm status at landfall and on arrival in the basin and climate status (one month prior to a tropical storm) were important to storm effectiveness during hurricane season. More detailed steps are listed under the section headed 'Statistical Modeling with Logistical

Regression'. Statistically insignificant covariates were eliminated by proposing models in sets as presented in the hypothesis. I decided to do this because there were ten covariates and the sample size (47 storms) would not be robust if all ten covariates were proposed in a single model. I determined significant variables in the following way.

1. Identify landfall location and storm status at landfall. Status in all cases is defined as atmospheric central pressure at the surface (hereafter referred to as atmospheric pressure or central pressure) and wind speed.
2. Identify storm status on its arrival in or near the basin. Juan 1985 is included in the data base even though the storm became extratropical near its landfall location in western Louisiana and atmospheric pressure and wind speed for the center of Juan 1985 were not recorded.
3. Determine the status of climate precursors by identifying the calculated monthly statistical index for the month prior to the storm.
4. Derive individual models for each single component (landfall, basin arrival and climate status) by the following steps.
    a. Propose a model that includes all covariates of a single component. For example, when climate was the single component the model was ln (p/1-p) ~ AI+PI+EI+QI+NI, where AI, PI, EI, QI and NI were all climate precursors.
    b. Evaluate model fit by analysis of residual deviance.
    c. Eliminate single component covariates that are not statistically significant.
    d. Once significant covariates have been determined by modeling single components, propose a new model with all statistically significant covariates. For example, if the AI proved significant after testing the fit of the model of

all climate precursor covariates and windspeed proved significant after testing the fit of the model of all landfall covariates, then AI and windspeed at landfall would entered into a new model as covariates in this way:

$$\ln(p/1\text{-}p) \sim \text{AI} + \text{landfall windspeed.} \tag{3}$$

e. Eliminate variables that fail to be significant in the new model to derive a final model.

Archival records of Qpeak and Qpd, the timing of tropical storms, their names, associated wind speeds, and atmospheric pressure as well as the status of climate were obtained for all events between 1950 and 2004. The time frame for the study was between 1950 and 2005 because, on preliminary inspection of the data sets, it could be seen that this time frame rendered the largest possible sample size for all variables, given data limitations. Beginning in 1950, stream gauges are more abundant and less likely to have missing data points. 1950 is also the advent of the tropical storm naming system, which lowers the risk of human error in identification. In addition, the period of interest is long enough to include at least one cycle for each climate factor (Baldwin *et al.*, 2001; Delworth and Mann, 2000: Mantua *et al.*, 1997; Rasmussen and Carpenter, 1982). Once a database was acquired, data were selected, time series were constructed, and data were further explored for knowledge enhancement and determination of the suitability for statistical analyses. Finally, models were proposed and fitted using logistical regression with maximum likelihood determination. Details regarding data sources, the selection criteria, data exploration and the method of statistical modeling follow.

Data Sources

Annual peak discharge records were obtained from the US Geological Survey, National Water Information System: Web Interface site at http://waterdata.usgs.gov/nwis and downloaded as needed. These data were supplemented with discharge records supplied by the Maryland, Virginia and West Virginia Water Science Centers and transmitted electronically to the author. Annual peak discharge is of interest in this study because it is not a statistic but rather the highest instantaneous discharge in a given water year (October 1 to September 30) and as such, it is robust and has as a sub-set the most extreme floods on record at a given gauging station. At the same time, in some years, hurricanes have been held responsible for drought mitigation. By using annual peak discharge one can also detect whether or not tropical storm moisture added to discharge in low flow periods.

Data regarding tropical storm track, status at landfall, and status near the Potomac River Basin was obtained by accessing the National Atlas of the United States of America® at http://www-atlas.usgs.gov/. Data was initially downloaded into ArcGIS 9.0 in 2004 and updated in 2006. The time series of Atlantic hurricane count estimates was obtained from Chris Landsea (personal communication). The National Atlas of the United States of America was used to acquire tropical storm data because it is stored in a format that makes it possible to map existing data, create new maps that incorporate data from various sources, all features are provided in tabular format and the data base is regularly updated.

Climate factor indices were obtained through the US National Oceanographic and Atmospheric Administration, Earth Systems Research Laboratory, Physical Science

Division, Climate Indices: Monthly Atmospheric and Ocean Time Series website at http://www.cdc.noaa.gov/ClimateIndices. These data were supplemented with information provided by personal communication with Philip Klotzbach. Climate indices were used because the index reports the status of a particular set of atmospheric and/or oceanic phenomena (climate factors) as a numerical value that can be easily used in statistical analysis. The values are obtained by continual observation of the phenomena of interest and adjustment to improve index reporting and skill development for forecasters. The indices used in this study are updated monthly and the significance level for these indices is 0.05. Which means the probability that the null hypothesis will be rejected when it is true is 5% or less.

Selection Criteria

Stream gauge, tropical storm and climate factor index data all had to be continuous during the period between 1950 and 2004. No further criteria were set for stream gauge data. In the case of tropical storms, the assumption was that any storm that came within the spatial range set by flood-generating storms was capable of producing an annual peak discharge. Tropical storms were therefore selected if they were named and tracked across the grid area or generated a significant annual peak discharge (Appendix Table 14). A storm was considered to have crossed the basin if its best track entered a grid bounded by -81.5° W and -73.0° W longitude and 40.5° N and 37.25° N latitude (Figure 17). The grid boundaries were chosen based on an assessment of storms that were known to produce annual peak discharges in the basin. Hurricane Juan (1985) was added to the data set but not used to set a boundary because the U.S. National Hurricane Center best track for this storm terminates several hundred kilometers from the Potomac River Basin. No other storm at this distance is listed (Paulson, *et al.*, 1991 and Perry *et al.*, 2001) as the cause of a flood I the Potomac River Basin.

Storms were classified as effective or ineffective based on whether or not gauges in the Potomac River Basin reported annual peak discharge within a time period extending from one day prior to landfall to three days after landfall. An acronym for tropical storm induced annual peak discharge (Qtap) was created and is used interchangeably with the term effective storm. Only one gauge needed to report annual peak discharge in order for a storm to be classified as effective. Since 37 gauges were used in the study, it is possible for more than one storm to be effective in a single hurricane season. Other classifications used to highlight the significance of a storm event are listed in Table 5.

Table 5. Effective Storm Classifications

Classification	Criteria Annual peak reported by the following:
Regional	One of the top 10 discharges ≥ 1 mainstem gauge plus ≥ 8 tributary gauges in ≥ 2 sub-basins
Sub-regional	≥ 8 tributary gauges in ≥ 2 sub-basins
Basin	≥ 3 tributary gauges in a single sub-basin
Local	≥ 2 tributary gauges within a 75 sq. km. area – not the same basin
Single	1 tributary gauge

Climate factor indices were required to be reported as a single value. The Sahelian Rainfall Index was rejected because the record was not continuous nor did it span the necessary time range. The status of the Madden-Julian Oscillation is reported as a group of indices that could not be transformed into a single value by the author and it was therefore, also eliminated. In some instances, more than one index reports the status of a climate factor. In those cases, the index that was available through the NOAA Climate

Prediction Center web site and evaluated and reported monthly was the one selected. In some instances, other factors were taken into consideration. For example, the North Atlantic Oscillation Index calculated by the NOAA Climate Prediction Center was used in preference to the NAO (Hurrell, 1995 and Jones, *et al.*, 1997). The latter NAO index provides additional information for winter months, which is not of interest to this study. Three indices of ENSO status were incorporated in initial models to determine their usefulness as predictors of storm effectiveness. Each was input separately to avoid confounding the statistical analysis. The Multivariate El Nino Index and Southern Oscillation Index were rejected because after the first iteration, they were not deemed statistically significant predictors. The Nino 3.4 Index was the third El Nino status indicator. This index is used by Klotzbach and Grey (2007) to aid in the prediction of Atlantic hurricane abundance. The Nino 3.4 Index is the status of east central tropical Pacific Ocean equatorial sea surface temperatures between 5°N and 5°S latitude and 120°W and 170°W longitude. The selection above criteria yielded 37 suitable stream gauges throughout the basin, 47 tropical storms (Figure 17) and 5 climate factors.

Method of Data Exploration

As a first order approach to understanding the possible connection between climate and floods, tropical storm status and climate indices were subjected to exploratory data analysis. A chart of the time series plots of tropical storm features and climate indices were constructed to establish the pattern of occurrence and coincidence with annual peak discharge and climate status. Probability distribution plots and box plots were constructed to determine the frequency and distribution of values, detect the presence of outliers and display a summary of the data (the median, 25th and 75th quantiles). A second set of box plots were constructed that displayed data distributions in the absence and presence of effective storms. A check for serial dependence was also done.

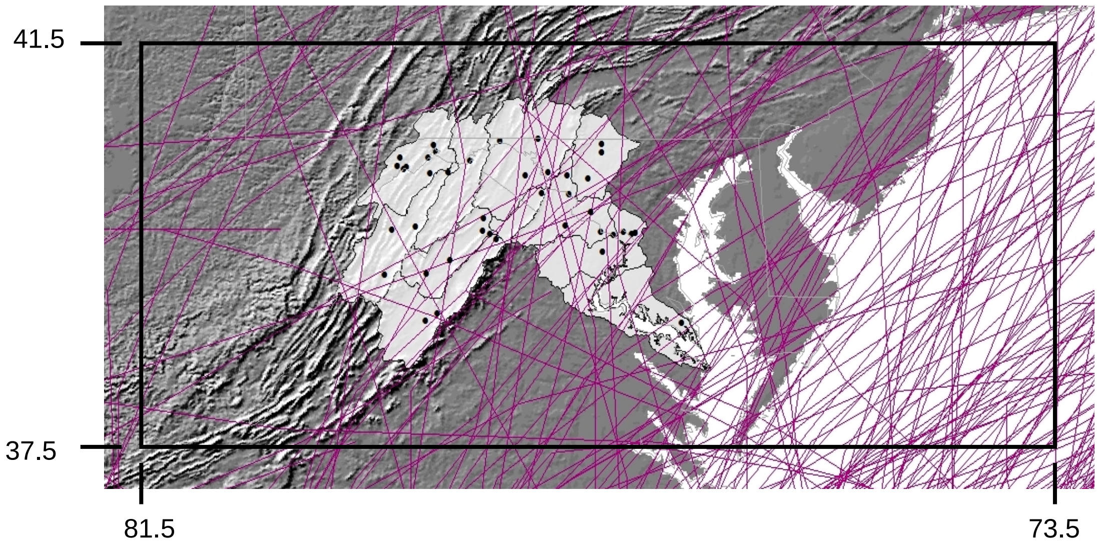


Figure 17. Map of tropical storm selection area. Potomac River grid area (black rectangle), select gauges (red circles) and storm tracks (purple lines). Lines represent the paths of 51 named tropical storm or hurricane events. In many instances, more than one line represents a single storm because of storm track patterns. The attributes for each line were obtained and the date, landfall location, wind speed and atmospheric pressure (when available) for each event was noted and a table compiled. Map constructed in ArcGIS 9.0. Data acquired in December 2006 from US Atlas Program. North is toward the top of the figure.

When determining landfall, storms were considered to have made landfall when the center made an initial pass over the United States mainland or a barrier island off of the mainland coast. Locations were determined by constructing maps in ArcGIS 9.0® based on storm track data provided by the US NOAA. Landfalls in the US Virgin Islands, Puerto Rico and north of Maryland were not considered in this study. In many instances, storms make landfall in more than one location. Only the initial landfall location was considered. Atmospheric pressure and wind speed are standard surface measurements taken with each storm. Atmospheric pressure is taken approximately 33 m above ground and in the center of the storm. Wind speeds are storm center surface wind speeds calculated as an average of measurements taken over the course of one minute as defined by the NOAA National Hurricane Center glossary at http://www.nhc.noaa.gov/aboutgloss.shtml. Data are provided by the NOAA through the USGS National Atlas.

Statistical Modeling with Logistical Regression

This section is a discussion of methods applied to explore the validity of explanatory variables by model fitting with the logit function. The response variable is binary (effective storm or ineffective storm). This time range was chosen after review of approximately 25 satellite images displaying cloud cover for storms between 1995 and present and storm best track reports. The images show cloud cover can extend over this region well in advance of landfall and best track reports indicate the average time between landfall and arrival in the vicinity of the Potomac River Basin is two days. Binary responses are marked by the absence/failure or presence/success of a particular event.

In logistic regression, an assumption is made that the probability of an event can be described by the logit function (odds ratio), which is the left-hand side of the following equation:

$$p\ (\text{event})/\ (1\text{-}p\ (\text{event})) = e^{\beta_0 + \beta_1 x}, \qquad (4)$$

where p is the probability of a particular event occurring, (in this case a tropical storm induced annual peak discharge), e is the exponential function and β_0 and β_1 are coefficients. Thus, the logarithm of the odds ratio is a linear function of the predictor. The logistic regression can therefore be fitted using maximum likelihood estimation (Devore, 2000).

The logit link (transformation) method of logistic regression is often used to evaluate the importance of explanatory variables when the response is binary (McCullagh and Nelder, 1989). A statistical model is proposed and evaluated iteratively by transformation using the logit function and maximum likelihood estimation. The method of transformation linearizes the explanatory variables (covariates) in the model and the response variable (effective storm/ineffective storm) becomes a function of the linearized explanatory variable (McCullagh and Nelder, 1989). The form of the logit link function is utilized in modeling for this study and presented in Equation 5.

$$\ln (p/ (1-p) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \dots \beta_n x_n, \quad (5)$$

where x is a covariate, p is the probability of Qtap occurring and all βs are constants. Elsner and Bossak (2004) used this technique to link major hurricane landfall and the Southern Oscillation Index (SOI).

Recall from the first paragraph in the Methods Section, explanatory variables or covariates were modeled individually for each of the three possible explanations listed in the hypotheses. Atmospheric pressure and wind speed for the storm at landfall was modeled, then atmospheric pressure and wind speed for the storm on arrival in the basin was modeled, and finally, the Atlantic Multidecadal Oscillation index (AI), El Nino 3.4 index (EI), North Atlantic Oscillation (NI), Pacific Decadal Oscillation index (PI) and Quasi-biennial Oscillation (QI) was modeled.

The objective in model fitting is to determine the least number of explanatory variables that describe variations in the observed data adequately. In order for explanatory variables to be included in the model, they must be statistically significant and offer the minimal residual deviance. With that in mind, the probability of an effective storm was determined by initially proposing a model with each explanatory variable added individually, then estimating the probability that an annual peak could have occurred by chance (p-value). After an estimate of the coefficients (β) was determined, then the model was tested by analysis of residual deviance. Variables with p-values >0.15 were deleted from the initial model, and then another model was proposed. Even though over- and under-dispersion were not a concern because the response variable is binary, analysis of deviance was determined using the 'F' statistic. Over- and under-dispersion is a measure of model adequacy, or the assumption that important variables have not been left out of the model. When the ratio between the residual deviance and the residual degrees of freedom is not equal to ~1 (high/low), then over- or under-dispersion exists. Once a model was accepted, probabilities were determined by back calculation and prediction plots were constructed based on Venables and Ripley (1997).

RESULTS

This section provides a discussion of the explanatory variables and modeling results. Findings from data exploration are presented first followed by the results of logistical regression.

Data Exploration

Only a small portion of the tropical storms that develop in the Atlantic Ocean Basin actually make landfall in the US and an even smaller portion are involved in the delivery of moisture into the Potomac River Basin. Between 1950 and 2006, there were 698 named storms in the Atlantic basin (Landsea, 2007). On average, 1.62 hurricanes made landfall in the United States each year and 0.64 of those hurricanes were in major status (Elsner and Bossak, 2004; Figure 18). As for the Potomac River Basin, fifty-one named storms impacted the Potomac River Basin from 1950 to 2004 and 10 of them were in major hurricane status at the time of landfall (Appendix Table 14 & Figure 18). Impact means the storms either entered the grid area or are reported by Paulson *et al.*, 1991 or Perry *et al.*, 2001 as the cause of floods in the Potomac River Basin.

Although 51 storms were observed, the count of 47 named storms impacting the Potomac River Basin between 1950 and 2004 was used to estimate the annual probability of storm occurrence because four storms that entered the grid made landfall in either New

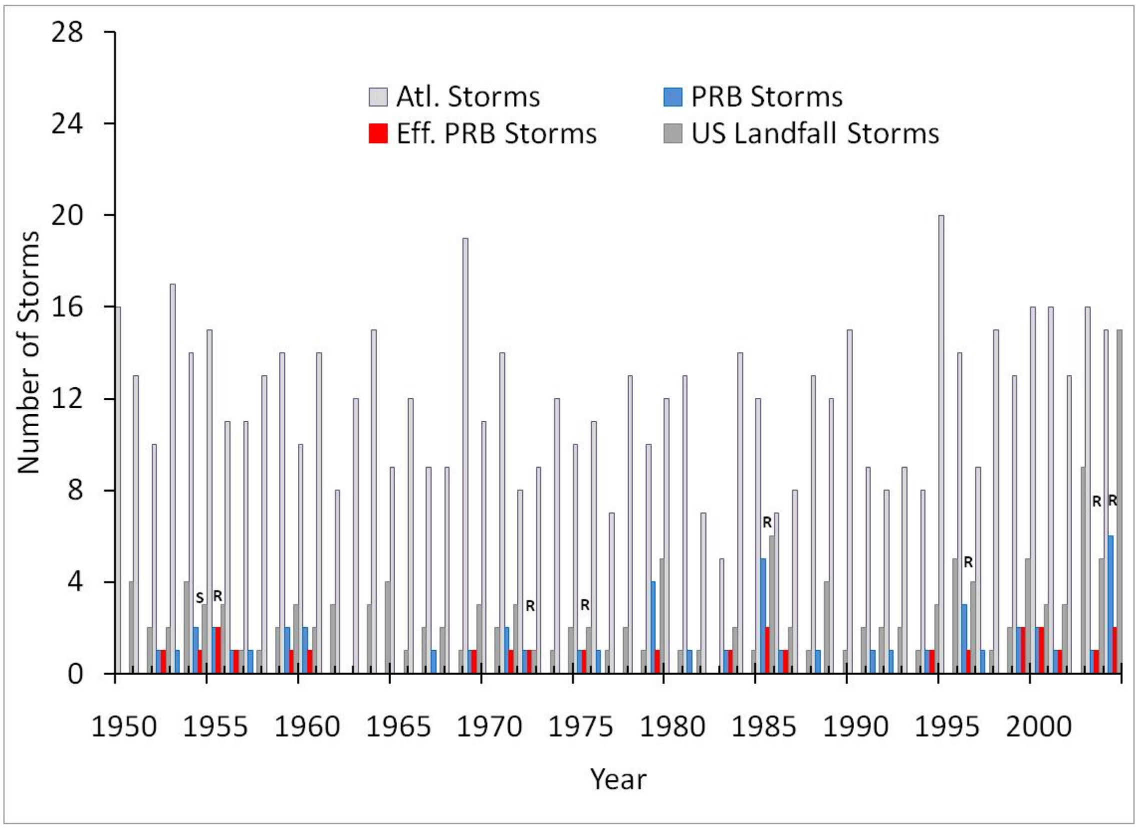


Figure 18. Time series of Atlantic tropical storms (light grey), storms that made landfall in the US (dark grey), select Potomac River Basin storms (blue) and the sub-set of Potomac River Basin storms that were effective (red). Notice the hiatus in select Potomac River Basin storms during the 1960s Northeast drought and the increased frequency of Potomac River Basin storms in the 1979, 1985 and 2004 hurricane seasons. R and S marks the timing of regional- scale and sub-regional-scale events that generated one of the top 10 discharges during the study period. Atlantic storm counts were provided by Landsea (2008).

York or Rhode Island and did not generate annual peak discharges on any of the study gauges. As a result, these storms were removed from the selection list (Appendix Table 14). The data has a Poisson distribution with a mean of 47/55. Confidence intervals were estimated by re-sampling annual storm counts 10,000 times (bootstrapping). It is expected that one named storm will deliver moisture to the Potomac River Basin each year (Appendix Table 16).

During the study period, as is the case with Atlantic named storms, Potomac River Basin storms occurred most frequently in September (18 times) and were in hurricane status at landfall (32 times) Typically, when storms reached the Potomac River Basin, they were downgraded to tropical storm status based on the Saffir-Simpson scale. Only once (Isabel 2003) did a storm in hurricane status actually cross the Potomac River Basin between 1950 and 2004. Hurricane Isabel (2003) and its impact on streamflow will be discussed in more detail in the next chapter.

As expected with a Poisson distribution, even though the average is approximately one storm per season, a number of times multiple storms occurred in a single hurricane season. Multiple storms (≥ 2 storms) crossed the basin in 10 of the 55 years between 1950 and 2004. The first time was in 1955, then in 1959, 1960, 1971, 1979, 1985, 1996, 1999, 2000 and 2004. In 1955, 1979, 2000 and 2004 successive storms had a lapse time of 10 days or less. In eight of the 10 years (80%) at least two of the storms made landfall in the same state. This suggests a climatic control on storm track, which will be evaluated in this chapter. Hydrological consequences of sequential tropical storms are discussed in Chapter 4.

Prior to 1979, not more than two storms occurred in a single season. Then, beginning in 1979, there was an increase in the maximum number of multiple storms from four to six over a 25-year period ending in 2004. Prior to that, the record was five events in 1985. There are also years when no storms passed over the basin. In fact, in the time period between 1961 and 1966 no storms entered the grid area in spite of the fact that storms made landfall in the United States and several times storms made landfall in Florida. The 1961 to 1966 period coincides with the 60s Northeast drought. In the period between 1987 and 1994, only three storms entered the grid and none of them were effective (Figure 18). A portion of this period coincides with the late-80s drought in the eastern United States.

The Timing of Effective Storms

Twenty-six of the 47 study storms were effective at generating annual peak discharges at at least one streamflow gauge in the Potomac River Basin (Appendix Table 17; Figure 18). Based on my definition presented in the methods section of this chapter, seven of the 47 storms generated regional floods. Even though storms most frequently enter the Potomac River Basin in September, in terms of the number of gauges reporting maximum discharges for the period of record; the most effective storms have occurred throughout hurricane season (Appendix Table 17).

Tropical Storm Landfall Location

Fifty-seven percent of the storms between 1950 and 2004 made landfall in either Florida or North Carolina (Figure 19; Appendix Table 14). An extreme case was in 2004 when four of the six storms that tracked over or near the Potomac River Basin made landfall in Florida. In fact, two of the most notable storms in the record (Agnes 1972 and Eloise 1975), in terms of magnitude and number of gauges reporting annual peak, made landfall in Florida. Storms that made landfall in Alabama, Georgia and Virginia were ineffective.

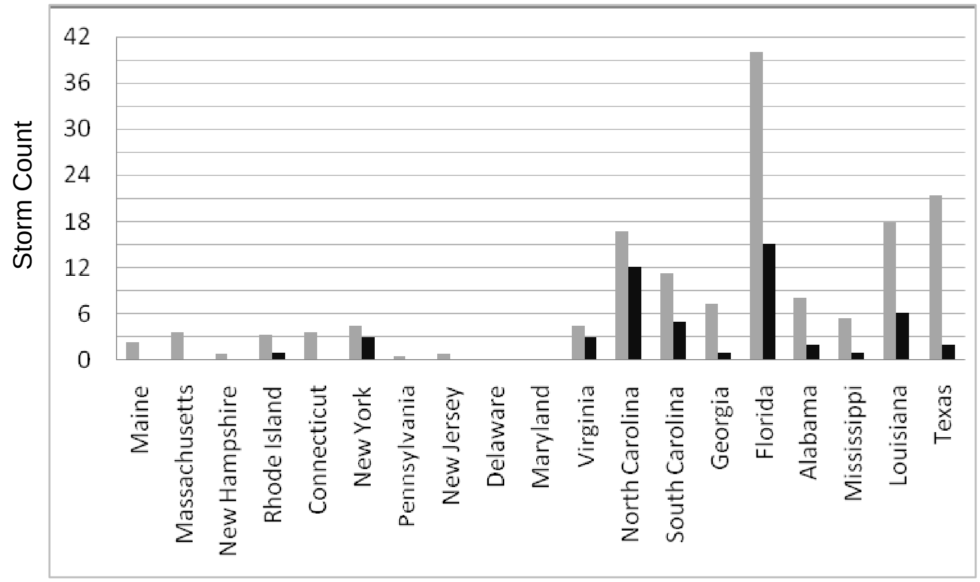


Figure 19. Estimated number of tropical storm strikes by state (grey) between 1950 and 2004 and the number of those storms that impacted the Potomac River Basin (black)

Tropical Storm Status at Landfall and on Arrival in the Potomac River Basin

As expected, there was a correlation between wind speed and atmospheric pressure. Recall that as the pressure gradient in a hurricane increases, so does wind speed. The correlation coefficient was -0.938 with a confidence interval estimate of -0.88 to -0.966. The correlation was addressed by modeling an interaction between the two explanatory variables and then testing the model fit (Figure 20).

Neither landfall nor atmospheric pressure readings were always available prior to 1969. As a result, four storms were removed from the original set of 47 prior to model fitting based on storm status at landfall (Appendix Tables 14 and 17). Twenty-four of the 43 remaining storms were effective. Atmospheric pressure ranges for the two leading landfall locations (NC and FL) were nearly equal. Slightly higher than average atmospheric pressure readings were recorded when storms made landfall in Virginia None of the Virginia-landfall storms were effective.

In terms of storm status on arrival in the basin, twelve storms were removed because of missing atmospheric pressure readings. Of the remaining set of 35 storms, 19 were effective. The range of atmospheric pressure values associated with basin arrival is narrower than those associated with landfall (Figure 21). All data sets are slightly skewed, which is reflective of the fact that most storms make landfall as hurricanes and then lose energy as they cross land and are downgraded to tropical storms or tropical depressions upon arrival in the Potomac River Basin. The contrast in the distribution of landfall and basin arrival pressure and wind speed in the presence and absence of an effective tropical storm suggests none are good predictors of storm effectiveness (Figure 21). If a choice was to be made on the basis of these distributions, then storm status on arrival in the basin would be a better measure of effectiveness. The interquartile ranges are much smaller and shift to higher readings for pressure and/lower readings for wind speed when storms do not generate annual peak discharge.

The status of climate when tropical storms affect the Potomac River Basin

The distribution of extracted monthly climate factor indices associated with the timing of storms that either crossed the Potomac River Basin grid area or caused notable floods in the basin displayed a slight skew but were normal (Figure 22, Appendix Tables 14 and 15). Most NI and PI values fall within one standard deviation of the mean when storms have entered the basin. In the case of the NI, these values are indicative of a weak NAO. A weak NAO is implicated when storms make landfall in the southern United States because of the position of the Bermuda High (Elsner and Bossak, 2004). As a result, storm-track recurvature is more likely to take place over the United States rather than over the Atlantic Ocean and lead to storms tracking into the Potomac River Basin. AI, EI and QI index values include extremes near those in the larger NOAA-distributed data base of all calculated indices.

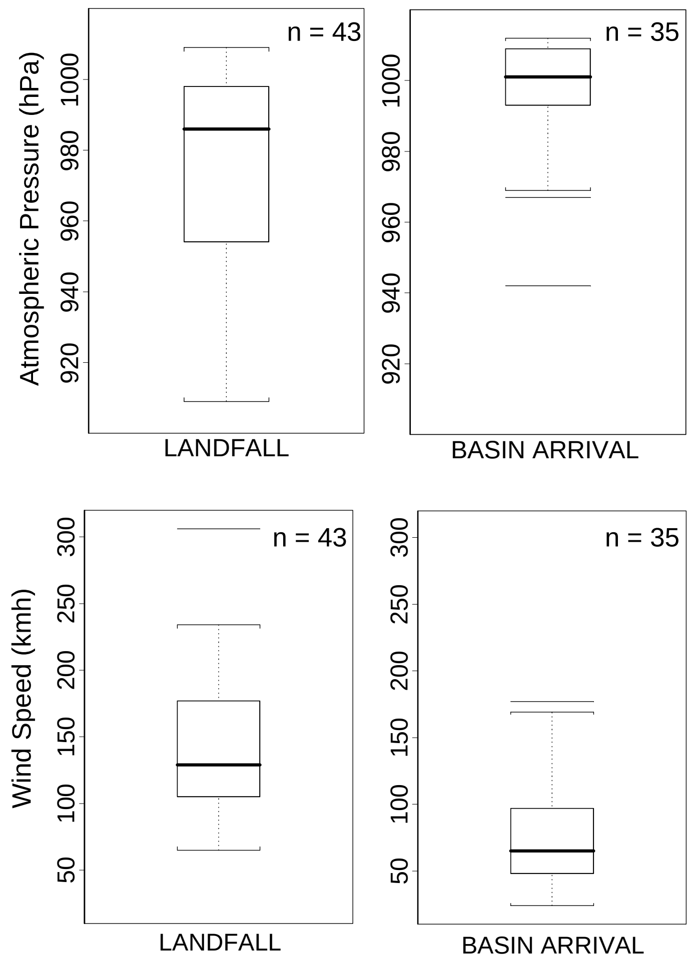


Figure 20. Tropical storm central atmospheric pressure and wind speed at landfall (left) and upon arrival in the Potomac River Basin (right). Horizontal braces represent maximum and minimum values, rectangles represent the range of values between the 25th percentiles (low) and 75th percentiles (high). Black horizontal lines within rectangles are median values. n = number of storms

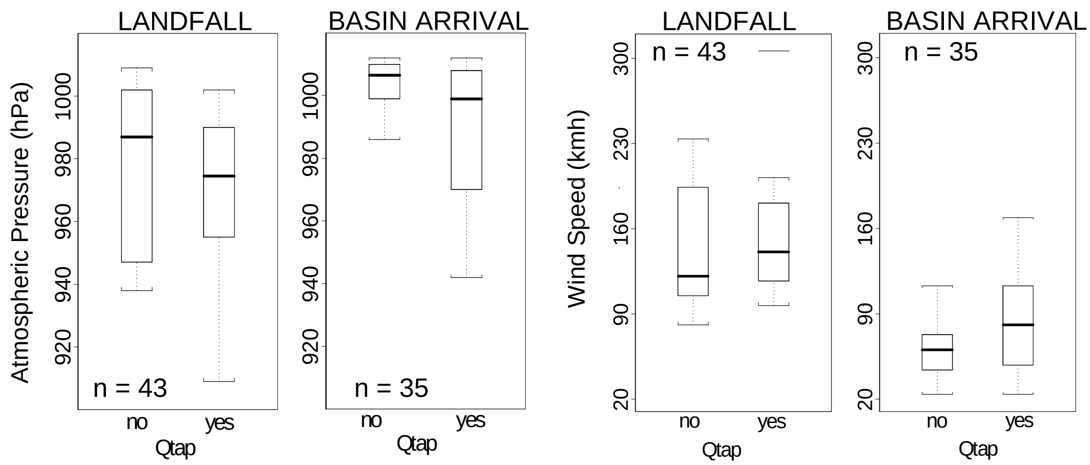


Figure 21. Comparison between the distributions of tropical storm central atmospheric pressure and wind speed in the absence (no) and presence (yes) of effective storms (Qtap). Horizontal braces represent maximum and minimum values, rectangles represent the range of values between the 25th percentiles (low) and 75th percentiles (high). Black horizontal lines within rectangles are median values.

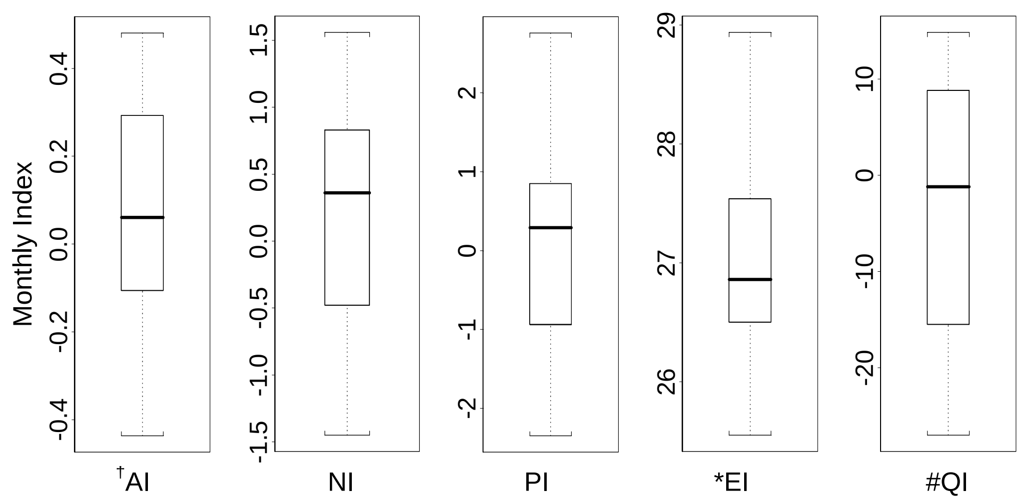


Figure 22. Box plots of monthly indices coinciding with the time of Potomac River Basin tropical storms. s.d. = index reported in standard deviations, †AI = index is detrended sea surface temperature,*EI = index is seasonally adjusted sea surface temperature, #QI = index is wind speed departure from adjusted average. Between 1950 and 2004 medians for AI = -0.005, EI = 26.9, QI = -2.9

To detect possible influences with respect to time, time series plots of AMO and PDO phases and effective storms were constructed (Figure 23). The AMO and PDO are of particular interest to this study because these two factors have been related to diminished/enhanced precipitation in this region (Nigam, 1999; Enfield *et al.*, 2001 and McCabe *et al.*, 2004). Aside from the monthly indices available through NOAA and based on Enfield et al. (2001), McCabe *et al.*, (2004) defines the status of the AMO and PDO as decadal-scale time series. The time series plot of the status of the AMO and PDO based on McCabe *et al.*, (2004) suggests Potomac River Basin storms are more often effective when there is a warm Atlantic Ocean (AMO+) than when there is a cool Atlantic Ocean (AMO-) Figure 23a.

There was an increase in the number of storms in a single year (multiple-storm year) after the McCabe *et al.*, (2004) PDO transitions to the warm/positive phase and the time series did not suggest it is driven by the AMO. To further examine a possible climatic influence, the12-month average of the PI was also calculated and plotted as a time series with Potomac River Basin storms (Figure 23b) and compared to Figure 23a. There is a shift toward increase in the number of storms in one season after 1976 (Figure 23b).

Comparison of monthly indices in the absence and presence of an effective tropical storm (Qtap; Figure 24) suggests the PI may be an influence on tropical storm effectiveness. The median values for the EI, PI and the QI are higher when there is no Qtap. However, there is substantial overlap in the EI and QI IQR while the PI IQR is narrower with very little overlap when the PI is negative. Even though some climate factor indices do not suggest an influence of storm effectiveness, all five variables were included in the initial model of the relationship between annual peak discharge and climate factors.

Statistical modeling

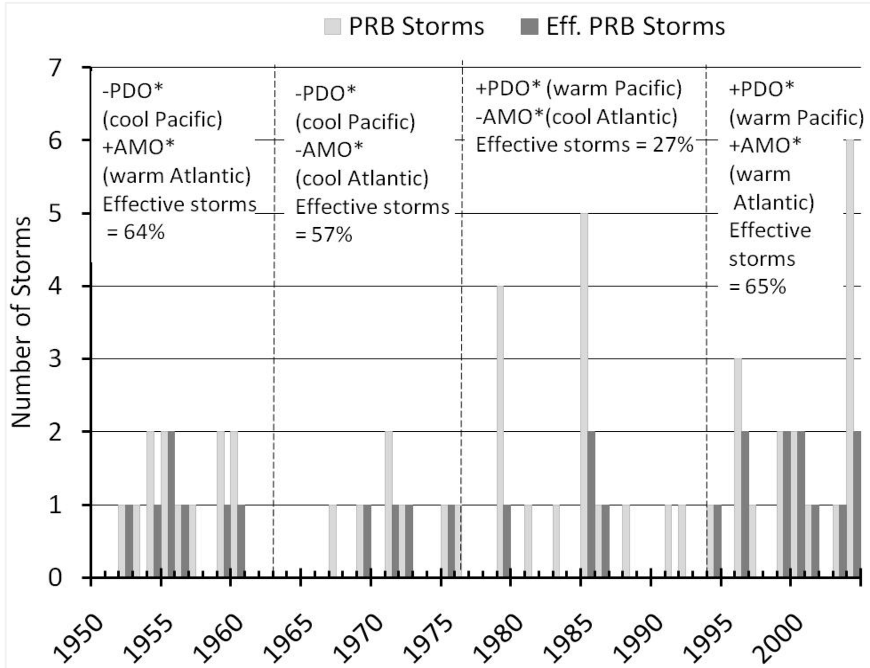
Recall from the methods section that initial models using explanatory variables were associated with the three components (storm landfall character, storm character and climate precursors) were proposed and modified after testing. The models were tested by analysis of residual deviance with an initial significance level (alpha) of 0.15. All references to atmospheric pressure are storm central pressure readings near the surface.

The first model proposed was based on the landfall character component and follows in the form of Equation 6.

$$\ln (p\,(Qtap)/\,(1\text{-}p\,(Qtap)) = \beta_0 + \beta_1 \text{ x lfl (landfall location) x } \beta_2 \text{ x lfp (atmospheric pressure at landfall) x } \beta_3 \text{ x lfw (wind speed at landfall)} + \beta_4 \text{ x lfl x } \beta_5 \text{ x lfp x } \beta_6 \text{ x lfw} \quad (6)$$

This model format assumes a correlation between atmospheric pressure, wind speed and landfall location. The fit of the model indicated all three variables were significant (Appendix A.1.). The final model is not presented here because it was decided that a less complex model would develop from assessment of atmospheric central pressure and wind speed by landfall location. As a result, atmospheric pressures and wind speeds for storms that made landfall in North Carolina, South Carolina and Florida were extracted from the larger data set and modeled separately.

a) Time series of PRB storm counts and AMO and PDO phases



b)Time series of PRB storm counts and the smoothed PDO# index

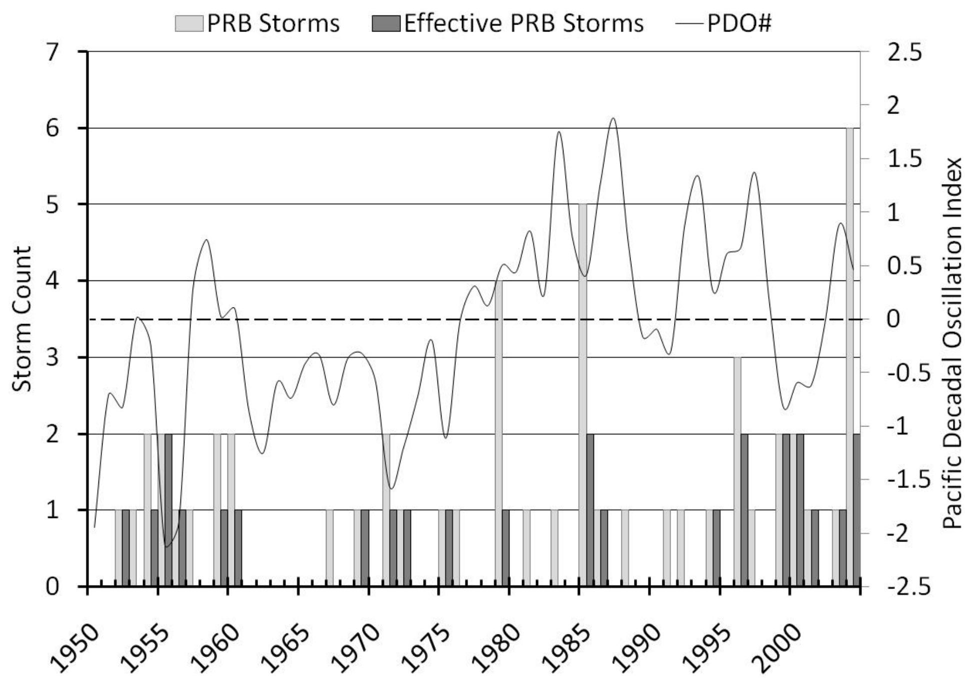
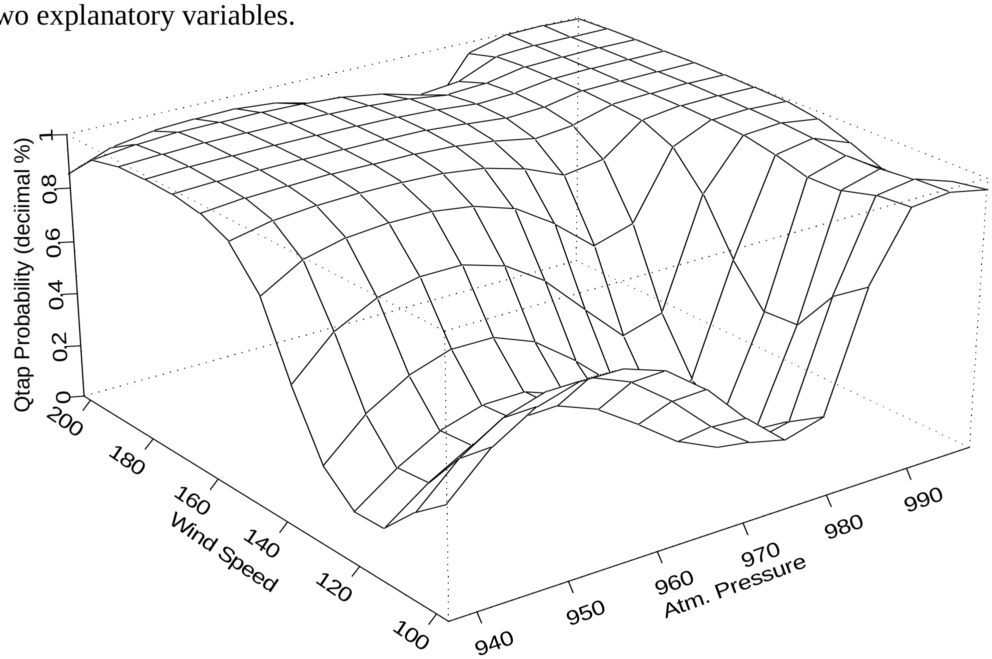


Figure 23. Contrast between AMO* and PDO* phases (a) and the smoothed monthly PI # (b). * = as defined by McCabe et al., 2004. # the monthly Pacific Decadal Oscillation index as defined by Enfield et al., 2001 smoothed by averaging January to December monthly index values.

These states were chosen because they were the landfall locations for more than 65% of the 43 storms in the data set. South Carolina storms were added to the North Carolina set because the two states share a common border and the bulk of storms that made landfall along the coast, north of Florida, did so in these two states. Combining data from the North Carolina/South Carolina (NCSC) data set also yielded a storm count of fourteen for NCSC and Florida (FL). Nine of the FL and 11 of the NCSC storms were effective. The two initial models were the same as Equation 6. The final models were different depending on location (Equations 7 and 8; Figure 25). When storms make landfall in the US through Florida, the interaction between wind speed and atmospheric pressure is important for Potomac River Basin annual peak production (Figure 25a). When wind speed is >160 kmh and atmospheric pressure is >990 mb, then there is a greater likelihood of Qtap. Regardless of pressure, annual peak discharge is least likely when wind speeds are between 120 and 140 kmh. There is however, a slight increase in probability at low wind speeds when pressure readings are <980 mb.

a) Probability of an effective storm (Qtap) given the landfall location is Florida where windspeed and central pressure are the explanatory variables and there is interaction between the two explanatory variables.



b) Probability of an effective storm (Qtap) given the landfall location is North Carolina/South Carolina where central atmospheric pressure is the explanatory

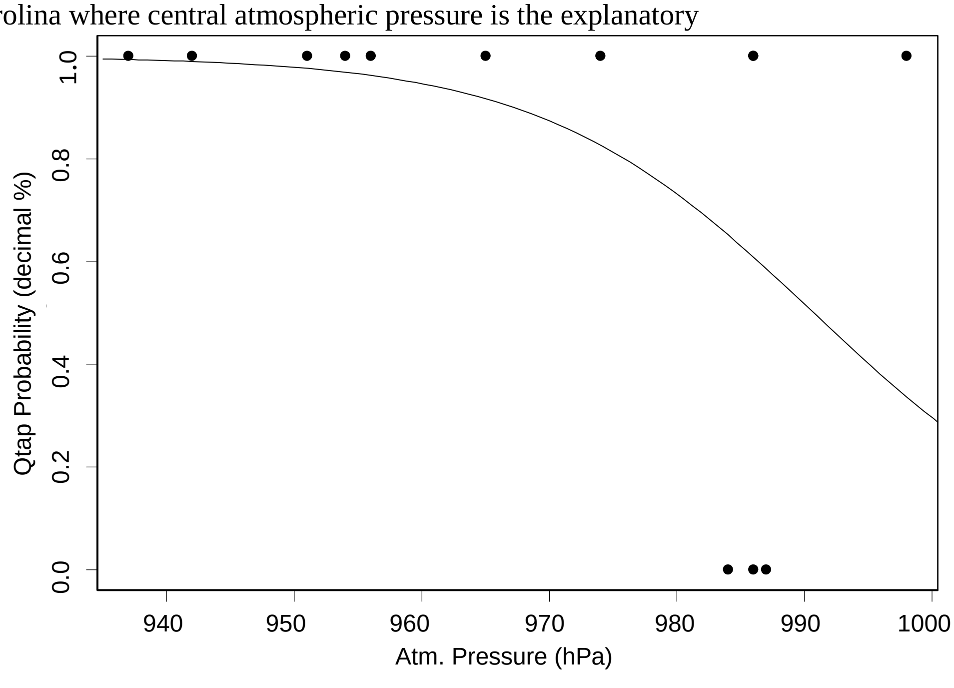


Figure 24. Prediction plots. Black circles = observed successes(1) and failures(0).Line are back calculated probability estimates. Wind speed is in kmh. Atm. Pressure = storm central pressure

When storms enter by way of the North Carolina/South Carolina coastline, atmospheric pressure was the only important explanatory variable. In this case, when storms have atmospheric pressure readings < 975mb, they are more likely to generate floods (Figure 26b). The equations for these models are listed below.

$$\ln (p(Qtap)/(1-p(Qtap)\ FL) = 305.61 - 0.31 \times lfp - 1.70 \times lfw + 0.0017 \times (lfp \times lfw) \quad (7)$$

$$\ln (p(Qtap)/(1-p(Qtap)\ NCSC) = 92.60 - 0.093 \times lfp \quad (8)$$

The second series of models proposed was based on the basin arrival component. The sample size for this analysis was reduced to 35 due to missing atmospheric pressure values during the early years of named tropical storms. The initial model proposed is Equation 9.

$$\ln (p(Qtap)/(1-p(Qtap)) = \beta_0 \times bp \times \beta_1 \times bw \quad (9)$$

Model fitting indicated atmospheric pressure on arrival in the basin was the only significant variable with a p-value of 0.025. On arrival in the basin, a storm with atmospheric pressure readings below approximately 980 hPa is more likely to be effective. The final model and prediction plot follows (Equation 10; Figure 27).

$$\ln(p(Qtap)/(1-p(Qtap)) = 66.26 - 0.07 \times bp \quad (10)$$

Climate Precursors as Explanations for Qtap

The purpose of this analysis was to examine the influence of antecedent climatic conditions on the tropical storms and hurricanes that affected streamflow in the Potomac River basin. The choice of climate factor was discussed previously. The explanatory variables that met the selection criteria were the Atlantic Multidecadal Oscillation (AI), El Nino 3.4 (EI), North Atlantic Oscillation (NI), Pacific Decadal Oscillation (PI) and Quasi-biennial Oscillation (QI). The initial model is Equation 12.

$$\ln(p(Qtap)/(1-p(Qtap)) = \beta_0 \times \beta_1 \times AI \times \beta_2 \times EI \times \beta_3 \times NI \times \beta_4 \times PI \times \beta_5 \times QI \quad (11)$$

There were weak correlations between the EI and PI (0.49) and the NI and PI (-0.47).

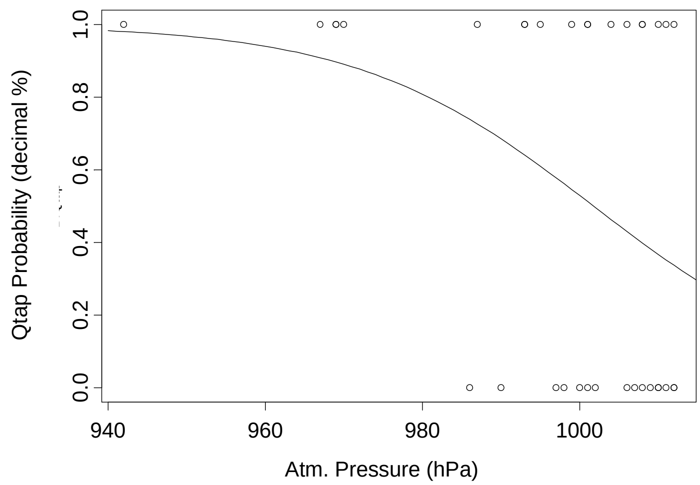


Figure 25. Prediction plot – atmospheric pressure on arrival in the Potomac River Basin grid. Circles are observed successes (1) and failures (0). The probability of an annual peak discharge decreases as atmospheric pressure increases. Notice similarity between this graph and the one for the probability of annual peak based on storm status at landfall. Effective storms occur at all pressure readings but ineffective storms are ones with readings higher than 980 hPa.

Therefore, this model assumes interaction among all variables to account for all possible correlations. However, the number of variables generated errors, so all variables were evaluated as interactions in iterations. For example, the model ln(p(Qtap)/(1-p(Qtap)) = $\beta_0 \times \beta_1 \times AI \times \beta_2 \times EI$ was proposed and when the AI did not fit, another model was proposed substituting the NI for the AI in the previous model and so on, until each covariate was modeled as an interaction with respect to all other covariates. None of the models proposed that included an interaction between variables proved significant so, models with no interaction were proposed. Analysis of residual deviance indicated all covariates except the EI (p-value = 0.018) and PI (p-value = 0.005) were not statistically significant (Appendix A. 2.). Since the PI p-value was lower after adjustment for EI and the order of each explanatory variable influences the outcome, the below model was proposed.

$$\ln(p(Qtap)/(1-p(Qtap)) = \beta_0 x + \beta_1 \text{ x EI} + \beta_2 \text{ x PI}. \quad (12)$$

The EI failed with a p-value of 0.288. The final model is Equation 13 and the probability plot is shown in Figure 28.

$$\ln(p(Qtap)/(1-p(Qtap)) = 0.48 - 1.26 \text{ x PI}. \quad (13)$$

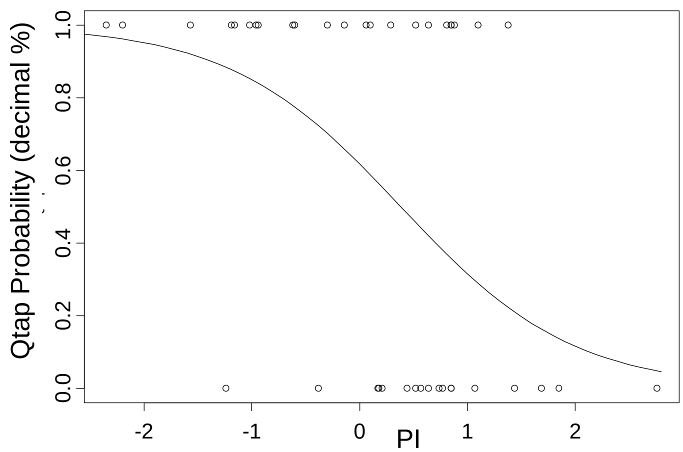


Figure 26. Probability plot of the Pacific Decadal Oscillation Index (PI) and Qtap. Circles are observed success (1) and failure (0). The vertical axis is the probability of success.

The above PI probability plot suggests effective storms are more likely when the Pacific Decadal Oscillation Index is negative.

In summary, the Pacific Decadal Oscillation explains storm effectiveness. Although there was a correlation between the North Atlantic Oscillation and the PI, interaction between the two was not statistically significant nor was the interaction between the PI and the EI.

Modeling Combined Significant Causal Mechanisms

The final step taken was to propose a model that combined landfall atmospheric pressure, basin arrival atmospheric central pressures and the PI. Since explanatory variables from each of the components proved significant with an α (significance level) of 0.15, it was changed to a more rigorous 0.05. Atmospheric central pressure was the only landfall status component covariate used in the combined model because it proved statistically significant with an α of 0.05for both North Carolina/South Carolina and Florida landfall locations. Thirty-five storms were analyzed because of the missing basin arrival atmospheric central pressure values. The final model is Equation 14.

$$\ln(p(Qtap)/(1-p(Qtap)) = 84.76 - 1.79 \text{ x } PI - 0.084 \text{ x } bp \quad (14)$$

The final prediction plots are shown in Figure 28. There is not interaction between the two explanatory variables, neither variable is conditional upon a specific value of the other or averaged over all values in the data sets. Therefore, neither variable influences the other and; given a tropical storm is present in the Potomac River Basin, the probability of an effective storm increases as both the PI decreases atmospheric pressure on arrival in the basin decreases.

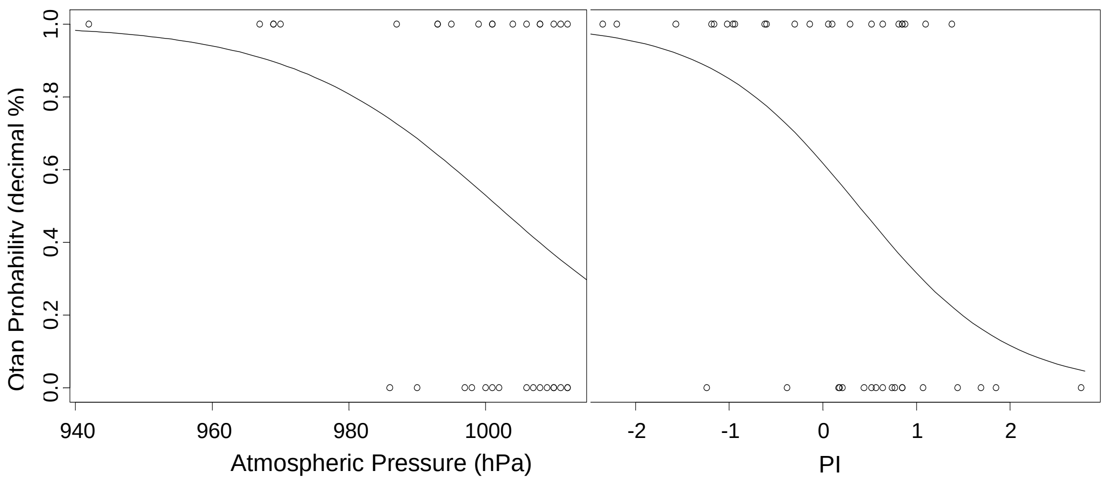


Figure 27. Plot of the probability (line) of annual peak discharge as a response to variation in atmospheric pressure on arrival in the Potomac River Basin (left) and the Pacific Decadal Oscillation Index (right). The vertical axis is the probability of annual peak generation. The probability of an annual peak discharge decreases as atmospheric pressure increases. In the case of the PI, floods are more likely when the PI is negative. Circles are observed annual peak occurrence (1) and no observed annual peak occurrence (0).

DISCUSSION

Between 1955 and 2004 it is estimated that 51 tropical storms advected moisture into the Potomac River Basin. Most storms came into the area in September, which coincides with the time when storms are most abundant in the Atlantic Ocean and when they make landfall in the United States. What doesn't coincide is the timing of extreme-flood generating tropical storms. Record setting floods have been due to storms that brought moisture to the region throughout hurricane season not only in September (e.g., Hazel 1954 was in October, Connie 1955 and Diane 1955 were in August, Agnes 1972 was in June and Juan was in November). More than half of the time, tropical storms were effective at generating an annual peak and ~30% of the time; the storms were effective on a sub-regional to regional scale.

Logistical regression indicates the PI offers the best explanation for effective tropical storms in the Potomac River Basin. When the PI is negative, storms are more likely to be effective. By relating Northeast precipitation to the PI and/or AI, the works of Nigam *et al.*, 1999, Barlow *et al.*, 2001, Enfield *et al.*, 2001 and McCabe *et al.*, 2004, support the results from this study and gives rise to the question of the influence of the AI and PI on tropical storm abundance. The efforts of the authors mentioned above the AMO and PDO as an influence on drought frequency, however, use of their work is applicable because drought frequency is related to precipitation severity and frequency. Also, some of the storms mentioned above are responsible for mitigating drought.

Nigam *et al.*, 1999 and *McCabe et al.,* 2004 hold Pacific Ocean and Atlantic Ocean sea surface temperatures responsible for the Northeast drought of the 1960s.While no formal analysis was done to assess the effectiveness of tropical storms at mitigating droughts, the time series graph suggests an AI and possibly a PI influence because it clearly shows no tropical storms advected moisture into the area during the period of the Northeast drought of the1960s in spite of the fact that storms were making landfall in Florida (Figure 18). The time series of Potomac River Basin storm counts and AMO and PDO phases (Figure 20).shows the decadal AMO is transitioning from warm phase to cool phase during the drought and that there is an increase in the number of storms that track into the area after the AMO is fully transitioned to the cool phase. The AMO transitions again around 1995, but the sense is opposite that of the 1960s transition and the difference in sense (warm phase to cool phase versus cool phase to warm phase) may lead to a difference in the hurricane-frequency response. Storm effectiveness was the primary concern in this study. An investigation with a focus on the importance of the AI and PI on Potomac River Basin storm abundance and its relationship to drought frequency may point to the influence of both indices on hurricane abundance and better clarify the role of hurricanes in drought mitigation.

When the Potomac River Basin storm time series is evaluated based on the McCabe *et al*. (2004) AMO (Figure 20a), there is an obvious increase in the number of effective storms when the AMO is in warm phase, which suggests an AMO influence. There is also the suggestion that the PDO influences the number of storms that enter the basin because the number of multiple storms increases when the PDO shifts to warm phase (Figure 20a). The PDO influences rainfall by extending the Bermuda High to the west when the Pacific is cool (Barlow, *et al*. 2001). At the same time, during hurricane season, the strength of the NAO plays a role in the position of the Bermuda High (Elsner and Bossak, 2004). The monthly PI averaged and plotted with the Potomac River Basin storm series (Figure 20b) reveals that, beginning in 1979, multiple effective storms are more frequent when the average yearly PI is normal (between -0.5 and +0.5). The possibility exists that in the years when multiple storms track into the Potomac River Basin the effect of the PDO is enhanced by the strength of the NAO.

Figure 20b shows the severe floods of 1955, 1972, and 1975 all occurred when the 12-month average of the monthly PI was < -1 while the 1985 and 1996 floods occurred when the 12-month average of the monthly PI was near normal. Not all of the events that managed to generate annual peak discharges in the basin were in hurricane status before landfall. For example in 1999, the first of two storms that year, (Dennis) was a named tropical storm that was effective on a sub-regional scale. Combined observation of the impact of Connie and Diane, both in 1955, highlight two results derived from this study.

One is that when a series of rainfall events occurs over the course of a few days or weeks, the subsequent storm/s may not have higher magnitude discharges or greater areal impact than the first storm in the series. The next chapter addresses the issue of subsequent storm effectiveness in the presence of a series of storms. That chapter will also contrast the difference in flood response to a single storm type when the method of delivery is a single intense storm and a series of storm. The other point that the Connie-Diane 1955 storm impact makes is that if a storm makes landfall in the south and travels north, then there should be a simple south to north gradient in storm effectiveness. Another series of storms, Dennis and Floyd in 1999 emphasizes the finding that storms that track through the area and have a nominal effect may have a greater impact further north along the storm track and outside of the Potomac River Basin. Dennis 1999 was effective on a sub-regional scale, while Floyd 1999, which happened about 10 days later, was more locally effective along the down stream end of the Potomac River Basin. However, Floyd 1999 is held responsible for ending the drought and causing severe floods in New York and Pennsylvania.

One more thing about storm proximity is that Floyd 1999 was a category 2 hurricane and equal in status to Agnes 1972 when it arrived in the Potomac River Basin grid area. Floyd 1999 tracked very near the eastern side of the Potomac River Basin and well within the limit of the Agnes 1972 storm track and yet it was not able to produce the type of flooding here that was attributed to Agnes 1972. In fact, storms that made landfall north of North Carolina did not manage to generate an annual peak at any one of the 37 study gauges. In other words, they were ineffective. The difference in Floyd's behavior compared with other storms in the historical record, shows that there is no simplistic model of storm effectiveness that can be derived by relating storm effectiveness to storm proximity, tropical storm category or tropical-storm sequence in a multiple-storm year.

Further support for the finding that storm landfall proximity alone is not always the determining factor in storm effectiveness comes from evaluation of the whole Potomac River Basin tropical storm data set. Most of the storms that have impacted this basin made landfall in either Florida or North Carolina (Figure 19). Storms that were effective also more frequently made landfall in Florida and North Carolina. All but one storm that made landfall in Virginia advected moisture into the Potomac River Basin but none of them were effective. In contrast, five storms made landfall in Louisiana and two of them were effective. So, again, proximity does not always translate into effectiveness.

When storms are binned by landfall in Florida and North Carolina/South Carolina, two models arise. In the case of storms that make Florida landfalls, the interaction between wind speed and atmospheric pressure explains much of the variability in annual peak discharge. When storms make landfall in North Carolina, atmospheric pressure alone is important.

CONCLUSIONS

The Pacific Decadal Oscillation has an influence on tropical storm effectiveness followed by atmospheric pressure on arrival in the Potomac River Basin. However, the influence of other climate factors that are related to Atlantic Ocean surface temperature and pressure cannot be ruled out. The time series plot of storms that advected moisture into the Potomac River Basin and AMO warm phases between 1950 and 2004 show coincidence with an increase in storm effectiveness that cannot be solely contributed to the PDO. The variability in storm effectiveness when the 12-month average of the monthly PI fluctuates, suggests the PDO may enhance NAO influences. Further study of the relationship between the latter two climate factors and storm effectiveness will prove useful for precipitation enhancement prediction when tropical storms bring moisture into the Potomac River Basin.

Chapter 4: Flood Response to Tropical Storms: 2003 and 2004

ABSTRACT

Peaks in streamflow can result from intense storm events or successive storm events over short time spans. The instantaneous record of streamflow related to four hurricanes was examined to contrast the relative importance of storm intensity and sequential storms in generating floods. This record was also used to determine whether or not antecedent moisture is a significant factor under a range of conditions. The hypothesis was that for a given watershed, the streamflow response to one intense storm would be similar to that of similar total rainfall distributed in successive storms $\leq$ 10 days apart. The data did not support this hypothesis, flood discharge was higher in response to an individual intense storm and an increase toward wetter antecedent conditions as a result of the successive storms did not generate a significant increase in runoff ratios.

INTRODUCTION

In the 20th century, Northern Hemisphere land and sea surface temperatures showed an increase (Smith and Reynolds, 2005). These temperature increases could lead to an increase in evaporation rates, which could then lead to lower streamflow in the Potomac River Basin, particularly during summer months. Temperature increases could lead to an increase in the number of Atlantic hurricanes, which might increase the number of storms that impact the Potomac River watershed thus leading to wetter conditions during hurricane season. Understanding how storms alter surface moisture and the role that surface moisture plays in the flood response to a storm event is essential to water resources management, natural hazard mitigation efforts and climate change prediction.

Statement of the Problem

Rhodes (this study) examined the conditions under which tropical storms and hurricanes generate floods in the Potomac River basin and found that in the period from 1950 to 2004, forty-seven storms impacted the basin. Approximately 40% of these storms were part of a storms series that advected moisture into the basin more than once in a single hurricane season. The years in which a series of tropical storms impacted an area were labeled multiple-storm years in this study.

The first in a series of storms is sometimes cited as the event that set the stage for later discharge extremes, in the presence of a second tropical storm, due to surface wetness (antecedent moisture) and the ability of soil to store moisture (soil moisture storage capacity) from a later storm (Dunne *et al*., 1991; Cey, *et al*., 1998; Cosh *et al*., 2004; Lana-Renault *et al*., 2007). At the same time, the importance of antecedent moisture is expected to decrease with an increase in flood magnitude (Wood *et al*. 1990; Sturdevant-Rees *et al*., 2001). Gauge records showed it was not always the case that a second storm caused higher magnitude discharges. For example, Connie 1955 was the first in a series of two storms and was effective at generating an annual peak discharge of 82 cms at the gauge on Difficult Run near Great Falls, VA and the second storm (Diane 1955), a week later, only generated a discharge of 46 cms.

In other instances, a single storm has generated higher discharges than the last in a series of storms. For example, Hazel was the only storm to track across the Potomac River Basin in 1954. Conditions prior to this storm were relatively dry, yet this storm generated higher discharges than Hurricane Diane 1955, which occurred a week after Hurricane Connie1955. Even though it is understood that the importance of antecedent moisture decreases with an increase in discharge, the discharge boundary at which the influence of antecedent moisture fails to be important is not defined (Sturdevant-Rees *et al*., 2001).

The hurricanes that occurred in September 2003 and September 2004 give rise to an opportunity to address this question. A set of circumstances similar to the series of events in 1954 and 1955 occurred in the 2003 and 2004 hurricane seasons. A single storm, Hurricane Isabel, in the first season generated more extreme floods over a broader region than the last in a series of three storms (Hurricane Jeanne) in the following season. One approach is to track changes in the flood response to sequential storms as conditions change from dry to wet and another is to examine the flood response to two different storms when initial surface conditions are similar.

In some multiple-storm years, the time intervals between storms were ≤ 10 days apart. In September 2004, surface conditions were dry when the first in a series of three storms delivered moisture to the western flank of the Potomac River Basin. After that, two more tropical storms delivered moisture to the same area at approximately 10-day intervals for the remainder of the month. Examination of the differences in rainfall depth and distribution combined with analysis of pre-storm surface conditions should provide the information on the importance of antecedent moisture conditions on flood response. The response of these three storms in September 2004 was compared with a single storm in 2003 to develop an understanding of flood response to tropical storm rainfall in the Potomac River Basin.

Research Objectives

In several examples reviewed above, a series of tropical storms occurred in a single hurricane season and generated a variety of flood responses. Antecedent moisture variations might play a role in those responses. In this study, I will first examine the likelihood that a series of storms will occur. I will then examine the changes is antecedent moisture condition and soil moisture storage capacities in response to tropical storms. The purpose of this study is to examine the probability of sequential tropical storms in the Potomac River Basin and the effects of these storms on runoff production and flood peaks. The objectives of the study are as follows:

1. Determine the distribution of time intervals between successive tropical storms in the Potomac River Basin.
2. Determine the average time interval to return to pre-storm discharge after a storm-related maximum discharge at study gauge sites.
3. Evaluate the flood response to changes in antecedent moisture as a result of Hurricanes Frances, Ivan and Jeanne in September 2004. Measures of peak discharge magnitudes, runoff ratios, and the lag in response to peak rainfall.
4. Compare antecedent moisture conditions and flood responses to Hurricanes Frances, Ivan and Jeanne in 2004, to flood responses to a solitary Hurricane Isabel in 2003.

Statement of Hypotheses

1. Sequential storms increase surface wetness and decrease soil storage capacity. Therefore at a given site, storms that occur later in a tropical storm series should generate proportionally larger runoff responses.

2. Runoff ratios (runoff/rainfall) show a positive correlation with antecedent moisture.
3. Runoff ratios (runoff/rainfall) show a negative correlation with soil moisture storage capacity.

DATA SOURCES AND METHODOLOGY

In summary, the steps taken to test the hypotheses were to determine the distribution of time intervals between storm events in multiple-storm years, estimate the length of time taken for discharge recordings to return to pre-storm rates (the memory of a storm event noted by discharge rate retention) by analysis of hydrographs, identify storm status at landfall and on arrival in the basin and determine the depth of peak 24-hour rainfall and the spatial distribution of rainfall by construction of isohyetal maps, determine pre-storm surface conditions based on antecedent moisture and soil moisture storage capacity indices. Flood response is evaluated by determining the relationship among rainfall, runoff, and discharge magnitude and rise time.

The storms used in the evaluation were Hurricanes Isabel 2003, Frances, Ivan and Jeanne 2004. The following three sub-basins were chosen to be the focus of this study: North Branch Potomac River, South Branch Potomac River and Shenandoah River basins (Figure 1, Chapter 1). These three sub-basins were chosen for the following reasons.

1. The sites are in the upland portion of the basin where small sub-basin areas are relatively small and the influence of individual storms is more easily discerned.
2. Tributaries in the three sub-basins deliver the bulk of the discharge to the mainstem.

3. Large portions of the sub-basins are forested or agricultural with little urban development, which implies similar land-uses among the basins.
4. There are many continuous-gauge records and long-term gauge records, which makes the confidence in recurrence interval estimation higher.

Data

Information regarding the status, track and speed of the four hurricanes was obtained by review of publications by Bell *et al*. (2004), Beven and Cobb (2004), and Beven (2005). In some instances a limited number of precipitation estimates were also available through these sources. Most precipitation data, however, were acquired by download from the U. S. National Climate Data Center at http://www.ncdc.noaa.gov/oa/climate/climatedata.html. The uncertainty in precipitation measurements is 10% (Dingman 2002). Streamflow real-time records and statistics were acquired through the U. S. Geological Survey at http://water.usgs.gov/. Qpd records were acquired from the Maryland, Virginia and West Virginia Water Science Centers by electronic submission to the author. The uncertainty in precipitation measurements is 5% (Dingman, 2002).

Selection Criteria

Precipitation gauge records were chosen if rainfall amounts were reported during two of the four storm events, readings were taken at least once every 24 hours and the gauge location was in close proximity to the study area. The yield was a total of 43 precipitation gauges. Twenty-three gauges were within basin boundaries (Appendix Table 18). Stream gauge records were used if annual peak discharge was reported continuously between

1950 and 2004; real-time discharge data were available at intervals of 30-minutes or less during September 2003 and September 2004. The real-time discharge data series is the record of instantaneous discharges recorded every 15 to 30 minutes by gauges throughout the United States. These data are most useful in analyses of the influence of precipitation events on streamflow variability. The other criterion for gauge record selection was the availability of daily and monthly statistics. The yield was 17 gauges listed in Appendix Table 12.

Estimating the Time Interval Probability of Storms in a Multiple-Storm Year

The historical record of named tropical storms and the timing of their occurrence were used to estimate time interval probability. The procedures detailed in this paragraph were previously described and carried out for the study discussed in Chapter 3. They are restated here for the reader's convenience. The count and timing of storms that advected moisture into the Potomac River Basin was determined by accessing hurricane data from the U.S. National Oceanographic and Atmospheric Administration (NOAA) and made available through the U.S. Geological Survey at http://www.nationalatlas.gov/index.html. A storm was considered to have advected moisture into the basin if it entered a grid with boundaries set between -81.5° W and -73.0° W longitude and 40.5° N and 37.25° N latitude (Figure 17, Chapter 3). The grid boundaries were chosen based on the fact that storms at this distance were known to produce annual peak discharges in the basin. Hurricane Juan (1985) was added to the data set but not used to set a boundary because the U.S. National Hurricane Center down-graded this storm to extra-tropical status while it was still several hundred kilometers from the Potomac River Basin (Figure 17, Chapter 3).

Next, the likelihood of given time intervals between storms was determined by probability analysis. Cumulative probability plots of the time interval between storms were constructed for a random distribution based on the historical record of tropical storms in the Atlantic Basin, Florida landfalls and Potomac River Basin arrivals and then compared.

Estimating Storm-Discharge Memory

Two samples of the time intervals between discharge peaks and a return to >80% of pre-storm discharges (discharge recovery) were taken. One set was taken from known extreme discharge events and the other set of samples does not consider cause or maximum discharge. This step was deemed necessary because both the antecedent moisture index and soil moisture storage index rely on the status of discharge. Further, it is hypothesized that sequential storms that occur <11 days apart are more likely to have a cumulative effect on discharge in the later event.

Storm Behavior Assessment and Precipitation Estimation

Base maps of the Potomac River Basin were constructed in Arc GIS 9.0. Storm tracks were overlaid on the maps by importing data from the US National Oceanographic and Atmospheric Administration (NOAA) and made available through the U.S. Geological Survey at http://www.nationalatlas.gov/index.html. Isohyets were constructed based on precipitation gauge data obtained from the NOAA Climate Data Center at http://cdo.ncdc.noaa.gov/CDO/cdo. Storm reports were also reviewed to determine storm speed, wind speed and atmospheric pressure at landfall and on arrival in the basin. Where possible, additional precipitation information was also extracted from these records and used to enhance the mapping of rainfall distribution. Precipitation gauge locations were mapped and recorded-depth contour lines drawn based on the date of peak rainfall for each storm. For example, as a result of Hurricane Isabel, most gauges reported the highest precipitation amounts on September 19. The maps were constructed based on readings from every gauge on that date. The uncertainty in precipitation gauge readings was assumed to be 10%. This is the uncertainty used when estimating annual or longer total areal precipitation (Dingman, 2002). In this study, rainfall is estimated for a period of ≤ 4 days, therefore 10% was considered a suitable estimate of error.

Calculating Antecedent Moisture and Soil Moisture Storage Indices.

Antecedent moisture and soil moisture storage capacity were determined based on Sturdevant-Rees *et al*. (2001). In their study, pre-storm surface conditions were derived based on stream gauge recordings to assess the Shenandoah River Basin flood response to Hurricane Fran in early-September1996. In their work, the antecedent soil moisture index (Qa) was used to measure surface wetness and it is calculated thusly.

$$Qa = Qps/ Qm, \tag{15}$$

where Qps is pre-storm discharge and Qm is median discharge for the month based on the period of record. Values >1.0 indicate wetter than average conditions.

In the same work, Sturdevant-Rees *et al*., 2001 used the soil moisture storage capacity index was a measure of a surface's capacity to accommodate additional water and calculated soil moisture storage capacity index (Smc) using the following equation.

$$Smc = Q90 / Q24, \tag{16}$$

where Q90 is the daily discharge value exceeded 90% of the time based on the period of record and Q24 is 24-hour average (daily) discharge on the day prior to a storm event. This ratio was used for the same purpose in this study.

Determining Flood Response

Flood response was determined by evaluation of each gauge's maximum instantaneous discharge associated with an event (Qmax), the ratio of Qmax to the 100-year R.I. discharge (Qmax/Q100), runoff estimation and runoff -ratio estimation (runoff volume/rainfall volume). Instantaneous discharge data were reported in 15- to 30-minute intervals on all gauges used in this study and were provided directly to me, after revision by state water science centers in Maryland, Virginia and West Virginia. Maximum instantaneous discharges in the provided data sets are not to be confused with annual peak discharges, as all study storms did not produce annual peak discharges. For example, the gauge on Wills Creek near Cumberland, MD reported a maximum discharge of 131 cms on September 19, 2003 and due to Isabel (Appendix Table 19). The annual instantaneous discharge for the year (226 cms), however, was set on January 1, 2003.The uncertainty in discharge measurements is 5% according to Soeder (2008).

Qmax/Q100 is a measure of whether an observed peak discharge (Qmax) is an outlier by relating the most extreme and statistically reliable peak discharge event (Q100) to the peak discharge of interest. Therefore, one can ascertain, at-a-glance, the severity of flooding. Bailey et al. (1975), Carpenter (1988) and others used this method as a measure of flood response due to tropical storms. For this study, values > 0.38 indicate extreme floods, values between 0.38 and to 0.10 are moderate floods and values < 0.10 are not floods.

Runoff was also estimated and plotted as a function of rainfall. In this study, runoff was calculated using the following equation.

$$R = (Qt - Qps) / D.A. \tag{17}$$

where R is estimated runoff, Qt is total discharge volume, Qps is pre-storm discharge volume and D.A. is drainage area. Total discharge volume was determined by summing instantaneous discharges between the rising and recession limb of hydrographs.

Hydrographs were constructed as a time series of instantaneous discharge between 12pm September 18, to 12 am September 22, 2003 (Hurricane Isabel) and 12am September 6, to 12 am October 1, 2004 (Hurricanes Frances, Ivan and Jeanne). These hydrographs were used to determine also used to determine lag-to-peak times and rise times.

Usually, where high resolution data is available, rainfall and flow rates are evaluated together and the centroid lag-to-peak can be determined, but high temporal resolution rainfall data were only available at a few sites in the study area. As a result, centroid lag-to-peak response could only be determined at the three locations where both data sets were available Moorefield, WV, Romney, WV and Springfield, WV.

The time of rise was determined at all sites. The time of rise is the amount of time necessary for discharge to reach a maximum after rainfall and includes the time it takes for rainfall to travel from a surface contact point to the recording station. Therefore, factors that affect the length of time, such as geology, surface wetness/dryness, stream length and land use are reflected in the rising limb of the hydrograph.

Potter and Faulkner (1987) showed assessment of the rising limb of a hydrograph is a good measure of discharge quantiles and therefore useful in determining the time to rise. This assertion was tested by comparing centroid lag-to-peak times and rise times between precipitation/streamflow gauges at Moorefield, WV/Moorefield, WV and Romney, WV/Springfield, WV where 15- or 30-minute streamflow data were available and hourly precipitation data were also available. Lag-to-peak time was calculated by first estimating the time to reach a rainfall centroid (t_{rc}) using the following formula.

$$t_{rc} = (\sum r*t)/r_{tot}, \quad (18)$$

where r was the recorded rainfall depth, t was the time at which rainfall was recorded and r_{tot} is total rainfall. Qmax was read directly from the table of instantaneous or real-time discharges for the period in question then lag-to-peak time was calculated by subtracting t_{rc} from initial Qmax.

Rise time (Rt) was calculated thusly,

$$Rt = t_p - t_i, \quad (19)$$

where t_i is the time at the point of inflection or that point on the rising limb of the hydrograph where the onset of a continuous rise in discharge begins and t_p is the time that discharges reached peak discharge (Figure 28).

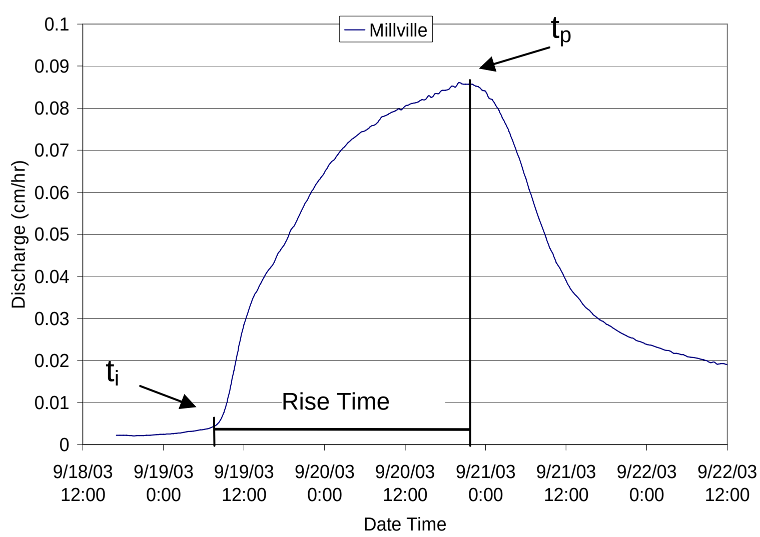


Figure 28. Rise time schematic. t_i = time of inflection, t_p = time of maximum event-related discharge.

Discharge recurrence intervals were estimated by non-parametric probabilities estimation using the following equation.

$$R.I = (m+1)/n, \tag{20}$$

where n is the rank of discharge (from highest to lowest) and m is the number of years in the gauge record. This is a traditional method of estimating probabilities that does not extrapolate to estimate recurrence intervals outside of the range of the record and is not influenced by discharge dimensions. Therefore it is considered to be robust.

RESULTS

Sequential Storms in the Potomac River Basin

In the period between 1950 and 2004, there were 10 multiple-storm years. Sixty percent of the time the first storm was a flood-generating event. In 2004, six tropical storms occurred and two of them generated significant flooding (Table 6).

Table 6. Potomac River Basin Multiple-Storm Years

Year	Number of tropical storm events	Effective storm sequence number
1955	2	1, 2
1959	2	2
1960	2	1
1971	2	1
1979	4	3
1985	4	3, 4
1996	3	1, 2
1999	2	1, 2
2000	2	1,2
2004	6	4, 6

The probability of a given interval between storms (in days) was evaluated by constructing cumulative frequency diagrams based on observed storm intervals (Figure

29). The probability distributions for the Potomac River Basin were then compared with the following distributions:

1. The distribution of the interval between storm events observed to track over Florida during hurricane season in multiple-storm years between 1950 and 2004.
2. The distribution of the interval between storm events derived by random number generation based on the interval between tropical storm events observed to track over Florida during hurricane season in multiple-storm years between 1950 and 2004.
3. The distribution of the interval between storm events derived by random number generation based on the interval between tropical storm events observed to track over Florida between September 1 through October 31 in multiple-storm years between 1950 and 2004.

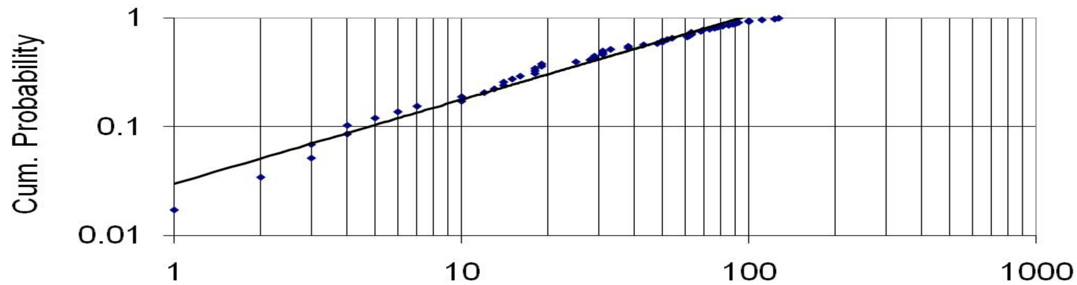
The number of storms that made landfall in Florida is different from the number of storms that arrived in the Potomac River Basin during the study period (Figures 29c and d). The probability of a given time period between storms that make landfall in Florida and ones that arrive in the Potomac River basin is also different as there are more observed events in the Florida data set than there are observed events in the Potomac-River-Basin-arrival data set. The time-interval-between-storms probability distribution based on observed Florida landfalls was very similar to the model results of randomly generated hurricanes over the hurricane season (e.g., 10% of the time the interval between storms was four days or less; 50% of the time the spacing is 43 days or less. The probability distribution based on the observed time intervals between storms that arrive in the Potomac River basin (Figure 29d) is considerably different from the random distribution of time intervals between tropical storms during hurricane season and the distribution of time intervals between storms that made landfall in Florida between 1950 and 2006 (Figures 29a and 29c). With regard to Potomac River Basin events, the cumulative probability of a time interval of 41 days between storms is 78%.

Even though the spacing between storms that arrive in the Potomac River in multiple-storm years is significantly different from the random distribution for the entire hurricane season, it was similar to the distribution generated by examining a shorter window in which tropical storms occurred between Sept. 1 and Nov. 1. The time-interval-between-storms probability distribution under these constraints indicated a 95% cumulative probability that storms would occur within 42 days of each other.

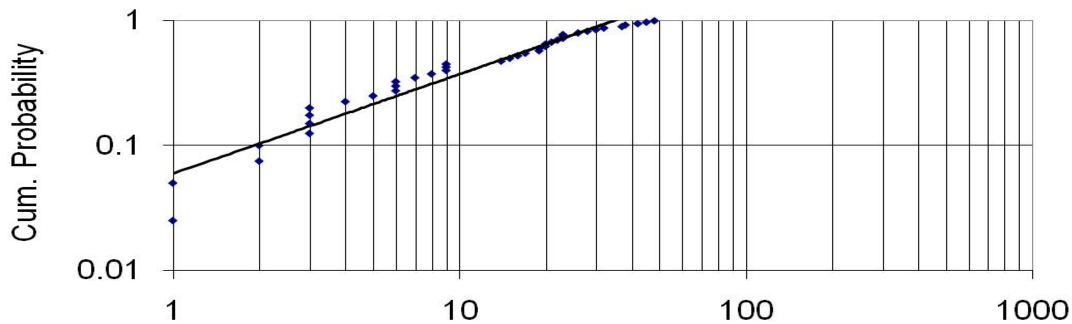
Both the time-of year data and these data suggest that although the Potomac River basin receives significantly fewer tropical storms than Florida, it is more likely to experience tropical storms later in hurricane season. In years with multiple storm events, therefore, these events might be more closely spaced than they might be earlier if they occurred earlier in a hurricane season. In the rest of this paper, I will examine the consequences of closely-spaced tropical storms on watershed runoff and flood responses by examining three tropical storm events that occurred in September 2004.

The interval between storms has an effect on antecedent moisture conditions and possibly flood magnitude and runoff depth. Therefore, the interval between storms influences storm hydrograph shape. Hence, storm influence can most effectively be evaluated by examination of the recession limb of the storm hydrograph.

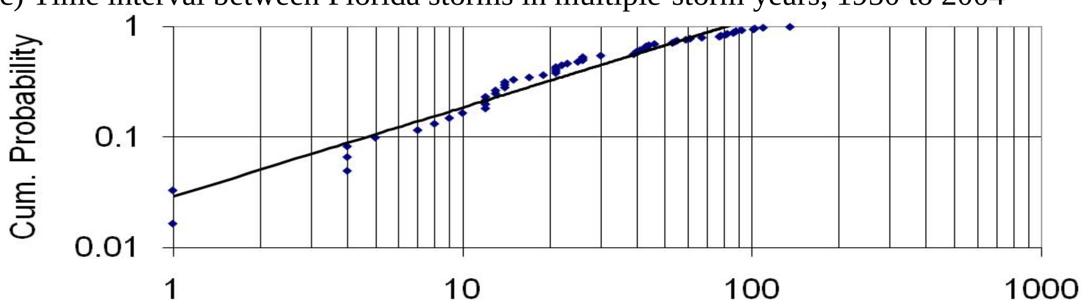
a) Randomly generated time interval between storms during hurricane season



b) Randomly-generated time interval between storms in September - October



c) Time interval between Florida storms in multiple-storm years, 1950 to 2004



d) Time interval between PRB storms in multiple-storm years, 1950 to 2004

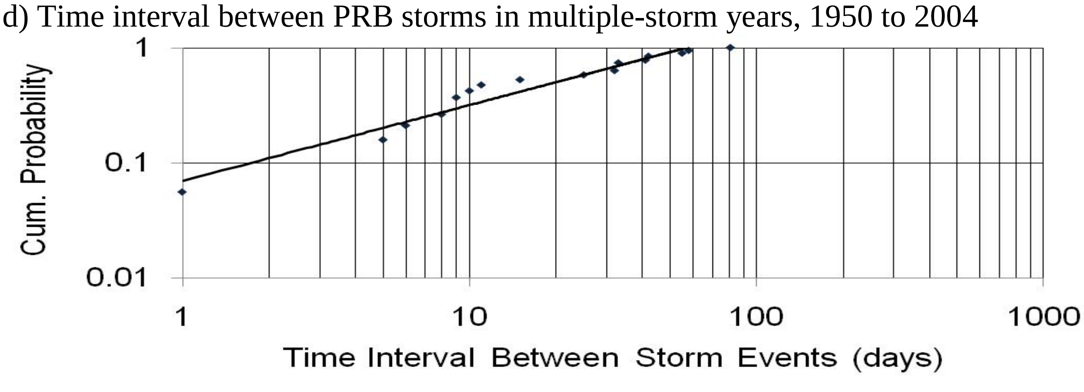


Figure 29. Cumulative probabilities derived from randomly generated and observed data sets.

Streamflow recession curves follow negative exponential functions defined in the following way:

$$Qi = Qmax * e^{-Kt}, \tag{21}$$

where Qi is instantaneous discharge, K is a coefficient, and t is the time interval between storm events in days. The suggestion is the shorter the time interval between storms, the larger discharge will be when the next storm occurs. Sampling of discharges by random selection of Qmax date (for a selected gauge's entire period of record) and study gauge showed that, when no new storm event occurred, an average of 12 days is required for return to pre-storm discharge regardless of Qmax recurrence interval, storm type, season of the year, study gauge location or watershed size.

When the sample selection was narrowed to extreme events, the time interval before return to pre-storm discharges increased to an average of 16 days. These data imply that storms that occur 16 days or less prior to a subsequent storm will likely have an impact on flood response. A look at the hydrograph of discharge due to sequential storms in September 2004 supports this as there was a continuous rise in both minimum and maximum discharges with each new storm event followed by a long recovery period (Figure 30). Since the sequential storms in 2004 occurred approximately 10 days apart, results from the following sections will indicate whether or not this is the case.

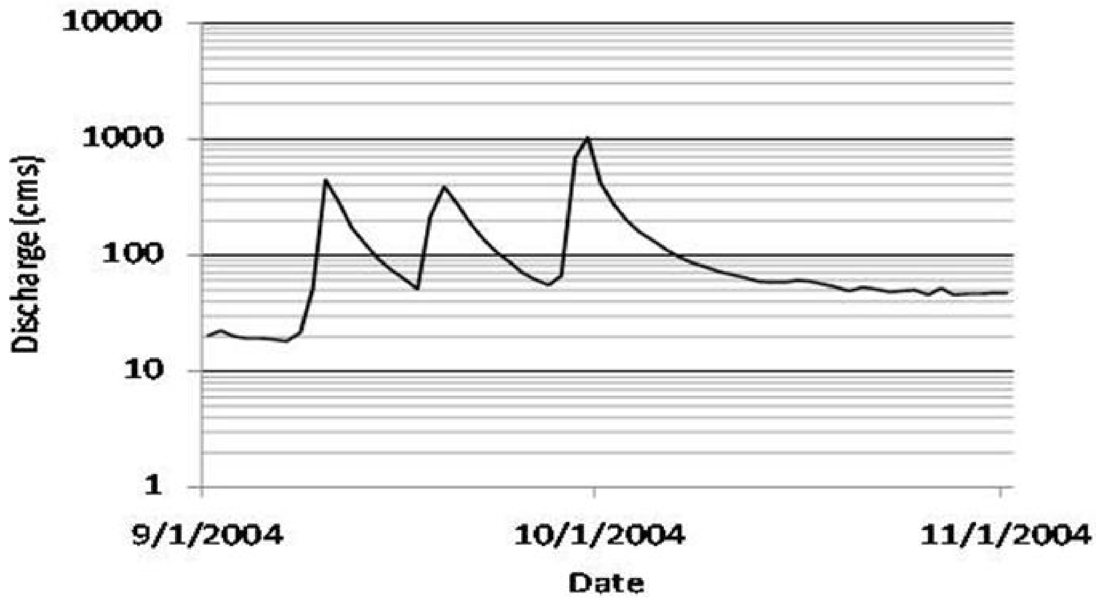


Figure 30. Hydrograph - Shenandoah River at Millville, WV-September to November 2004. The graph illustrates the point that the flood response to one storm can follow upon the recession limb of the previous storm without return to pre-storm discharge rates given an interval between storms of < 16 days.

Effects of Sequential Storms on Flood Response During the 2004 Hurricane Season

Hurricane Isabel 2003 was the only storm in the 1950-2004 record that crossed the Potomac River Basin in hurricane status (NOAA, Figure 31). In comparison with the September 2004 storms, it had the shortest time between landfall and basin arrival and was the only storm that made landfall in North Carolina. Along with Jeanne (September 28, 2004), it also had the fastest overall forward speed. The three 2004 storms in this study all made landfall in Florida and skirted the Potomac River Basin. The time intervals between landfalls for the storms in 2004 were 11 and 10 days respectively. The time intervals between arrivals in the basin were 10 and 9 days respectively (Table 7).

Figure 31. Storm tracks for Hurricanes Isabel in September 2003 (red), Frances, Ivan and Jeanne all in September 2004 (blue). Arrows indicate storm track direction. Ivan's track appears twice because it recurved to the east and returned south over the Atlantic Ocean. Potomac River Basin (white) sub-basins are outlined in black (top right).Warm colors = high elevation, cool colors = low elevation.

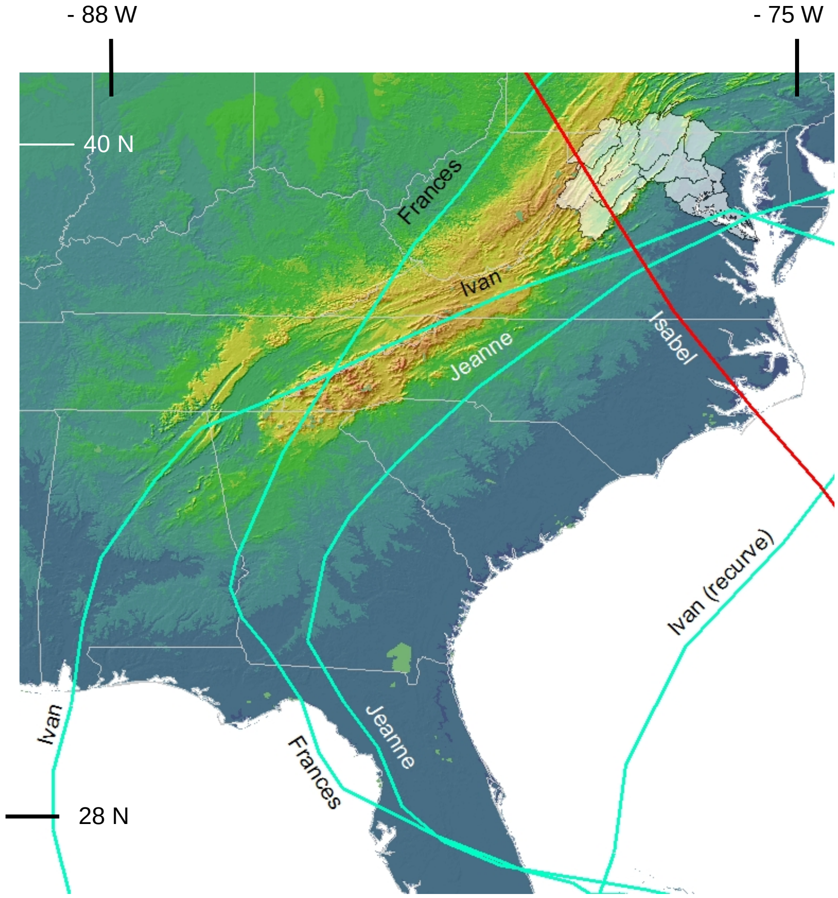


Table 7. September 2003 and 2004 Storm Status Summary

Name	Landfall State	Status at Landfall	Time of Landfall (UTC)	Status on Arrival in Basin	Time of Arrival (UTC)*	Estimated Forward Speed (kph)
Isabel	NC	H2	1800 9/18/03	H1	0000 9/19/03	29
Frances	FL	H2	0600 9/5/04	ET	0600 9/9/04	23
Ivan	FL	H3	0600 9/16/04	TD	0600 9/19/04	27
Jeanne	FL	H3	9/26/04 0400	TD	1800 9/28/04	29

Beven and Cobb (2004), Hx = hurricane status, ET = extratropical, TD = tropical depression,*time of arrival = estimated time storm entered or arrived at the closest point to the Potomac River Basin boundary.

Total rainfall was higher due to Isabel 2003 than due to any other storm event. Except for the case of Hurricane Ivan; however, total rainfall ranges were similar (Figure 32). Average cumulative rainfall after Isabel 2003 and Ivan 2004 (both events in mid-September) was nearly equal (Figure 33). After Jeanne (the event at the end of September 2004), the three sequential storms managed to accumulate ~50 mm more rainfall than was accumulated after Isabel (the single event in mid-September 2003; Figure 31).

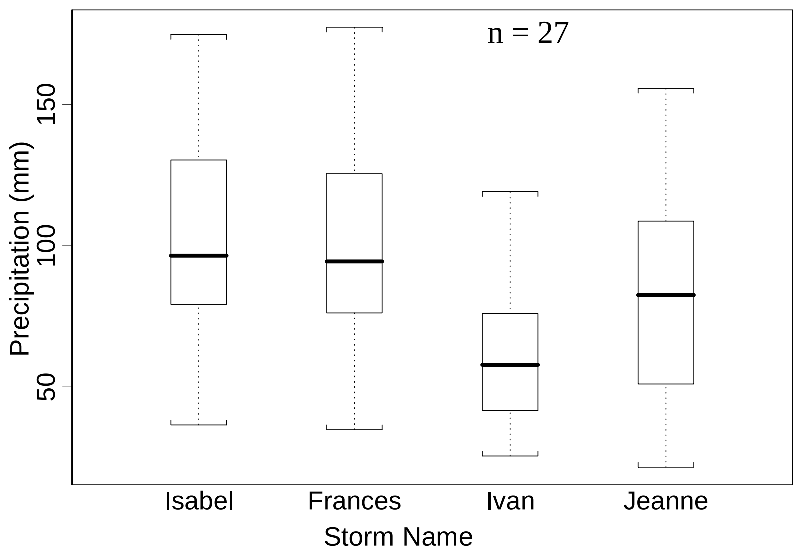
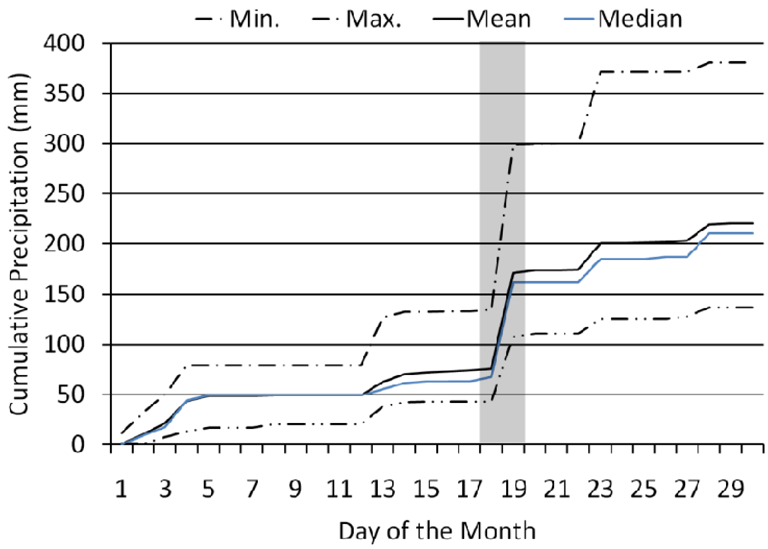


Figure 32. The distributon of gauge precipitation totals for each storm. Rectangles define the ranges in values between the 25th and 75th percentiles, bold black lines = median precipitation, horizontal brackets = maximum and minimum precipitation, n = sample size.

The patterns of rainfall on the isohyetal maps suggest that storm track was most important for rainfall distribution followed by orographic enhancement, particularly in the case of Hurricane Isabel (Figure 34). Hurricane Isabel had a northwest trajectory perpendicular to the northeast trending Blue Ridge Mountains and a 'best track' center across the study area (Figure 31). The areas of highest rainfall along the eastern watershed boundary and in the southwest portion of the basin are indicative of the orographic effect. The pocket of extreme rainfall to the north and in the rain shadow is suggestive of the processes described by Barros and Kuligowski (1998), wherein smaller clouds in the area of the rainshadow are seeded by larger clouds as they traverse mountains. The tongue of extreme rainfall perpendicular to the Blue Ridge Mountain ranges is indicative of the pattern described by Klein et al. (2007) wherein orographic lifting led to the concentration of rainfall left of the storm track.

The isohyetal map of September 9, 2004, rainfall reveals a complex rainfall pattern with highs in the northwest corner of the watershed and closest to the track of the storm (Figures 33 and 34). This complex pattern may be due to tailing convective storms associated with weakening tropical storms (Klein *et al.*, 2007). The rainfall patterns associated with Hurricanes Ivan and Jeanne are similar in the east central section (Figure 34). There were highs along the eastern boundary of the watershed and near the basin boundary near the apex. These two storms tracked sub-parallel to one another and changed trajectories from northeast to a more eastward direction near the area of highest rainfalls (Beven and Cobb, 2004; Figure 31). The slower forward speed of the storm (Table 7) and pattern of intensified rainfall due to orographic uplift are apparent in the isohyetal maps. In summary, the combined influence of topography and storm track is apparent in the set of four isohyetal maps.

a) September 2003 – Hurricane Isabel, September 19, 2003



b) September 2004 – Hurricanes Frances, Ivan and Jeanne, September 6, 17, and 29, 2004

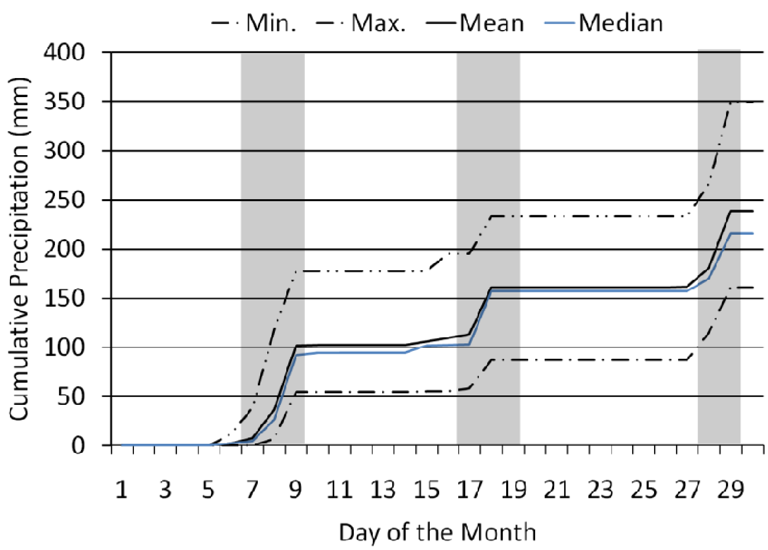


Figure 33. Cumulative precipitation during two Septembers. Shaded areas highlight the timing of storm-related rainfall. Note cumulative rainfall in mid-September 2003 and 2004 are nearly equal and cumulative rainfall at the end of September 2004 exceeds that of mid-September 2003. Forty-two precipitation gauges were used to construct the figure.

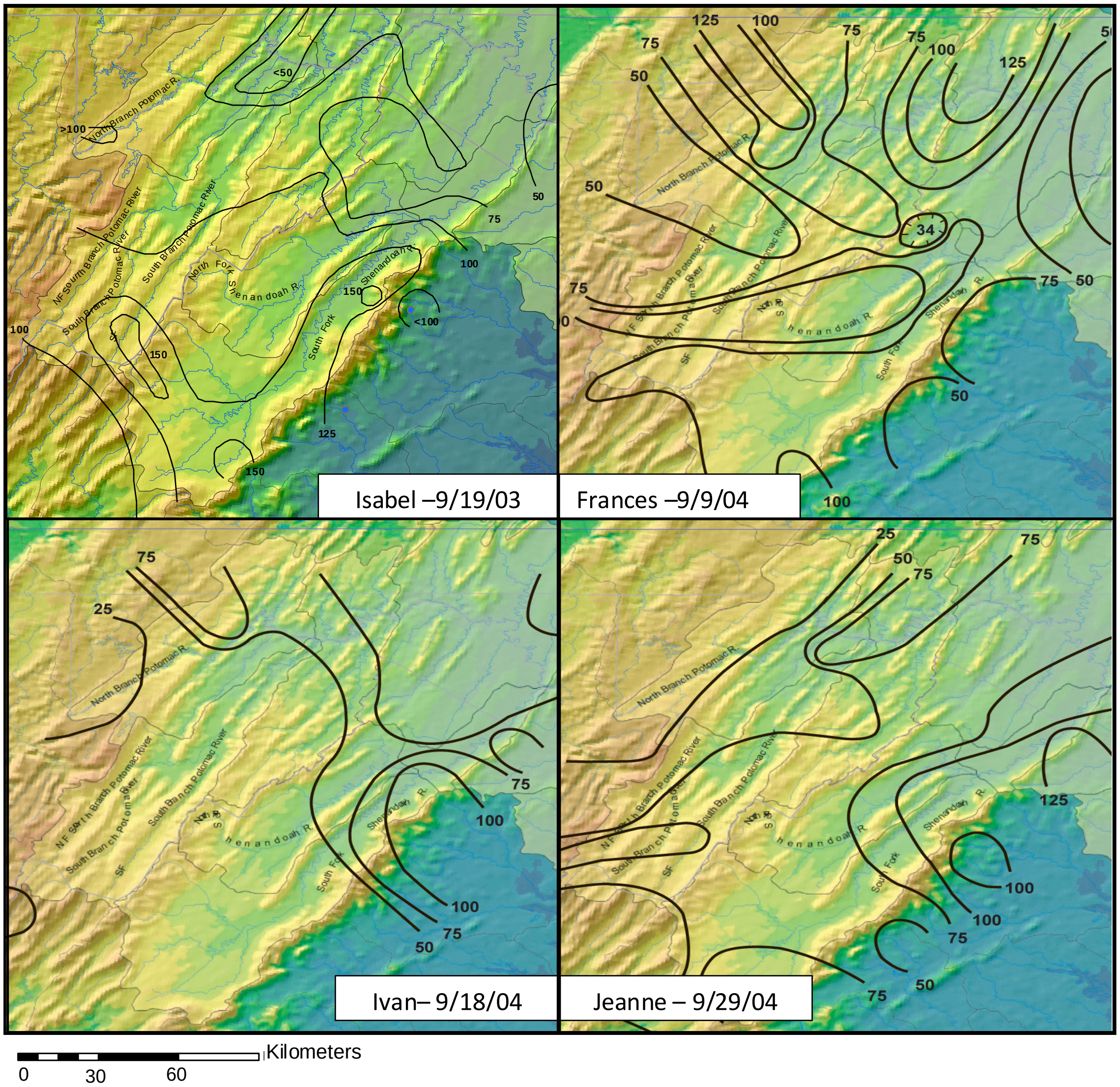


Figure 34. Isohyets of 24-hour rainfall over the North Branch Potomac River, South Branch Potomac River and Shenandoah River Sub-basins. Values shown are in millimeters. Highest rainfall totals are perpendicular to the storm track in the case of Isabel and parallel to the storm track in the case of the three storms in September 2004.

Effects of Sequential Storms on Antecedent Moisture Conditions

Qas were plotted as functions of basin area to determine the heterogeneity in surface wetness and detect possible scaling relationships (Figure 35). Recall Qps is pre-storm discharge and Qm, is median September discharge estimated from data for the period of record.

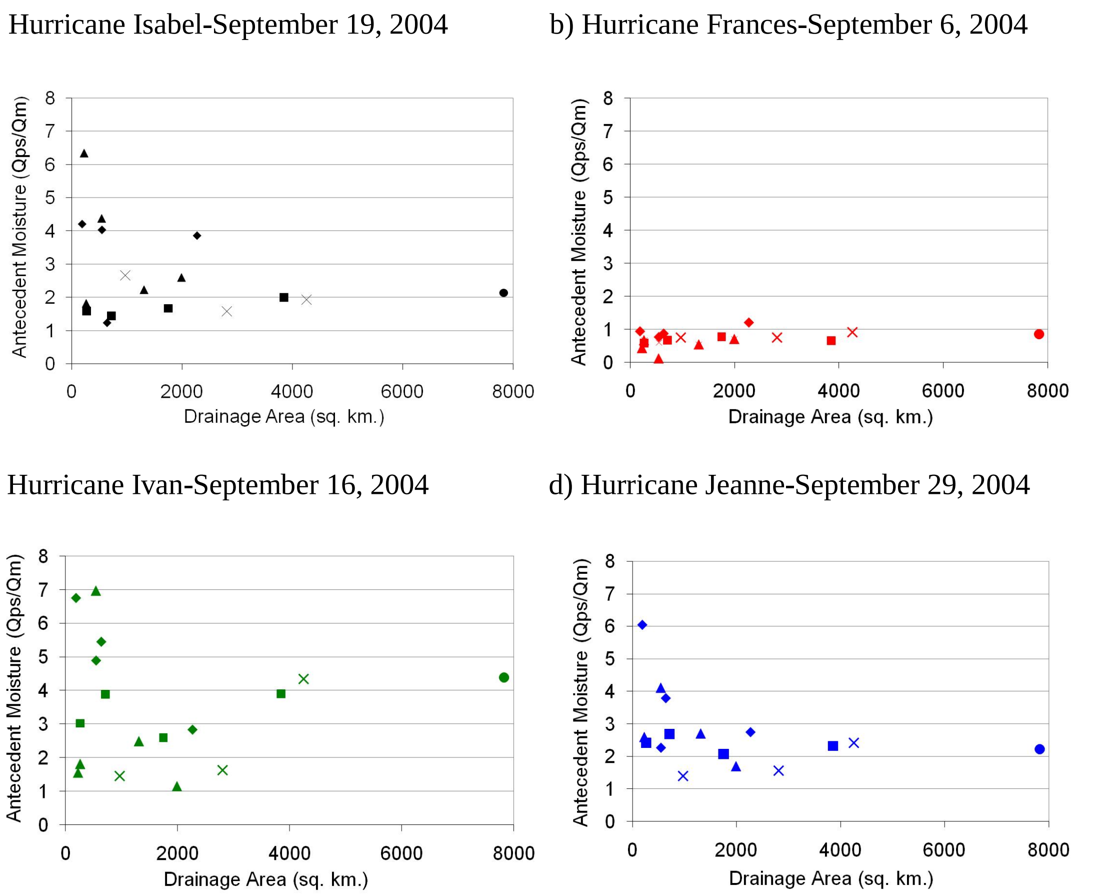


Figure 35. Antecedent moisture indices (Q_{ps}/Q_m) versus drainage basin areas. Individual sub-basin gauges are identified by diamonds (North Branch Potomac River), squares (South Branch Potomac River), triangles (North Fork Shenandoah River) and xs (South Fork Shenandoah River).

The general shape of the plot of Qa values implies there was a more pronounced and heterogeneous response in discharges in smaller basins as a result of Isabel, Ivan and Jeanne. Antecedent moisture shows no drainage basin dependency based upon the plots. September 2003 was a relatively wet month probably due to local convective storms or frontal cyclones because there were no hurricanes, other than Isabel, that advected moisture into the region that year (Appendix Figures 45-49). Prior to Isabel, the index suggests wet conditions everywhere. This is due to a frontal cyclone that effected the entire study area ~6 days prior to Isabel-related rainfall. The greatest variability in the ratio Qps/ Qm is in the smallest basins, which is also probably due to the difference in rainfall depths during the event prior to Isabel.

In the case of Frances the next year, albeit moderately so, surface conditions were modestly dry throughout the basin because neither of the two tropical storms that tracked into the region prior to Frances 2004 had much of an effect on the study area. No rain fell in the month of September prior to Frances 2004 making landfall in the United States on September 5 (Appendix Figures 50-53). Qps/Qm in mid-September 2004 prior to Ivan indicated surface moisture conditions were wetter than those of mid-September 2003 (Isabel), with few exceptions. This is indicative of the fact that cumulative rainfall in September 2003 prior to Isabel was not as high as rainfall due to Frances in early-September 2004. Index values prior to Jeanne were slightly less than those prior to Ivan, which was a reflection of the low rainfall amounts associated with Ivan, and seasonally high evapotranspiration rates. The result was that pre-storm surface conditions closely matched those prior to Isabel, particularly in the Shenandoah River Basin.

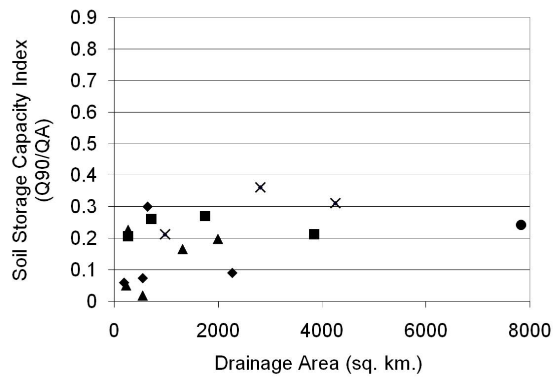
Antecedent moisture index (Qps/ Qm) variation coincides relatively well with recorded rainfall variation and indicate sub-basin surface wetness is a reflection of accumulated rainfall prior to each tropical storm (Figures 33 to 35). Assessment of the sequential storms in 2004 indicates evapotranspiration has an influence on the transfer of rainfall into streamflow if a subsequent storm is a minor rainfall producer or occurs more than 10 days after a prior rainfall event that is also minor. After the results from soil moisture storage capacity are presented, the flood response to each of the storms will be examined and the relationship between discharges, runoff, Qa and Smc presented and discussed.

Soil Moisture Storage Capacity and Storms

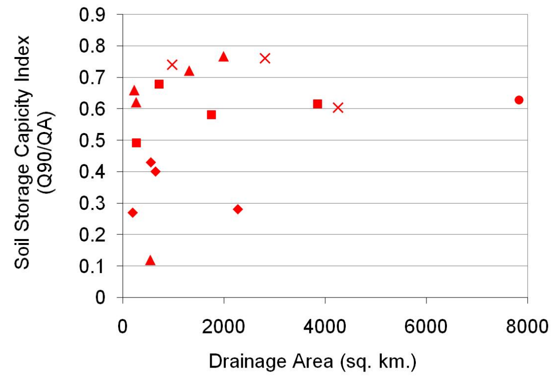
The graphs presented below are designed to assess soil moisture storage capacity prior to each storm in 2003 and 2004 and to evaluate whether or not there is any variation in soil moisture storage capacity with watershed size (Figure 36). The Smc (Q90 / QA) is the ratio between pre-storm 24-hour discharge (QA) and the discharge for the day that is exceeded 90% of the time (Q90), based on the period of record. This procedure removes seasonal and dimensional influences and generates an unbiased Smc ratio. September is a month when monthly discharge is at a seasonal low, therefore discharges less than Q90 for a day in September are base flow. Thus, they are indicative of drained soil surfaces and surfaces with high moisture storage capacities. With a storm-event generated increase in 24-hour discharges, the Smc approaches zero, indicating soil moisture storage capacity is low.

There is no statistically significant relationship between the Smc and drainage basin area, but a slight trend exists in the plots of storage capacity indices and drainage areas based on data related to Isabel and Frances (Figure 36). Except for instances in early-September 2004, Smcs are < 0.4. Prior to Isabel, Q90 /QA ratios are lower in the North Branch Potomac River Basin and in the North Fork Shenandoah River at Cootes Store, VA sub-basin than in the rest of the study area. Precipitation earlier in the month is nearly equal throughout the study area; therefore, the index variations may be due to differences in soil thickness and/or underlying bedrock type. Thin soils overlying bedrock surfaces with low permeability result in low storage capacities and higher runoff (Smith *et al.,* 1982). In the North Branch Potomac River and North Fork Shenandoah River near Cootes Store, VA sub-basins, the surfaces are composed of thin soil cover overlying low permeability shales (Smith *et al.*, 1982; Trapp and Horn, 1997). Therefore, soil storage capacity is small and the Smcs should be low.

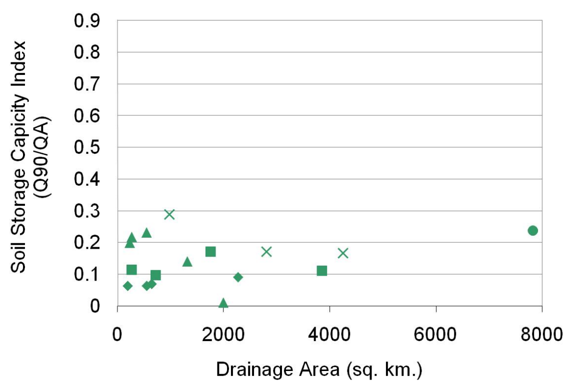
a) Hurricane Isabel-September 19, 2003



b) Hurricane Frances-September 6, 2004



c) Hurricane Ivan-September 16, 2004



d) Hurricane Jeanne-September 29, 2004

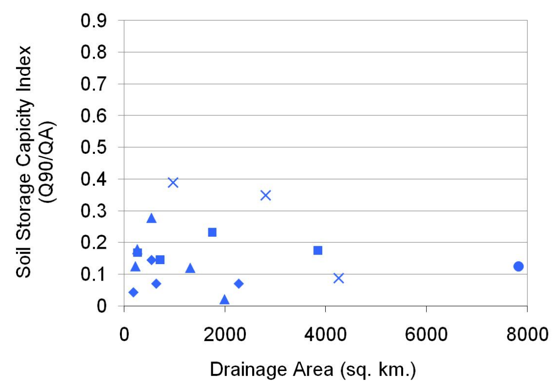


Figure 36. Smc (Q_{90}/Q_A) versus drainage area. red=Frances, green=Ivan, blue=Jeanne. Individual sub-basin gauges are identified by diamonds = North Branch, squares = South Branch, triangles = North Fork Shenandoah, xs = South Fork Shenandoah and circles = Shenandoah at Millville, WV

Predictably, higher Smcs are associated with Frances and the North Fork Shenandoah River at Cootes Store, VA location. It has an anomalously low index compared to the rest of the study area, the two other lows are on the North Branch Potomac River and probably due to conditions similar to the ones discussed above. Smc ratios are similar prior to each of the last two storms in September 2004. In general, a portion of the variations in Q90/QA ratios can be explained by variations in precipitation. There also variations that suggest a substrate control.

The Streamflow Response to 2003 and 2004 Storms

The streamflow response to a storm is the integration of precipitation input, surface conditions including land use and substrate character, which, in turn determine flow pathways and temporary storage areas, evaporation and groundwater recharge. In this section, streamflow responses to the four study storms are reported as the results of evaluation of hydrographs, discharge versus drainage area relationships, rainfall-runoff relationships, and rise time.

Hydrographs

All hydrographs show the influence of rainfall variability and, in some cases lend support to the hypothesis that sequential storms will lead to an increase in discharge peaks with each successive storm (Appendix Figures 50 to 53). In general, Isabel-generated hydrographs had steep rising limbs except for those gauges on the South Fork Shenandoah River and the two easternmost mainstem gauges. These exceptions are to be expected because the drainage areas for these basins are the largest of the study set. The recovery time to pre-storm discharges was on the high end of average ranges based on 10- to 20-day recovery times. Rainfall was highest in the vicinity of gauges in the South Branch Potomac River and North Fork Shenandoah River and it is reflected in gauge responses. The time to return to pre-storm discharge could not be ascertained because new precipitation events interfered.

Four hydrograph patterns emerged as a result of storms in September 2004 (Appendix Figure 54 to 58). These patterns are more indicative of rainfall patterns than they are indicative of storm track. For example, the two gauges (Headsville, WV, and Petersburg, WV; Appendix Figure 56) that had the highest maximum discharges in response to

Frances and then to Jeanne are in valleys that lie along the same trend. These two gauges also experienced rainfall depths that were very similar as a result of the three sequential storms in 2004. Only two gauges (Buckton, VA, and Winchester, VA; Figure 58), reported an increase in peak discharge with each new storm and thus responded according to the hypothesis. The time to return to pre-storm discharges could not be ascertained because after each event, subsequent storms occurred too quickly.

Peak Discharge and Runoff Estimation

Of the four tropical storms in 2003 and 2004, more study gauges reported both bankfull and annual peak discharges due to Isabel-related rainfall than any other storm (Appendix Table19). Also, Isabel related discharge and precipitation recurrence intervals were correlated but none of the September 2004 storm related discharge and precipitation recurrence intervals were correlated (Figure 37; Table 8).

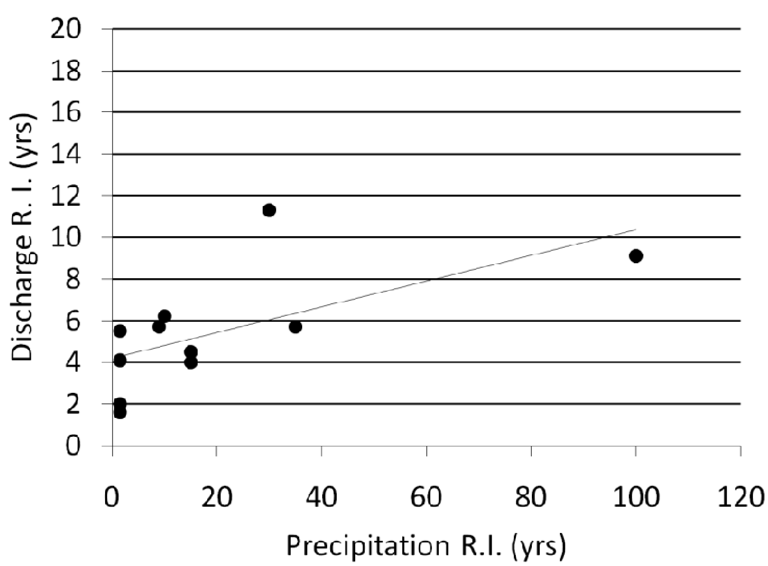


Figure 37. Hurricane Isabel related discharge R.I.versus precipitation R.I. Note 20-yr. precipitation generates up to 10-year R.I. discharge.

Table 8. Regression equations and correlations for discharge R.I. ($Q_{R.I.}$) as a function of precipitation R.I.

Storm	Equation (number)	R^2
Isabel	$Q_{R.I.} = 0.06\ ppt_{R.I.} + 4.2^{‡}$ (22)	0.40
*	$Q_{R.I.} = 0.14\ ppt_{R.I.} + 3.3$ (23)	0.43
Frances	$Q_{R.I.} = 0.27\ ppt_{R.I.} + 0.6$ (24)	0.85
*	$Q_{R.I.} = 0.02\ ppt_{R.I.} + 2.0$ (25)	0.01
Ivan	$Q_{R.I.} = 0.09\ ppt_{R.I.} + 1.4$ (26)	0.06
Jeanne	$Q_{R.I.} = 0.01\ ppt_{R.I.} + 0.01$ (27)	0.01
Note: ‡The equation describes the graph in Figure 36 above. Graphs for other equations are not shown.*Extreme precipitation R.I. removed, r = Pearson's correlation coefficient.		

Overall, maximum discharges due to the storms (Qmax) and related discharge recurrence intervals; flood discharge (Qmax/Q100) ratios, and total runoff were higher for Isabel than for any of the storms in September, 2004 (Figures 36-39, Tables 8 to 10). Fifteen of the 17 study gauges reported floods and 13 reported annual peak discharges as a result of Isabel rainfall. In fact, this storm impacted ~50% of the Potomac River Basin and 22 of the 37 gauges used in earlier parts of the study reported discharges in the top 14% of the record between 1950 and 2006.

In September, 2004, three of the 17 study gauges reported floods and annual peak discharges as a result of precipitation derived from Frances in early September (Appendix Table 19). In mid-September, two gauges reported discharges slightly higher than bankfull as a result of Ivan and nine gauges reported both floods and annual peak discharges as a result of moisture derived from Jeanne in late September.

Flood responses for the month of September, 2004 were also more local than the mid-September 2003 flood responses. Only the North Branch basin gauges reported floods due to TS Frances and TS Ivan related rainfall. With the exception of the gauge at Moorefield, WV (SB), no gauges reported floods in either the North Branch or South Branch basins as a result of Jeanne-related rainfall. Although there was general

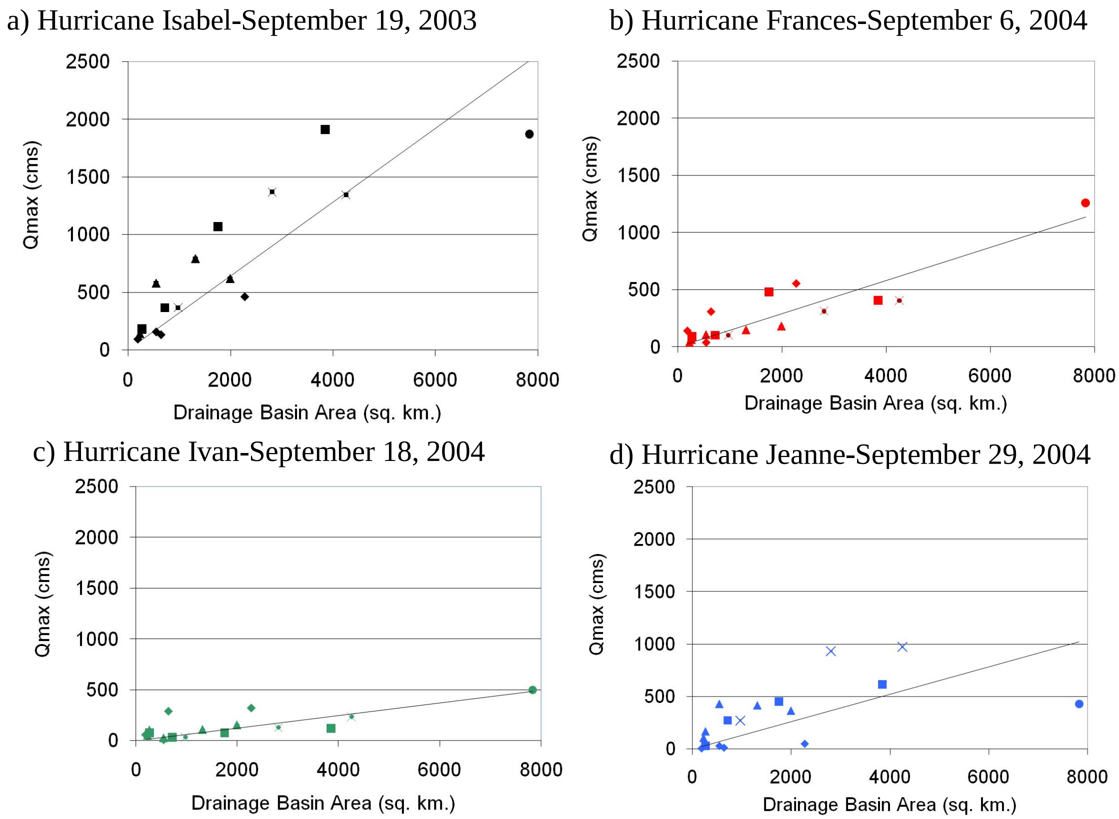


Figure 38. Event-related maximum (Qp) discharge versus drainage area by storm. On average, there was better correlation between discharge as a result of Isabel 2003 and drainage area than for discharge as a result of storms in 2004 and drainage area. Individual sub-basin gauges are identified by diamonds = North Branch, squares = South Branch, triangles = North Fork Shenandoah, xs = South Fork Shenandoah, circles = Shenandoah at Millville, WV.

Table 9. Peak discharge versus drainage basin area regression equations.

Storm	Regression equation* (number)	R^2
Isabel	$Q_{max} = 0.32$ D.A. (28)	0.71
Frances	$Q_{max} = 0.15$ D.A. (29)	0.81
Ivan	$Q_{max} = 0.06$ D.A. (30)	0.52
Jeanne	$Q_{max} = 0.01$ D.A. (31)	0.14
Note: R^2 = coefficient of determination, r = Pearson’s correlation coefficient. *Regression lines have intercepts = to zero.		

agreement between the estimated spatial distribution of rainfall and streamflow in terms of event probability and runoff, high recurrence interval discharges did not necessarily translate into high runoff volumes. The lack of translation, as previously mentioned in the section on soil moisture storage, was probably due to the effects of sub-basin substrate and land use on infiltration and runoff. As previously mentioned, substrate composition alters pre-storm surface conditions and therefore infiltration and runoff. In highly-vegetated areas, particularly forests, runoff can be lower due to rainfall interception and evapotranspiration (Appendix Table 19).

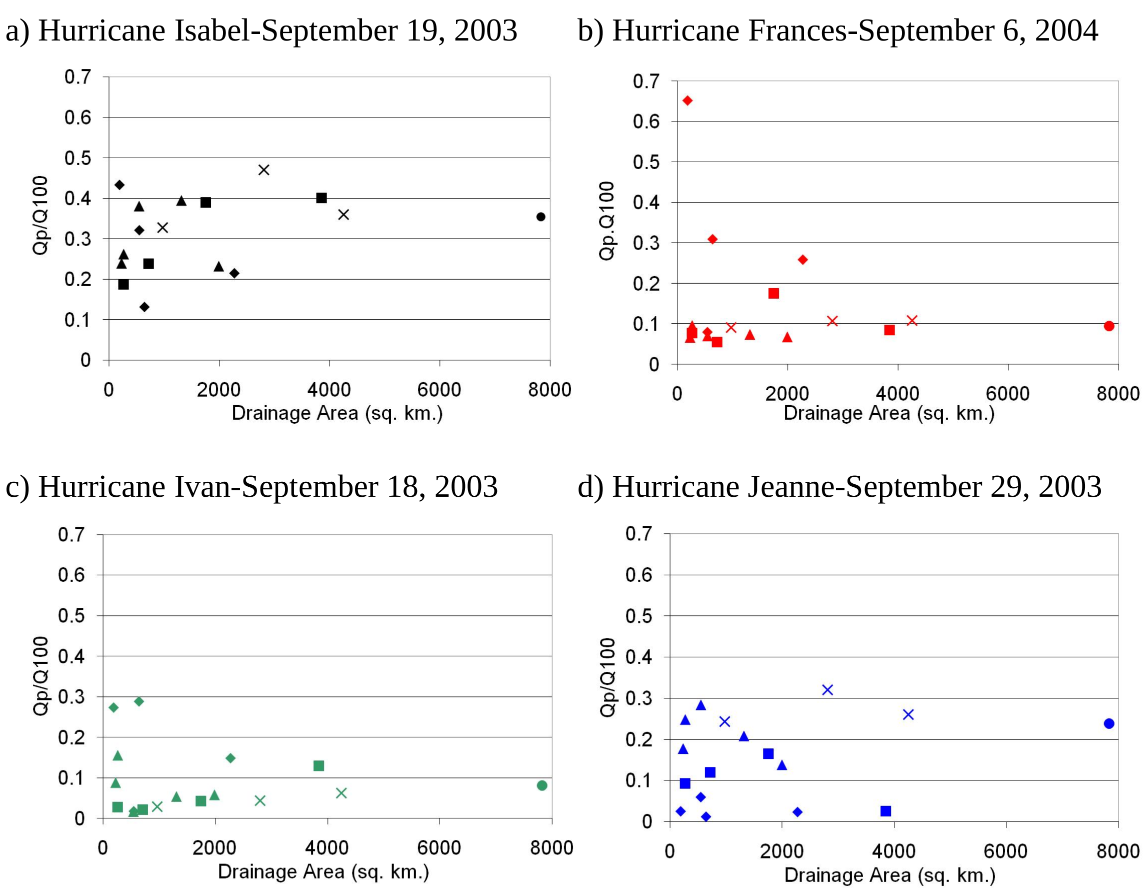


Figure 39. The ratio of storm event maximum discharge (Q_p/Q_{100}) versus drainage area. Individual sub-basin gauges are identified by diamonds = North Branch, squares = South Branch, triangles = North Fork Shenandoah, xs = South Fork Shenandoah, circles = Shenandoah at Millville, WV

The results of this portion of the study suggest areas with relatively high infiltration rates can show a marked response to intense storm events, as was seen in the case of Isabel 2003. All 2004 storm-related regressions show a linear increase in discharge with drainage basin area (Figures 37 to 39). With the exception of Jeanne, this relationship is statistically significant (Tables 8 & 9). Drainage area does not show a significant influence however, on normalized values such as Qmax/Q100 and runoff ratio (Figures 39 and 40).

Dimensionless flood ratios, Qmax/Q100, confirm Isabel-related flooding was more substantial than the events in 2004, with one exception on Georges Creek near Franklin, MD during Hurricane Frances (Figure 39 and Appendix Table 19). The precipitation gauge at Frostburg, MD, which is at the head of Georges Creek, reported extreme rainfall during Frances. The rainfall extreme there likely translated into high discharge downstream at Franklin, MD. For this study, values > 0.38 indicate extreme floods, Qmax/Q100 values between 0.38 and to 0.10 are moderate floods and values < 0.10 are not floods. The ranges were derived by comparison of study gauge Qmax/Q100 with discharge recurrence intervals for the period of record. Every basin reports at least one extreme or nearly extreme flood due to Isabel while basins report moderate floods at best to the 2004 storms. Extremes due to Isabel, however, are not outliers in the gauges' discharge distributions because ratios Qmax/Q100 are ≤ 0.40 rather than ≥ 1.

In this study, runoff volumes ((Qt - Qps) / D.A.) are a more robust measure of flood response than Qmax/D.A. and Qmax/Q100 because runoff volume ((Qt - Qps) / D.A.) quantifies the distribution of discharges throughout the watershed and is the most representative of overall watershed flood response. Qa and Smc are representations of the overall state of surface conditions prior to a storm event. The latter two measures report at-a-point flood responses, which can be perturbed by basin characteristics. Contrasts between runoff volume, Qa and Smc are most useful because the purpose of this study is to evaluate the flood response to changes in Qa as a result of a series of tropical storms in September 2004 and compare antecedent moisture conditions and flood responses to the series of storms in 2004 and flood responses to a solitary tropical storm in 2003.

The hydrological characteristics in September 2004 provide an opportunity to define when antecedent moisture fails to be important to flood response. These characteristics include initial dry surface conditions, the moderate rainfall associated with each storm event, and the lack of extreme discharge events results from Hurricanes Frances, Ivan and Jeanne in 2004. When floods are extreme, discharges are high enough that the effect of antecedent moisture on flooding is minimal (Wood *et al.*, 1990 and Sturdevant-Rees *et al.*, 2001).

Runoff can also be directly compared to rainfall because the dimensions are the same and it provides a robust measure of how the watershed is affected by a rainfall event. The correlation between runoff and precipitation during the study period is on the low end of statistical significance; as on average, the correlation coefficient (r) is ~0.60 (Figure 40; Table 8). A correlation coefficient of ~0.60 implies an influence from surface conditions, groundwater recharge rates and evapotranspiration.

This is not observed in the sub-basin responses to Frances and Ivan. In general, runoff is higher as a result of Isabel than as a result of Ivan, despite the more saturated conditions prior to Ivan and similar cumulative rainfall for the month is prior to these two events. After Jeanne, cumulative rainfall is even higher in comparison to Isabel but, on average runoff is lower. There is also similarity in the heterogeneity of responses to these two latter events because the upper and lower limits of runoff values narrow with an increase in drainage basin area (Figure 41). Possible explanations for these conditions are discussed below.

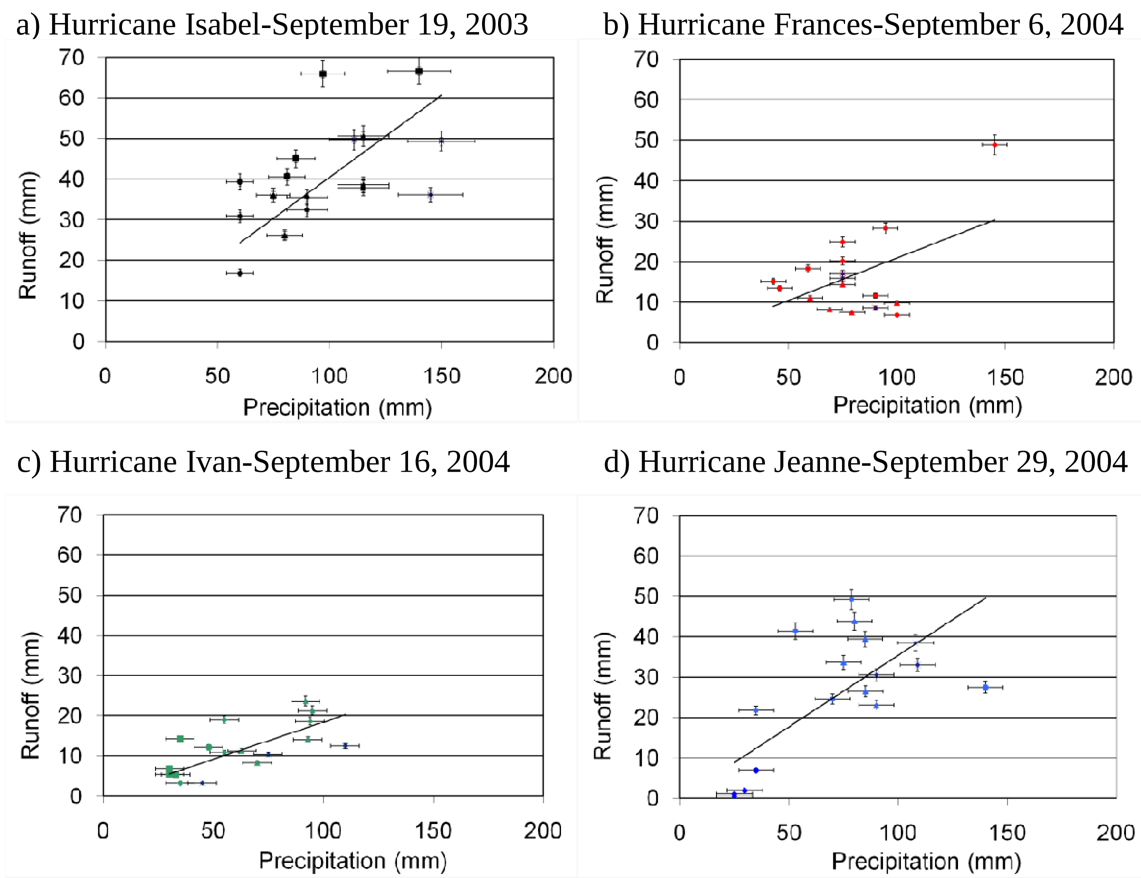


Figure 40. Contrast in runoff versus precipitation – Hurricanes Isabel, Frances, Ivan and Jeanne. Rainfall and precipitation are used interchangeably.

Table 10. Regression equations and coefficients of variation - precipitation versus runoff

Storm	Equation (number)	R^2
Isabel	Runoff (mm) = 0.44 rainfall (mm) (32)	0.33
Frances	Runoff (mm) = 0.16 rainfall (mm) (33)	0.20
Ivan	Runoff (mm) = 0.18 rainfall (mm) (34)	0.09
Jeanne	Runoff (mm) = 0.33 rainfall (mm) (35)	0.44
Note: The intercept is set at zero to produce the equations.		

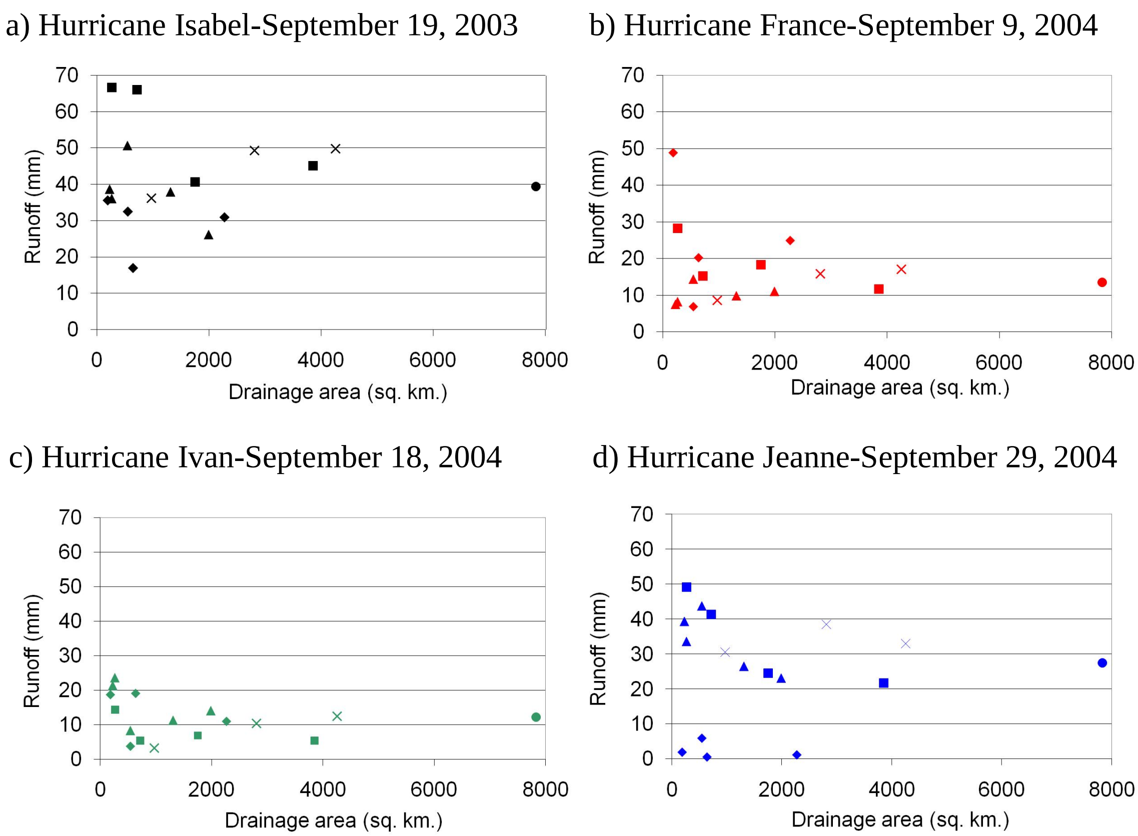


Figure 41. Runoff versus drainage area. There is no correlation between runoff amount and drainage area for any storm. Smaller drainage basins show greater variation in runoff response than larger basins. Individual sub-basin gauges are identified by diamonds = North Branch, squares = South Branch, triangles = North Fork Shenandoah, xs = South Fork Shenandoah, circles = Shenandoah at Millville, WV.

Two observations could immediately be made from the plots of runoff as a function of drainage area (Figure 41). One is that runoff due to Isabel and Jeanne are similar and the other is that many of the sub-basins respond to Isabel and Jeanne in a similar fashion. This is not observed in the sub-basin responses to Frances and Ivan. In general, runoff is higher as a result of Isabel than as a result of Ivan, despite the more saturated conditions prior to Ivan and similar cumulative rainfall for the month is prior to these two events. After Jeanne, cumulative rainfall is even higher in comparison to Isabel but, on average runoff is lower. There is also similarity in the heterogeneity of responses to these two latter events because the upper and lower limits of runoff values narrow with an increase in drainage basin area (Figure 41, Table 10). Possible explanations for these conditions are discussed below.

Prior to Hurricane Isabel 2003, the ground surface is relatively moist and rainfall intensity and amount is sufficient to generate moderate to significant floods. Hurricane Frances 2004, generated rainfall similar to Isabel, but Frances related rainfall distribution is much more complex and surface conditions were much drier prior to Frances rainfall. Isabel and Ivan, however, had very similar surface moisture conditions, but very different runoff responses, probably due to lower rainfall intensity during Ivan. For Hurricane Jeanne 2004, cumulative rainfall is higher than cumulative rainfall for Hurricane Isabel 2003 but the runoff response as a function of drainage area is about the same for Isabel and Jeanne.

Hydrograph Rise-Time

The precipitation gauges and streamflow gauges at Star Tannery, VA/Winchester, VA, Moorefield, WV/Moorefield, WV and Romney, WV/Springfield, WV are in close proximity to one another and record data every hour or less. The lag-to-peak response and estimated rise times at those two locations were therefore used to get an idea of how well rise time represented lag-to- peak time.

At the three locations mentioned above, where both rainfall/discharge centroid lag-to-peak and rise time could be calculated, centroid lag-to-peak times and rise times differ depending upon distance between the rainfall and streamflow gauging stations. At Moorefield, where the rainfall and stream gauges are in closest proximity, lag-to-peak and rise times are similar, both times increase or decrease together. That is not so for the other two locations where the rainfall gauges are upstream from the discharge gauges.

Since the sample size is small and from successive events, a statistical analysis of the differences was not undertaken, but results from the Moorefield, WV gauges were considered similar enough to conclude rise time was a fairly good measure of streamflow response. Rise time results are summarized in Figure 42, Table 11 and Appendix Table 20.

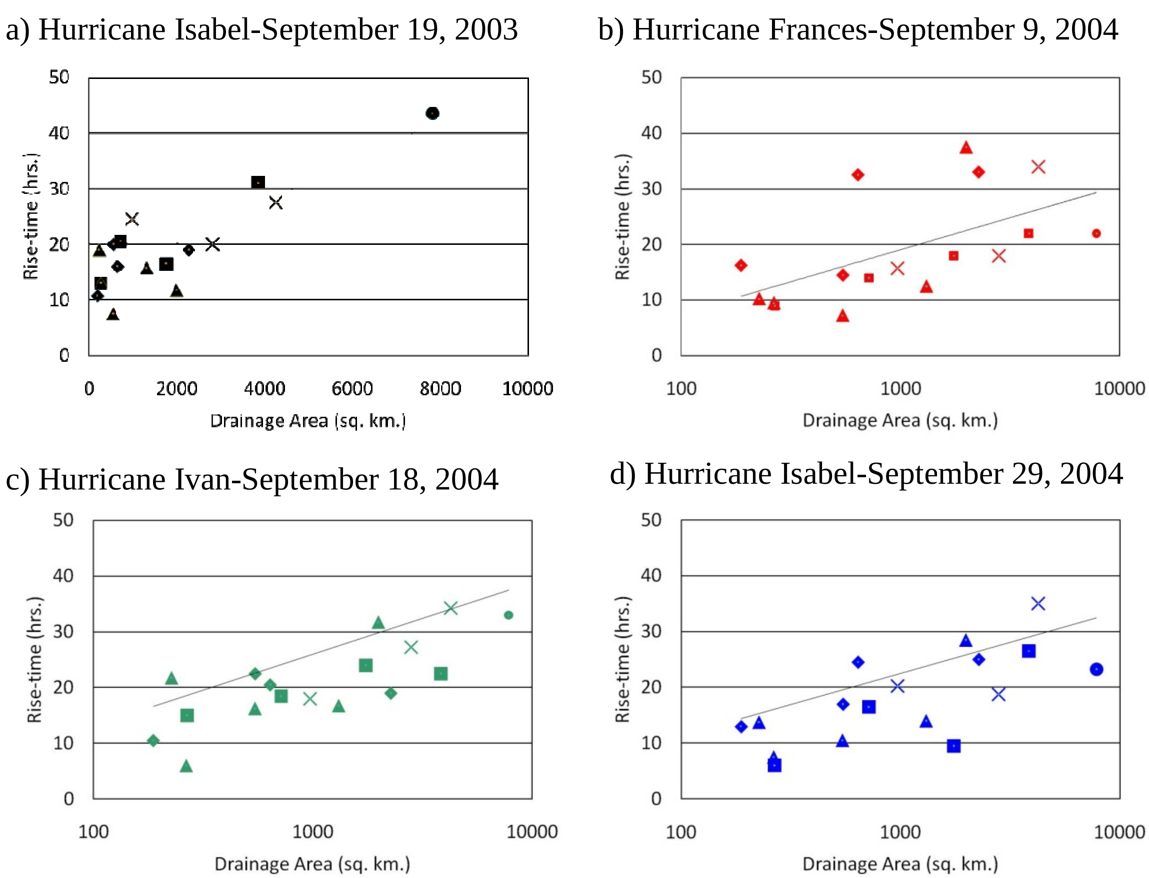


Figure 42. Rise time (T_i-T_p) v. drainage area. The relationship between rise time and drainage basin area after Isabel 2003 is linear but the three storms in 2004 yield a log-linear relationship between drainage basin area and rise time. Individual sub-basin gauges are identified by diamonds = North Branch, squares = South Branch, triangles = North Fork Shenandoah, xs = South Fork Shenandoah, circles = Shenandoah at Millville, WV.

Table 11. Rise time-drainage area regression equations

Storm	Equation (number)	R^2
Isabel	$y = 0.0037x + 12.8$ (36)	0.73
	$y = 5.4\ln(x) + 17.9$ (37)	0.49
Frances	$y = 0.0021x + 15.4$ (38)	0.19
	$y = 5.0\ln(x) + 15.6$ (39)	0.35
Ivan	$y = 0.0027x + 16.2$ (40)	0.52
	$y = 5.2\ln(x) + 15.2$ (41)	0.60
Jeanne	$y = 0.0024x + 14.9$ (42)	0.34
	$y = 5.0\ln(x) + 16.6$ (43)	0.49

On average, rise-time increases with drainage area when all basins are considered (Figure 42). The relationship between rise time and drainage basin area varies depending upon individual storm s. The strength of correlation between the two variables also varies with storm event (Table 11). The relationship between drainage area and lag time is linear for Isabel 2003. The other three storms are better fitted to a log-linear curve. In general, storm-average rise time varied by < 2 hours for each station (Appendix Table 20). During Frances (early-September, 2004) and Jeanne (late-September, 2004) the longest rise times were reported in the upstream North Branch basin.

Hydrologic response of the watershed as a function of surface conditions

To evaluate the hydrologic response of the watershed due to surface conditions, Qa and Smc were plotted against dimensionless rainfall-runoff ratios. The average runoff ratios for each storm fell within a fairly narrow range for all storms but Jeanne (Appendix Table 20). All but Ivan show heterogeneity in rainfall-runoff ratios, (Figure 43). The average runoff/rainfall ratio is ~0.40, which is higher than average for the Potomac River Basin, where the ratio is usually 0.08-0.16 (Woodruff and Hewlett, 1970). The average ratio is closely matched by Jeanne with an average of approximately 0.35. Frances and

Ivan have smaller ratios of ~0.20. This suggests that there is an expansion of contributing drainage areas that generate runoff during the larger storms or a more substantial groundwater contribution to runoff but the upper and lower bounds adjust with the mean runoff coefficient.

Changes in the runoff ratio suggest different proportions of the sub-basins are contributing runoff due to variations in rainfall. Expansion of runoff is most often associated with changes in soil moisture (Dunne *et al*., 1975). With regard to the increase in groundwater contribution, this can occur due to piezometric head adjustments, which has been observed using oxygen isotopes, etc. in large watersheds and measured directly in small watersheds (Bonnel, 1993).

The relationship between Smc and runoff/rainfall ratios as a whole reveals a bounding curve defined by data from the September 2003 and 2004 hurricanes (Figure 44). The relationship between these two ratios is not linear, but they suggest that when Q90/QA is less than 0.30, rainfall ratios vary more than when Q90/QA ratios are higher than 0.30. The runoff-rainfall ratio due to Isabel shows a negative trend and so does the response to Frances. The negative trends were tested for statistical significance by regression analysis as individual data sets and as a combined data set. There was no statistical significance ($r = 0.20$) based on any of the three analyses. Interestingly, Jeanne reports higher rainfall-runoff ratios than Isabel even though the streamflow response was not as impressive in terms of flood magnitude.

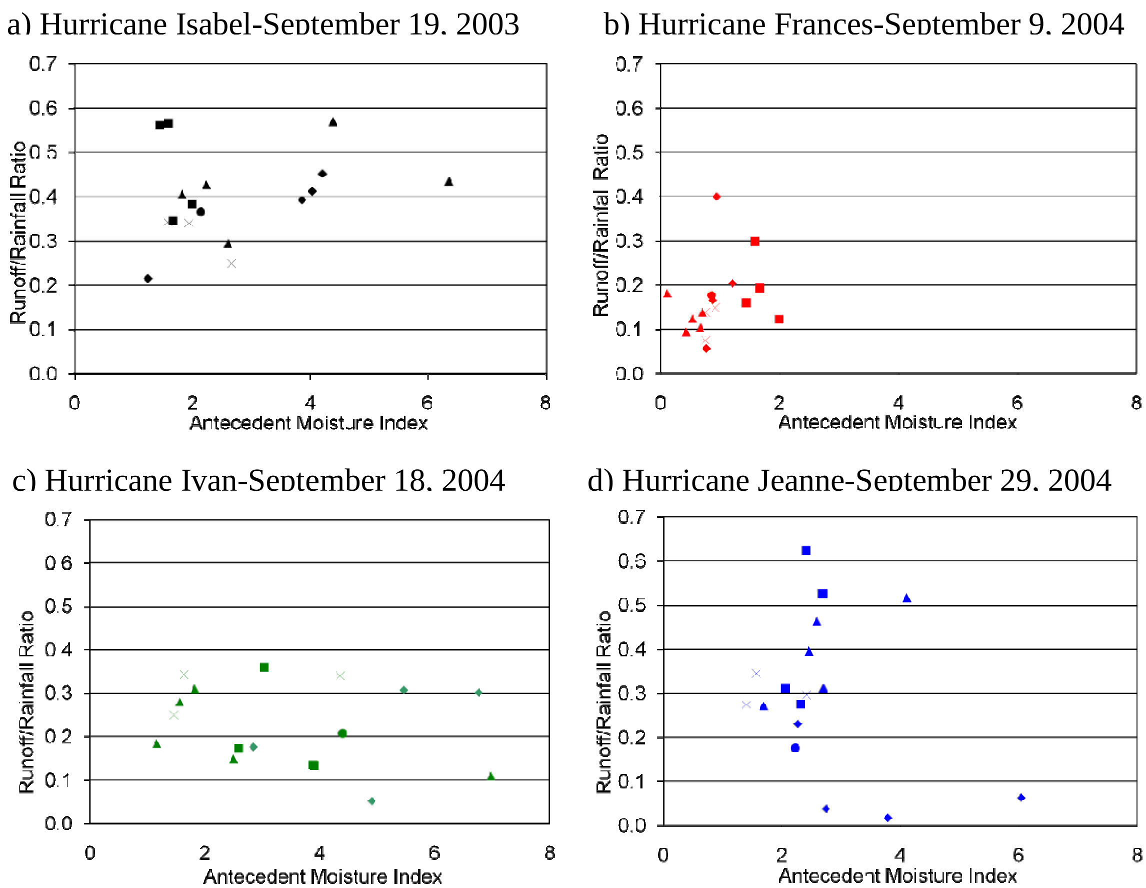


Figure 43. Rainfall-runoff ratios versus antecedent moisture (Q_{ps}/Q_m). Individual sub-basin gauges are identified by diamonds = North Branch, squares = South Branch, triangles = North Fork Shenandoah, xs = South Fork Shenandoah, circles = Shenandoah at Millville, WV.

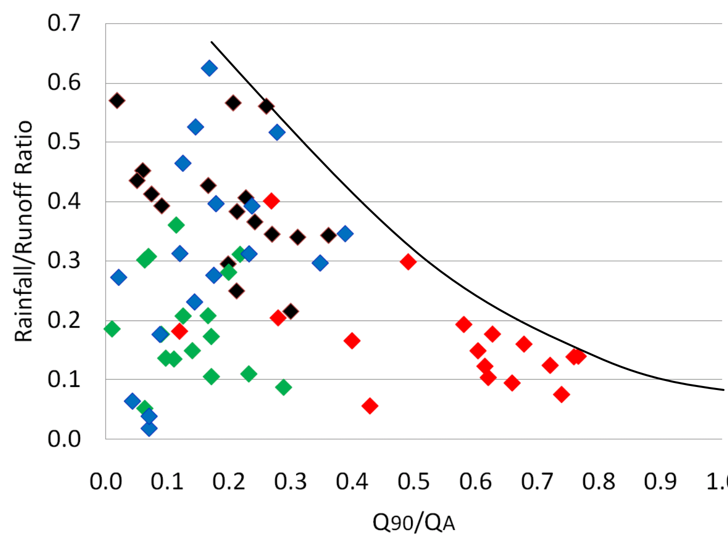


Figure 44. Rainfall-runoff versus soil moisture storage capacity index (Q90/QA). Isabel 2003 (black), Frances (red), Ivan (green), Jeanne (blue)

DISCUSSION AND CONCLUSIONS

Results from this endeavor indicate that when no other meteorological circumstances interact with tropical storm moisture, a single intense storm that directly crosses the basin exacts more influence on discharge than a series of less intense storms. Even though surface wetness and soil storage capacity were similar prior to Isabel and Ivan, the latter storm with smaller rainfall totals proved to have little impact on flood discharges in the study area. Due to a combination of rainfall and higher antecedent conditions, the last of the three storms in September of 2004 was able to generate a response in some sub-watersheds that was similar to that of the 2003 event. Hydrograph shapes suggest the areal distribution of rainfall affected discharge responses in 2004.

Substrate conditions, regulation and land use influences affect flood responses in various parts of the basin, particularly during less intense events. Even though surfaces are wet and storage capacity is low based on the index values prior to Jeanne, runoff is negligible in the North Branch due to this event, while the South Branch Potomac River and North Fork Shenandoah River sub-basins show significant responses. The absence of field observations is an obvious drawback to more concrete conclusions, although these data are difficult to obtain in large watersheds such as the Potomac River Basin. This research points to the need for continued combined study of meteorological and surface conditions that vary streamflow.

Qa and Smc are representations of the overall state of surface conditions prior to a storm event. The two measures report at-a-point flood responses, which can be perturbed by basin characteristics. Contrasts between runoff volume, Qa and Smc are most useful because the purpose of this study is to evaluate the flood response to changes in Qa as a result of a series of tropical storms in September 2004 and to compare antecedent moisture conditions and flood responses to the series of storms in 2004 and flood responses to a solitary tropical storm in 2003.

Chapter 5. Discussion and Conclusions

In this study I assessed the meteorological causes of extreme floods, the relationship between climate, tropical storms and floods and the effect of sequential tropical storms on flood response in the Potomac River Basin.

As a result of this study it is now understood that extreme flood-generating storms occur at distinct times of the year as tropical storms and winter season storms generate the largest floods in the basin. Of the two storm types, tropical storms generate the largest flood events in most parts of the basin, but winter season storms generate more systemic flood responses (See scaling relationships in Chapter 1.). Tropical–storm related floods are also up to ten times larger than bankfull floods while winter season storm related floods are only six times or less larger. It is also now known that tropical storms that generate floods tend to occur in the latter part of hurricane season. As a consequence of their late season occurrence, sequential storms are sometimes closely spaced, which can affect flood response.

Floods generated by tropical storms are an important part of the extreme flood distribution in the Potomac River Basin. As such, during their occurrence, drastic alteration to stream channels and landscape may be taking place as sediment is transported and deposited downstream and preferred surface storage locations are exploited. Better understanding of the influence of tropical storms on flood response will aid in the understanding of the influence of tropical storms on landscape alteration.

Other findings from this study were the following.

1. A statistically significant relationship exists between the monthly Pacific Decadal Oscillation Index and the ability of tropical storms arriving in the Potomac River Basin to generate floods.
2. There is a possibility that the interaction between the Atlantic Multidecadal Oscillation and Pacific Decadal Oscillation affects Potomac River Basin floods as the two factors are known to effect precipitation in the Northeast.
3. A disproportionate number of the storms that make landfall in North Carolina enter the Potomac River Basin. However, these storms are not the most effective at generating floods. Storms that make landfall in Florida are more likely to generate significant floods. This is in contrast to the rainfall distribution model proposed by Tuleya *et al*., 2007.

These findings show watershed-scale flood responses can be linked to climate-scale factors and possibly aid in the prediction of floods and long-term water resource availability.

Finally, if sequential tropical storms are closely spaced (less than 10 days apart), one event can establish antecedent moisture conditions and occupy moisture storage space that influences flood response when another storm occurs; flood responses were always heterogeneous as the earlier portion of the study indicated and; in general, runoff ratio increased with sequential events. These findings indicate that even within single storm type variations in delivery can effect response. Another suggestion is that evapotranspiration rates may be high enough to mute the flood response to low precipitation tropical storms even when surfaces are wet and soil moisture storage capacity is low.

Appendix

Table 12. Selected Streamflow Gauges.

†Map ID No.	Gauge Number	Site Name	‡Period of Discharge Record†	Drainage Area (sq. km)	Elev. (m.a.s.l)	Date of Maximum Discharge
1	1596500	Savage River Near Barton, MD	1949	127	489	10/15/1954
2	1598500	North Branch Potomac River At Luke, MD	1900-1906, 1924, 1936, 1950	1,052	288	10/15/1954
3	1599000	*Georges Creek At Franklin, MD	1931	188	292	3/17/1936
4	1600000	North Branch Potomac River At Pinto, MD	1924, 1936	1,544	198	3/29/1994
5	1601500	*Wills Creek Near Cumberland, MD	1930	640	195	1/19/1996
6	1603000	*North Branch Potomac River Near Cumberland, MD	1889, 1924, 1930	2,271	178	3/17/1936
7	1604500	*Patterson Creek Near Headsville, WV	1939	546	190	8/18/1955
8	1606500	*South Branch Potomac River Near Petersburg, WV	1878, 1924, 1929	1,751	294	11/5/1985
9	1607500	*South Fork South Branch Potomac River At Brandywine, WV	1878, 1896, 1944	267	475	6/17/1969
10	1608000	*South Fork South Branch Potomac River Near Moorefield, WV	1924, 1929	717	263	11/5/1985
11	1608500	*South Branch Potomac River Near Springfield, WV	1878, 1900-1906, 1929	3,849	171	11/5/1985
12	1610000	Potomac River At Paw Paw, WV	1936, 1939	8,104	149	3/18/1936
13	1613000	Potomac River At Hancock, MD	1889, 1924, 1929, 1933	10,593	117	3/18/1936
14	1614500	Conococheague Creek At Fairview, MD	1889, 1924, 1929	1,279	119	6/23/1972
15	1616500	Opequon Creek Near Martinsburg, WV	1906, 1936, 1948	707	108	1/20/1996

Table 12. Selected Streamflow Gauges.

†Map ID No.	Gauge Number	Site Name	‡Period of Discharge Record†	Drainage Area (sq. km)	Elev. (m.a.s.l)	Date of Maximum Discharge
16	1619500	Antietam Creek Near Sharpsburg, MD	1928	728	95	7/20/1956
17	1625000	*Middle River Near Grottoes, VA	1924, 1928	971	324	9/7/1996
18	1628500	*South Fork Shenandoah River Near Lynnwood, VA	1931	2,808	309	9/7/1996
19	1631000	*South Fork. Shenandoah River At Front Royal, VA	1900-1905, 1931	4,253	143	10/16/1942
20	1632000	*North Fork. Shenandoah River At Cootes Store, VA	1924, 1926	544	321	9/6/1996
21	1633000	*North Fork Shenandoah River At Mount Jackson, VA	1943	1,311	256	9/6/1996
22	1634000	*North Fork Shenandoah River Near Strasburg, VA	1926	1,989	151	9/7/1996
23	1634500	*Cedar Creek Near Winchester, VA	1936, 1938	264	197	10/15/1942
24	1635500	*Passage Creek Near Buckton, VA	1933	227	160	9/6/1996
25	1636500	*Shenandoah River At Millville, WV	1870, 1896-1908, 1924, 1929	7,827	89	10/16/1942
26	1637500	Catoctin Creek Near Middletown, MD	1948	173	117	10/9/1976
27	1638500	Potomac River At Point Of Rocks, MD	1889, 1895	24,996	61	3/19/1936
28	1639500	Big Pipe Creek At Bruceville, MD	1948	264	104	9/26/1975
29	1643000	Monocacy River At Jug Bridge Near Frederick, MD	1889, 1930	2,116	71	6/22/1972
30	1644000	Goose Creek Near Leesburg, VA	1889, 1910-1912, 1930	860	76	6/22/1972
31	1646000	Difficult Run Near Great Falls, VA	1935	150	46	6/22/1972
32	1646500	Potomac River Near Wash, DC Little Falls Pumping Station	1931	29,940	12	3/19/1936
33	1648000	Rock Creek At Sherrill Drive Washington, DC	1930	161	45	6/22/1972

Table 12. Selected Streamflow Gauges**.**

†Map ID No.	Gauge Number	Site Name	‡Period of Discharge Record†	Drainage Area (sq. km)	Elev. (m.a.s.l)	Date of Maximum Discharge
34	1649500	Northeast Branch Anacostia River At Riverdale, MD	1933, 1939	189	4	6/22/1972
35	1651000	Northwest Branch Anacostia River Near Hyattsville, MD	1933, 1940	128	5	6/22/1972
36	1654000	Accotink Creek Near Annandale, VA	1947	61	58	6/22/1972
37	1661500	Saint Marys River At Great Mills, MD	1947	62	3	8/20/1969

Note: †Map ID Numbers are for the purpose of locating a gauge on Figure 1. * Study gauges used in Chapter 4. ‡Breaks in the record are indicated by a comma. A single year at the beginning of a series indicates a single year of operation. A single year at the end of a series indicates the gauge has been in operation continuously from the year shown to present. Shorter spans of operation are indicated by a dash between two years.

Table 13. Significant floods in the Potomac River Basin 1889-2003

Date	Affected area based on gauge record††	R. I.	Comments	Number ##
June, 1889	Potomac River basin	Unknown	Un-named hurricane§§	7/7
Mar. 26, 1913	Shenandoah River basin	>100	Frontal storm causing heavy rainfall§§	2/2
Mar. 28-30, 1924	Potomac River basin.	20 to >100	Rain on snow#	5/6
Aug. 23-24, 1933	Potomac River basin	10 to >100	Un-named hurricane#	8/23
Mar. 17-19, 1936	Potomac River basin.	20 to >100	Rain on snow and frozen ground#	23/26
Apr. 26, 1937	Western Potomac River basin	2 to >100	Nor'easter§§	18/23
Oct. 15-16, 1942	Shenandoah River basin	10 to >100	Un-named hurricane†	23/29
June 17, 1949	Potomac River basin	>50	Severe Thunderstorm	9/36
Oct. 14-16, 1954	North Branch Potomac	25 to >100	Hurricane Hazel#	15
Aug. 12-13, 1955	W. Potomac River basin and mainstem	5 to 10	Hurricane Diane ††	18
Jul. 20, 1956	Eastern Potomac River basin	1 to >100	Nor'easter§§	4
Aug. 20, 1969	Potomac River Basin	2 to >100	Hurricane Camille††	9
Jun 21-23, 1972	Potomac River Basin	50 to >100	Hurricane Agnes#	29
Sep. 23-26, 1975	Monocacy River basin	10 to >100	Hurricane Eloise#	17
Oct. 9, 1976	Potomac River basin	2 to >100	Frontal storm causing heavy rainfall§	27
Feb. 26, 1979	Great Mills, Potomac River mainstem	2 to >10	Rapid snowmelt over frozen ground‡	3
Sept. 5-6, 1979	Rock Creek	50 to >100	Hurricane David#	10
Feb. 15, 1984	Potomac River basin	2 to >40	Frontal storm causing heavy rainfall§	18
Nov. 4-7, 1985	Potomac River basin.	2 to >100	Hurricane Juan ‡	24
May 6, 1989	SE Potomac River basin	1 to 40	Severe thunderstorms§	17
Mar. 29, 1994	Shenandoah River basin	2 to 10	Frontal system causing heavy rainfall§§	30
Jan. 19-20, 1996	Potomac River basin	2 to >100	Rain on snow*	32
Sept. 6-8, 1996	Potomac River basin	4 to >100	Hurricane Fran*	32
September 19, 2003	Potomac River Basin	2 to 10	Hurricane Isabel††	**22

Note: Table constructed from data provided by #Paulson et al. (1991), *Doheny (1997); ‡Perry et al. (2001); †Sturdevant-Rees et al. (2001), §NOAA Storm Data (var. years), §§Monthly Weather Review (var. years), ††Rhodes (this study). ** Number of gauges reporting Qpd. ##Fractions = number of gauges reporting per total number of study gauges in operation.

Table 14. Select Tropical Storms and Their Character

Landfall Observations					Basin Observations			
Date	Loca-tion	Atm. Press. (mb)	Wind Speed (kmh)	Storm Cat.	Date	Atm. Press. (mb)	Wind Speed (kmh)	Storm Cat.
8/31/1952	SC	ND	169	H2	9/1/1952	ND	73	TS
8/14/1953	NC	987	169	H2	8/14/1953	ND	121	H1
10/15/1954	SC	937	202	H3	10/15/1954	970	145	E
8/12/1955	NC	965	129	H1	8/13/1955	969	97	TS
8/17/1955	NC	986	137	H1	8/18/1955	1001	97	TS
9/28/1956	LA	985	137	H1	9/28/1956	ND	65	E
6/27/1957	LA	946	234	H4	6/29/1957	ND	73	E
7/9/1959	SC	ND	121	H1	7/10/1959	ND	65	TS
9/29/1959	SC	951	194	H3	10/1/1959	ND	56	E
7/30/1960	FLG	ND	81	TD	7/30/1960	ND	48	TS
9/10/1960	FLG	938	226	H4	9/12/1960	ND	177	H2
9/16/1967	NC	ND	65	TS	9/16/1967	990	113	TS
8/17/1969	MS	909	306	H5	8/20/1969	ND	48	TD
8/27/1971	NC	998	97	TS	8/28/1971	993	105	TS
9/30/1971	NC	984	121	H1	10/3/1971	ND	56	TD
6/19/1972	FLG	986	121	H1	6/22/1972	ND	97	TS
9/23/1975	FLG	998	202	H3	9/24/1975	1004	40	E
7/14/1979	LA	991	121	H1	7/14/1979	1010	40	TD
7/24/1979	TX	1002	81	TS	7/29/1979	1011	24	TD
9/5/1979	FLG	970	161	H2	9/5/1979	987	73	TS
9/14/1979	AL	946	210	H4	9/14/1979	997	65	TS
7/1/1981	VA	1000	97	TS	7/1/1981	1006	56	TD
9/30/1983	VA	1009	105	TS	9/30/1983	1010	73	TS
7/25/1985	FLG	1002	121	H1	7/25/1985	1002	56	TD
8/19/1985	LA	988	145	H1	8/19/1985	1012	48	E
9/27/1985	NC	942	145	H2	9/27/1985	942	169	H2
10/29/1985	LA	975	129	H1	11/5/1985	NA	NA	NA
8/18/1986	FLG	991	121	H1	8/18/1986	1012	121	H1
8/28/1988	GA	1005	81	TS	8/29/1988	1009	40	TD
9/25/1992	VA	1007	105	TS	9/25/1992	1007	105	TS
8/17/1994	FLG	1000	97	TS	8/17/1994	1011	24	TD
7/12/1996	NC	974	169	H2	7/13/1996	993	113	TS
9/6/1996	NC	954	185	H3	9/7/1996	995	56	TD
10/8/1996	FLG	983	113	TS	8/10/1996	986	73	E

Table 14. Select Tropical Storms and Their Character

Landfall Observations					Basin Observations			
Date	Loca-tion	Atm. Press. (mb)	Wind Speed (kmh)	Storm Cat.	Date	Atm. Press. (mb)	Wind Speed (kmh)	Storm Cat.
7/24/1997	LA	986	121	H1	7/24/1997	1000	73	TS
9/4/1999	NC	986	113	TS	9/6/1999	1008	40	TD
9/16/1999	NC	956	169	H2	9/16/1999	967	113	TS
9/19/2000	FLG	989	113	TS	9/19/2000	1010	40	E
9/24/2000	FLG	1001	97	TS	9/24/2000	1008	81	TS
6/6/2001	TX	1002	105	TS	6/6/2001	1006	48	SD
9/18/2003	NC	956	169	H2	9/19/2003	969	121	H1
8/12/2004	FLG	1002	81	TS	8/12/2004	1008	48	TD
8/13/2004	FLG	947	234	H4	8/15/2004	1012	73	E
8/29/2004	SC	986	121	H1	8/31/2004	1001	65	TS
9/5/2004	FLG	958	177	H2	9/9/2004	1001	48	E
9/16/2004	AL	943	194	H3	9/19/2004	998	40	TD
9/26/2004	FLG	941	194	H3	9/29/2004	999	48	TD

Note: *H3 = category 3 hurricane, E=extra-tropical storm, SD= sub-tropical depression, TS=tropical storm, TD=tropical depression.

Table 15.Select Climate Indices

Date	Atlantic Multidecadal Index	El Nino 3.4 Index	North Atlantic Oscillation Index	Pacific Decadal Oscillation Index	Quasi-Biennial Oscillation Index
8/31/1952	0.427	26.83	-0.28	-0.6	-8.15
8/14/1953	0.368	27.65	-0.71	0.74	-1.21
10/15/1954	0.013	25.55	0.6	-0.94	-10.35
8/12/1955	0.293	26.39	1.07	-2.35	7.2
8/17/1955	0.293	26.39	1.07	-2.35	7.2
9/28/1956	-0.073	25.98	0.24	-1.16	-14.67
6/27/1957	-0.096	28.13	-0.72	0.57	3.21
7/9/1959	-0.034	27.37	0.74	0.44	3.15
9/29/1959	0.151	26.04	0.88	-0.62	11.69
7/30/1960	0.346	27.35	0.35	0.64	-13.86
9/10/1960	0.361	26.9	0.39	-0.38	-16.01
9/16/1967	-0.136	26.04	0.93	-1.24	-6.06
8/17/1969	0.123	27.28	-1.45	0.1	9.78
8/27/1971	-0.318	26.64	1.55	-2.2	8.34
9/30/1971	-0.335	25.88	0.39	0.21	8.47
6/19/1972	-0.437	28.36	0.88	-1.57	-10.7
9/23/1975	-0.354	26.41	1.56	-1.02	4.47
7/14/1979	0.146	27.76	0.83	0.17	-21.27
7/24/1979	0.146	27.76	0.83	0.17	-21.27
9/5/1979	0.061	26.69	1.01	0.52	-22.7
9/14/1979	0.061	26.69	1.01	0.52	-22.7
7/1/1981	-0.019	27.41	-0.45	1.69	-3.49
9/30/1983	-0.114	26.53	-1.12	1.85	-7.75
7/25/1985	-0.08	26.86	1.22	0.18	11.1
8/19/1985	-0.106	26.69	-0.48	1.07	11.08
9/27/1985	-0.23	26.5	-0.52	0.81	11.72
10/29/1985	-0.201	26.19	-0.67	0.29	11.45
8/18/1986	-0.199	27.37	-1.09	1.38	-9.6
8/28/1988	0.166	28.8	0.04	0.64	-2.58
9/25/1992	-0.335	26.64	-0.44	1.44	1.3
8/17/1994	-0.183	27.35	0.38	0.06	-27.02
7/12/1996	-0.081	27.32	0.67	1.1	-23.93
9/6/1996	0.04	26.56	-0.86	-0.14	-26.02
10/8/1996	-0.062	27.09	1.02	0.77	-25.85
7/24/1997	0.058	28.94	0.34	2.76	14.85
9/4/1999	0.366	25.59	0.39	-0.96	11.18

Table 15.Select Climate Indices

Date	Atlantic Multidecadal Index	El Nino 3.4 Index	North Atlantic Oscillation Index	Pacific Decadal Oscillation Index	Quasi-Biennial Oscillation Index
9/16/1999	0.366	25.59	0.36	-0.96	11.18
9/19/2000	0.155	26.72	-0.21	-1.19	-15.52
9/24/2000	0.155	26.72	-0.21	-1.19	-15.52
6/6/2001	0.038	27.6	-0.02	-0.3	-23.31
9/18/2003	0.481	26.85	0.01	0.88	-22.51
8/12/2004	0.286	27.69	-0.48	0.85	8.82
8/13/2004	0.286	27.69	-0.48	0.85	8.82
8/29/2004	0.286	27.69	-0.48	0.85	8.82
9/5/2004	0.373	27.54	0.38	0.85	7.22
9/16/2004	0.373	27.54	0.38	0.85	7.22
9/26/2004	0.373	27.54	0.38	0.85	7.22

Table 16. Estimated Annual Frequency of Tropical Storms and Hurricaes in the Potomac River Basin

		S.E.	BCCL 0.5	BCCL 0.95
Named Storms				
Min.	0			
Mean	0.93	0.17	0.68	1.24
Variance	1.46	0.48	0.9	2.64
Max.	6			
Hurricanes				
Min.	0			
Mean	0.69	0.14	0.47	0.92
Variance	1.1	0.39	0.64	2.08
Max.	5			
Tropical Storms				
Min.	0			
Mean	0.26	0.06	0.16	0.35
Variance	0.23	0.06	0.17	0.39
Max.	2			

Note: S.E. = standard error, BCCL = bias corrected confidence limit after bootstrapping.

Table 17. Storm Effectiveness

Storm Name	Date	Effective Storm*	Areal Extent
Able	8/31/1952	y	local
Barbara	8/14/1953	n	
Carol	8/31/54	Removed from set	NA
Hazel	10/15/1954	y	subregional
Connie	8/12/1955	y	local
Diane	8/17/1955	y	regional
Flossy	9/28/1956	y	local
Audrey	6/27/1957	n	
Cindy B	7/9/1959	n	
Gracie	9/29/1959	y	local
Brenda	7/30/1960	y	single
Donna	9/10/1960	n	
Doria1 B	9/16/1967	n	
Camille	8/17/1969	y	subregional
Doria	8/27/1971	y	basinwide
Ginger B	9/30/1971	n	
Agnes B	6/19/1972	y	regional
Eloise	9/23/1975	y	regional
Belle	9/8/1976	Removed from set	NA
Bob	7/14/1979	n	
Claudette	7/24/1979	n	
David	9/5/1979	y	subregional
Frederic	9/14/1979	n	
Bret	7/1/1981	n	
Dean	9/30/1983	n	
Bob 2	7/25/1985	n	
Danny	8/19/1985	n	
Henri	9/23/1985	Removed from set	NA
Gloria	9/27/1985	y	single
Juan B	10/29/1985	y	regional
Charley B	8/18/1986	y	single
Chris	8/28/1988	n	
Bob	8/19/1991	Removed from set	NA
Daniell	9/25/1992	n	
Beryl	8/17/1994	y	local
Bertha	7/12/1996	y	single
Fran	9/6/1996	y	regional
Josephine	10/8/1996	n	
Danny B	7/24/1997	n	

Table 17. Storm Effectiveness

Storm Name	Date	Effective Storm*	Areal Extent
Dennis	9/4/1999	y	subregional
Floyd	9/16/1999	y	basinwide
Gordon	9/19/2000	y	local
Helene	9/24/2000	y	single
Allison	6/6/2001	y	basinwide
Isabel	9/18/2003	y	regional
Bonnie	8/12/2004	n	
Charley2	8/13/2004	n	
Gaston B	8/29/2004	n	
Frances	9/5/2004	y	basinwide
Ivan	9/16/2004	n	
Jeanne	9/26/2004	y	regional
Note: *Effective storm = a tropical storm that is able to generate an annual peak discharge in the Potomac River Basin			

A.1 Landfall Character Factor Regression Analysis

Location	W.Speed	Pressure
Min.: 1.000	Min.: 64.37376	Min.: 909.0
1st Qu.: 4.000	1st Qu.:110.64240	1st Qu.: 955.5
Median: 4.500	Median:132.77088	Median: 985.5
Mean: 5.659	Mean:145.20672	Mean: 976.0
3rd Qu.: 8.000	3rd Qu.:170.99280	3rd Qu.: 998.5
Max.:12.000	Max.:305.77536	Max.:1009.0

Call: glm(formula = Qtap ~ Location + W.Speed + Pressure, family = binomial, data = winds)
Deviance Residuals:

Min	1Q	Median	3Q	Max
-1.566882	-1.124564	-0.0003850006	1.154493	1.448494

Coefficients:

	Value	Std. Error	t value
(Intercept)	48.33482642	39.41089382	1.2264331
Location	-0.01193560	0.09283167	-0.1285725
W.Speed	-0.01709478	0.01827389	-0.9354757
Pressure	-0.04690829	0.03789783	-1.2377565

(Dispersion Parameter for Binomial family taken to be 1)
Null Deviance: 60.99695 on 43 degrees of freedom
Residual Deviance: 58.77788 on 40 degrees of freedom
Number of Fisher Scoring Iterations: 4

A.2 Climate Factor Regression Analysis

NI	QI	EI	PI	AI	I.Qtap
Min.:-1.45	Min.:-27.02	Min.:25.55	Min.:-2.35	Min.:-0.437	Min.:0.00
1st Qu.:-0.465	1st Qu.:-15.52	1st Qu.:26.515	1st Qu.:-0.78	1st Qu.:-0.101	1st Qu.:0.00
Median: 0.36	Median: -1.21	Median:26.86	Median: 0.29	Median: 0.061	Median:1.0000
Mean: 0.19638	Mean: -3.7566	Mean:27.002	Mean: 0.10489	Mean: 0.0680426	Mean:0.5532
3rd Qu.: 0.83	3rd Qu.: 8.645	3rd Qu.:27.54	3rd Qu.: 0.85	3rd Qu.: 0.2895	3rd Qu.:1.0000
Max.: 1.56	Max.: 14.85	Max.:28.94	Max.: 2.76	Max.: 0.481	Max.:1.0000

Call: glm (formula = I.Qtap ~ NI + QI + EI + PI + AI, family = binomial, data = climin)
Deviance Residuals:

Min	1Q	Median	3Q	Max
-2.175021	-0.8384771	0.2724965	0.7984332	1.803333

```
Coefficients:
                   Value  Std. Error    t value
(Intercept)  21.18536915 15.23763316  1.3903320
         NI  -0.90873203  0.60514170 -1.5016847
         QI  -0.03581328  0.02879085 -1.2439120
         EI  -0.76540692  0.56396692 -1.3571841
         PI  -1.40759383  0.51860933 -2.7141699
         AI   0.77030118  1.49407614  0.5155702

(Dispersion Parameter for Binomial family taken to be 1 )
    Null Deviance: 64.62291 on 46 degrees of freedom
Residual Deviance: 46.31008 on 41 degrees of freedom
Number of Fisher Scoring Iterations: 5

Correlation of Coefficients:
   (Intercept)         NI         QI         EI         PI
NI -0.1147299
QI -0.2084840   0.3716029
EI -0.9995893   0.1044799  0.2116505
PI  0.0826675   0.5519241  0.1932258 -0.0959739
AI  0.2062552   0.0179705  0.0163163 -0.2088532 -0.0769974

Analysis of Deviance Table
Binomial model
Response: I.Qtap
Terms added sequentially (first to last)
     Df Deviance Resid. Df Resid. Dev  F Value     Pr(F)
NULL                   46   64.62291
  NI  1  0.30146        45   64.32146 0.274213 0.6033389
  QI  1  0.59897        44   63.72248 0.544841 0.4646374
  EI  1  7.01369        43   56.70880 6.379841 0.0155009
  PI  1 10.13131        42   46.57749 9.215714 0.0041570
  AI  1  0.26741        41   46.31008 0.243247 0.6245024

Call: glm(formula = I.Qtap ~ EI + PI, family = binomial, data = climin)
Deviance Residuals:
       Min         1Q    Median        3Q      Max
 -2.214547 -0.8713517 0.3046688 0.8786977 1.721506

Coefficients:
                  Value Std. Error   t value
(Intercept)  16.0959060 14.4236087  1.115942
```

```
         EI  -0.5786045  0.5335333 -1.084477
         PI  -1.0750135  0.4418697 -2.432875

(Dispersion Parameter for Binomial family taken to be 1 )
    Null Deviance: 64.62291 on 46 degrees of freedom
Residual Deviance: 49.91281 on 44 degrees of freedom
Number of Fisher Scoring Iterations: 4

Correlation of Coefficients:
   (Intercept)         EI
EI -0.9996638
PI  0.2661765  -0.2759135

Analysis of Deviance Table
Binomial model
Response: I.Qtap
Terms added sequentially (first to last)
     Df Deviance Resid. Df Resid. Dev  F Value      Pr(F)
NULL                      46   64.62291
  EI  1 6.760307        45   57.86261 6.480346 0.01448675
  PI  1 7.949800        44   49.91281 7.620579 0.00838281

Call: glm(formula = I.Qtap ~ PI + EI, family = binomial, data = climin)
Deviance Residuals:
       Min         1Q    Median        3Q      Max
 -2.214547 -0.8713517 0.3046688 0.8786977 1.721506

Coefficients:
                  Value Std. Error   t value
(Intercept)  16.0959060 14.4236087  1.115942
         PI  -1.0750135  0.4418697 -2.432875
         EI  -0.5786045  0.5335333 -1.084477

(Dispersion Parameter for Binomial family taken to be 1 )
    Null Deviance: 64.62291 on 46 degrees of freedom
Residual Deviance: 49.91281 on 44 degrees of freedom
Number of Fisher Scoring Iterations: 4
Correlation of Coefficients:
   (Intercept)         PI
PI  0.2661765
EI -0.9996638  -0.2759135
```

```
Analysis of Deviance Table
Binomial model
Response: I.Qtap
Terms added sequentially (first to last)
     Df Deviance Resid. Df Resid. Dev  F Value     Pr(F)
NULL                        46   64.62291
  PI  1 13.50408        45   51.11883 12.94484 0.0008084
  EI  1  1.20603        44   49.91281  1.15608 0.2881405


Call: glm(formula = I.Qtap ~ PI, family = binomial, data = climin)
Deviance Residuals:
      Min        1Q    Median        3Q      Max
 -2.07865 -0.960018 0.2767583 0.8774427 1.733801

Coefficients:
                Value Std. Error   t value
(Intercept)  0.481127  0.3666839  1.312103
         PI -1.255469  0.4269397 -2.940624

(Dispersion Parameter for Binomial family taken to be 1 )
    Null Deviance: 64.62291 on 46 degrees of freedom
Residual Deviance: 51.11883 on 45 degrees of freedom
Number of Fisher Scoring Iterations: 4
Correlation of Coefficients:
   (Intercept)
PI -0.3758532

Analysis of Deviance Table
Binomial model
Response: I.Qtap
Terms added sequentially (first to last)
     Df Deviance Resid. Df Resid. Dev  F Value        Pr(F)
NULL                        46   64.62291
  PI  1 13.50408        45   51.11883 13.78164 0.0005635572
```

A.3 Basin Character Factor Regression Analysis

```
   Atm.Pressure      Wind.Speed       Qtap
    Min.: 942.0      Min.: 24.19355   n:16
 1st Qu.: 993.0   1st Qu.: 48.38710   y:19
```

```
  Median:1001.0    Median: 64.51613
    Mean: 997.3      Mean: 73.50230
 3rd Qu.:1009.0   3rd Qu.:100.80645
    Max.:1012.0      Max.:169.35484
Call: glm(formula = Qtap ~ Atm.Pressure * Wind.Speed, family = binomial, data = Basin)
Deviance Residuals:
       Min        1Q    Median       3Q      Max
 -1.648529 -1.040088 0.2493924 1.196128 1.409876
Coefficients:
                                Value    Std. Error     t value
            (Intercept) -9.7078788921 125.831527572 -0.07714981
           Atm.Pressure  0.0091610818   0.125132309  0.07321116
             Wind.Speed  0.7279677913   1.325029364  0.54939748
Atm.Pressure:Wind.Speed -0.0007201098   0.001319956 -0.54555591
(Dispersion Parameter for Binomial family taken to be 1 )
    Null Deviance: 48.26284 on 34 degrees of freedom
Residual Deviance: 42.08527 on 31 degrees of freedom
Number of Fisher Scoring Iterations: 6
Correlation of Coefficients:
                        (Intercept) Atm.Pressure Wind.Speed
           Atm.Pressure -0.9999679
             Wind.Speed -0.9391304   0.9399516
Atm.Pressure:Wind.Speed  0.9372825  -0.9381881   -0.9999337

Analysis of Deviance Table
Binomial model
Response: Qtap
Terms added sequentially (first to last)
                        Df Deviance Resid. Df Resid. Dev  F Value     Pr(F)
                   NULL                    34   48.26284
           Atm.Pressure  1 5.691746        33   42.57110 5.537032 0.0251411
             Wind.Speed  1 0.133736        32   42.43736 0.130101 0.7207740
Atm.Pressure:Wind.Speed  1 0.352092        31   42.08527 0.342522 0.5626136



Analysis of Deviance Table
Binomial model
Response: B.Qtap
Terms added sequentially (first to last)
           Df Deviance Resid. Df Resid. Dev  F Value      Pr(F)
      NULL                    34   48.26284
```

```
B.Pressure  1 5.691746        33   42.57110 5.749361 0.02231047

Call: glm(formula = B.Qtap ~ B.Pressure, family = binomial, data = basin)
Deviance Residuals:
      Min        1Q    Median       3Q      Max
 -1.63998 -1.021221 0.4372276 1.128358 1.474989
Coefficients:
                   Value  Std. Error   t value
(Intercept)  66.26033293 34.28590015  1.932583
 B.Pressure  -0.06614349  0.03424234 -1.931629
(Dispersion Parameter for Binomial family taken to be 1 )
    Null Deviance: 48.26284 on 34 degrees of freedom
Residual Deviance: 42.5711 on 33 degrees of freedom
Number of Fisher Scoring Iterations: 4
Correlation of Coefficients:
           (Intercept)
B.Pressure -0.9999428
```

A.4 Landfall Basin and Climate Factor Regression Analysis

```
Call: glm(formula = Qtap ~ LF.Pressure + B.Pressure + PI, family = binomial
       data = lfbaci)
Deviance Residuals:
      Min         1Q     Median        3Q      Max
 -1.52951 -0.6717275 0.09020453 0.4846365 2.339734

Coefficients:
                   Value  Std. Error    t value
(Intercept)  85.27914770 47.65274310  1.7895958
LF.Pressure  -0.01825086  0.02402475 -0.7596692
 B.Pressure  -0.06641704  0.05150394 -1.2895526
         PI  -1.91936950  0.79943749 -2.4009000
(Dispersion Parameter for Binomial family taken to be 1 )
    Null Deviance: 46.66233 on 33 degrees of freedom
Residual Deviance: 27.02641 on 30 degrees of freedom
Number of Fisher Scoring Iterations: 6
Correlation of Coefficients:
            (Intercept) LF.Pressure B.Pressure
LF.Pressure -0.0710474
 B.Pressure -0.8896433  -0.3921521
```

```
         PI -0.2568951   0.2724351   0.1058751

Analysis of Deviance Table
Binomial model
Response: Qtap
Terms added sequentially (first to last)
            Df Deviance Resid. Df Resid. Dev  F Value     Pr(F)
       NULL                    33   46.66233
LF.Pressure  1  2.64640        32   44.01593  2.62360 0.1157517
 B.Pressure  1  3.92217        31   40.09376  3.88837 0.0579038
         PI  1 13.06734        30   27.02641 12.95473 0.0011334

step(all.glm)
Start:  AIC= 35.0264
 Qtap ~ LF.Pressure + B.Pressure + PI
Single term deletions
Model:
Qtap ~ LF.Pressure + B.Pressure + PI
scale:  1
            Df Sum of Sq      RSS       Cp
     <none>              30.26079 38.26079
LF.Pressure  1  0.577097 30.83788 36.83788
 B.Pressure  1  1.662946 31.92373 37.92373
         PI  1  5.764321 36.02511 42.02511

Step:  AIC= 33.6082
 Qtap ~ B.Pressure + PI
Single term deletions
Model:
Qtap ~ B.Pressure + PI
scale:  1
           Df Sum of Sq      RSS       Cp
    <none>              29.08990 35.08990
B.Pressure  1  2.908781 31.99868 35.99868
        PI  1  6.007097 35.09700 39.09700
Call:
glm(formula = Qtap ~ B.Pressure + PI, family = binomial, data = lfbaci)
Coefficients:
 (Intercept)  B.Pressure        PI
    84.75809 -0.08379953 -1.788417
Degrees of Freedom: 34 Total; 31 Residual
Residual Deviance: 27.60821
```

```
Analysis of Deviance Table
Binomial model
Response: Qtap
Terms added sequentially (first to last)
            Df Deviance Resid. Df Resid. Dev  F Value     Pr(F)
       NULL                    33   46.66233
 B.Pressure  1  6.55552        32   40.10681  6.49903 0.0161448
         PI  1 12.49859        31   27.60821 12.39088 0.0014001
LF.Pressure  1  0.58180        30   27.02641  0.57679 0.4535007

Call: glm(formula = Qtap ~ B.Pressure + PI, family = binomial, data = lfbaci)
Deviance Residuals:
   Min         1Q     Median        3Q      Max
 -1.51 -0.6905269 0.09212873 0.5066516 2.277192
Coefficients:
                   Value  Std. Error   t value
(Intercept)  84.75809282 49.29273793  1.719484
 B.Pressure  -0.08379953  0.04913444 -1.705515
         PI  -1.78841727  0.72968688 -2.450938
(Dispersion Parameter for Binomial family taken to be 1 )
    Null Deviance: 46.66233 on 33 degrees of freedom
Residual Deviance: 27.60821 on 31 degrees of freedom
Number of Fisher Scoring Iterations: 6
Correlation of Coefficients:
           (Intercept) B.Pressure
B.Pressure -0.9999300
        PI -0.2161633   0.2093468

Analysis of Deviance Table
Binomial model
Response: Qtap
Terms added sequentially (first to last)
           Df Deviance Resid. Df Resid. Dev  F Value      Pr(F)
      NULL                    33   46.66233
B.Pressure  1  6.55552        32   40.10681  6.98597 0.01276741
        PI  1 12.49859        31   27.60821 13.31927 0.00095726
```

```
Analysis of Deviance Table
Response: Qtap
            Terms Resid. Df Resid. Dev    Test Df Deviance F Value     Pr(F)
1 B.Pressure + PI        31   27.60821
2    b2 + p2 + bp        30   26.57230 1 vs. 2  1 1.035918 1.11805 0.2987792
Analysis of Deviance Table
Binomial model
Response: Qtap
Terms added sequentially (first to last)
           Df Deviance Resid. Df Resid. Dev  F Value      Pr(F)
      NULL                    33   46.66233
        PI  1 13.72905        32   32.93327 14.63053 0.00059269
B.Pressure  1  5.32506        31   27.60821  5.67471 0.02353031
```

Table 18. Selected Precipitation Gauge Descriptions

†Map ID No.	Station ID Number	Station Name, State	Decimal Latitude	Decimal Longitude	Elevation	Sub-basin
38	182282	*Cumberland 2 , MD	39.65	-78.75	222.5	NB
39	182285	*Cumberland Police Barracks, MD	39.63	-78.83	295.7	NB
40	183415	*Frostburg 2, MD	39.67	-78.93	661.4	NB
41	183980	Hagerstown Police Barracks, MD	39.60	-77.73	170.7	
42	186620	Oakland 1 SE, MD	39.40	-79.40	737.6	
43	188065	*†§Savage River Dam, MD	39.52	-79.13	455.7	NB
44	188207	Sharpsburg 5 S, MD	39.40	-77.72	152.4	
45	440720	† Big Meadows, VA	38.53	-78.43	1079.0	
46	442064	Craigsville 2 S, VA	38.07	-79.40	542.5	
47	442208	*†§Dale Enterprise, VA	38.45	-78.93	426.7	SF
48	442663	*Edinburg,VA	38.82	-78.57	256.0	NF
49	443229	*†§Front Royal,VA	38.90	-78.18	283.5	SF
50	443470	Goshen,VA	37.98	-79.50	411.5	
51	444876	Lexington,VA	37.80	-79.42	342.9	
52	444909	Lincoln, VA	39.08	-77.70	152.4	
53	445096	*Luray 5 E, VA	38.67	-78.37	426.7	SF
54	445150	Madison, VA	38.38	-78.25	176.8	
55	445595	†Millgap 2 NNW, VA	38.35	-79.73	768.1	
56	445851	*†§Mount Weather, VA	39.07	-77.88	524.3	SR
57	447904	Somerset, VA	38.25	-78.27	155.4	
58	447985	Sperryville, VA	39.65	-78.23	228.6	
59	448046	*†§ Star Tannery, VA	39.08	-78.45	289.6	NF
60	448062	*†§ Staunton Sewage Plant, VA	38.18	-79.08	499.9	SF
61	448941	*Waynesboro Sewage, VA	38.08	-78.88	390.1	SF
62	449181	Winchester, VA	39.18	-78.15	219.5	
63	449186	Winchester 7 SE, VA	39.18	-78.12	207.3	
64	449263	*Woodstock 2 NE,	38.90	-78.48	207.3	NF

Table 18. Selected Precipitation Gauge Descriptions

†Map ID No.	Station ID Number	Station Name, State	Decimal Latitude	Decimal Longitude	Elevation	Sub-basin
		VA				
65	460527	*Bayard, WV	39.27	-79.37	723.9	NB
66	460712	Berkeley Springs 3 S, WV	39.57	-78.25	285.0	
67	461324	† §Cacapon State Park 2, WV	39.50	-78.32	289.6	
68	461397	Canaan Valley 2,WV	39:05	-79.45	987.6	
69	463215	*Franklin 2 Ne, WV	38.68	-79.32	579.1	SB
70	464840	*Keyser 2 SSW, WV	39.42	-79.00	274.3	NB
71	465453	Lost River, WV	38.95	-78.80	515.1	
72	465706	Martinsburg, WV 2	39.47	-77.97	164.6	
73	465707	†§Martinsburg E WV	39.40	-77.98	162.8	
74	466163	*†§Moorefield 1 SSE, WV	39.05	-78.97	271.3	SB
75	466952	*Petersburg, WV	38.98	-78.18	295.0	SB
76	467730	*†§Romney 1 SW, WV	39.33	-78.77	219.5	SB
77	468589	*Sugar Grove 4 NNE, WV	38.57	-79.28	533.4	SB
78	469281	Wardensville R M Farm, WV	39.12	-78.58	292.6	
79	724053	Winchester Regional Airport,VA	39.15	-78.15	222.0	
80	724165	Petersburg/Grant AI, WV	38.98	-79.13	293.0	SB

Note: †Map ID Numbers are for the purpose of locating a gauge on Figure 1.

Table 19. Discharge and Runoff September 2003 and 2004

	Peak Discharge (cms)				Peak Discharge R.I. (years)				Q/Q100				Runoff			
	Tropical Storm															
Gauge Location	Isabel	Fran	Ivan	Jean	Isabel	Fran	Ivan	Jean	Isabel	Fran	Ivan	Jean	Isabel	Fran	Ivan	Jean
North Branch Potomac River																
Franklin, MD	93	140	59	5	6	19	2	1	0.43	0.65	0.27	0.03	35.5	48.9	18.6	1.9
Headsville, WV	156	39	9	29	4	1	1	1	0.32	0.08	0.02	0.06	32.4	6.2	3.7	5.9
Wills Creek Cumberland, MD	131	309	289	12	2	5	4	1	0.13	0.31	0.29	0.01	16.9	20.2	19.0	0.5
NB Potomac Cumberland, MD	462	555	320	50	2	3	1	1	0.21	0.26	0.15	0.02	30.9	24.9	10.9	1.1
Basin Average	211	261	169	24	3	7	2	1	0.28	0.32	0.18	0.03	28.9	25.1	13.0	2.4
South Branch Potomac River																
Brandywine, WV	182	90	76	28	4.0	2	1	2.0	0.19	0.08	0.03	0.09	66.6	28.2	14.3	49.2
Petersburg, WV	1068	481	77	453	9.1	2	1	1.6	0.39	0.18	0.04	0.17	40.5	18.3	6.8	24.6
Moorefield, WV	365	101	33	272	6.2	2	1	2.8	0.24	0.06	0.02	0.12	65.9	15.1	5.4	41.4
Springfield, WV	1911	407	119	617	10	1	2	1.0	0.40	0.09	0.13	0.02	45.0	11.6	5.3	21.7
Basin Average	882	270	76	342	7	2	1	1.8	0.3	0.1	0.1	0.1	54.5	18.3	7.9	34.2
North Fork Shenandoah River																
Cootes Store, VA	577.7	106.8	26.1	430.4	7	1	1.0	4.1	0.38	0.07	0.02	0.28	50.6	14.4	8.3	43.8
Mount Jackson, VA	790.0	148.1	108.7	416.3	8.8	1.3	1.1	3.0	0.39	0.07	0.05	0.21	37.9	9.8	11.3	26.5
Winchester, VA	176.7	64.3	104.8	167.1	4.1	1.4	2.1	3.7	0.26	0.10	0.16	0.25	36.0	8.2	23.6	33.6
Buckton, VA	141.3	39.4	52.1	104.5	4.7	1.4	1.6	3.1	0.24	0.07	0.09	0.18	38.6	7.5	21.3	39.4
Strasburg, VA	617.3	180.4	155.2	365.3	4.5	1.4	1.3	2.3	0.23	0.07	0.06	0.14	26.1	11.1	14.1	23.1
Basin Average	460.6	107.8	89.4	296.7	5.9	1.3	1.4	3.2	0.3	0.1	0.1	0.2	37.8	10.2	15.7	33.3
South Fork Shenandoah River																
Grottoes, VA	365.3	101.4	32.8	271.6	5.7	1.3	1.0	3.5	0.33	0.09	0.03	0.24	36.2	8.6	3.2	30.5
Lynnwood, VA	1370.5	311.5	128.8	931.6	11.3	1.4	1.0	4.9	0.47	0.11	0.04	0.32	49.3	15.9	10.3	38.5
Front Royal, VA	1345.1	404.9	234.5	974.1	6.3	1.4	1.1	3.6	0.36	0.11	0.06	0.26	49.7	17.1	12.5	33.0
Basin Average	1345.1	404.9	234.5	974.1	6.3	1.4	1.1	3.6	0.4	0.1	0.1	0.3	49.7	17.1	12.5	33.0
Shenandoah River Mainstem																
Millville, WV	1871.8	1260.1	498.4	427.6	5.5	1.2	1.1	2.8	0.35	0.09	0.08	0.24	39.3	13.5	12.2	27.4
Storm Average	683.8	278.8	136.6	326.7	5.9	2.6	1.5	2.5	0.31	0.15	0.09	0.16	41.0	16.4	11.8	26.0
Storm Standard Deviation	611.8	301.1	130.0	301.4	2.7	4.2	0.8	1.3	0.10	0.15	0.08	0.10	12.8	10.3	6.1	15.5

Table 20. Rise Time and Pre-Storm Surface Conditions - September 2003 and 2004.

Gauge Location	Isabel	Frances	Ivan	Jeanne	Isabel	Frances	Ivan	Jeanne	Isabel	Frances	Ivan	Jeanne
	Rise time (hours)				Antecedent Soil Moisture Index				Soil Storage Capacity Index			
North Branch Potomac River												
Wills Creek Cumberland, MD	16.0	32.5	20.5	24.5	1.2	0.9	5.5	3.8	0.3	0.4	0.1	0.1
Headsville, WV	20.0	14.5	22.5	17.0	4.0	0.8	4.9	2.3	0.1	0.4	0.1	0.1
Franklin, MD	10.8	16.3	10.5	13.0	4.2	0.9	6.8	6.0	0.1	0.3	0.1	0.0
NB Potomac Cumberland, MD	19.0	33.0	19.0	25.0	3.9	1.2	2.8	2.8	0.1	0.3	0.1	0.1
Basin Average	16.4	24.1	18.1	19.9	3.3	1.0	5.0	3.7	0.1	0.3	0.1	0.1
South Branch Potomac River												
Moorefield, WV	20.5	14.0	18.5	16.5	1.5	0.7	3.9	2.7	0.3	0.7	0.1	0.2
Brandywine, WV	13.0	9.0	15.0	6.0	1.6	0.6	3.0	2.4	0.2	0.5	0.1	0.2
Petersburg, WV	16.5	18.0	24.0	9.5	1.7	0.8	2.6	2.1	0.3	0.6	0.2	0.2
Springfield, WV	31.0	22.0	22.5	26.5	2.0	0.7	3.9	2.3	0.2	0.6	0.1	0.2
Basin Average	20.3	15.8	20.0	14.6	1.7	0.7	3.4	2.4	0.2	0.6	0.1	0.2
North Fork Shenandoah River												
Strasburg, VA	11.8	37.5	31.8	28.5	2.6	0.7	1.2	1.7	0.2	0.8	0.0	0.0
Mount Jackson, VA	15.8	12.5	16.8	14.0	2.2	0.5	2.5	2.7	0.2	0.7	0.1	0.1
Cootes Store, VA	7.5	7.3	16.3	10.5	4.4	0.1	7.0	4.1	0.0	0.1	0.2	0.3
Winchester, VA	13.0	9.5	6.0	7.5	1.8	0.7	1.8	2.5	0.2	0.6	0.2	0.2
Buckton, VA	19.0	10.3	21.8	13.8	6.4	0.4	1.6	2.6	0.1	0.7	0.2	0.1
Basin Average	13.4	15.4	18.5	14.9	3.5	0.5	2.8	2.7	0.1	0.6	0.2	0.1
Shenandoah River												
Millville, WV	43.5	22.0	33.0	23.3	2.1	0.9	4.4	2.2	0.2	0.6	0.1	0.2
Front Royal, VA	27.5	34.0	34.3	35.0	1.9	0.9	4.4	2.4	0.3	0.6	0.2	0.1
Lynnwood, VA	20.0	18.0	27.3	18.8	1.6	0.8	1.6	1.6	0.4	0.8	0.2	0.4
Grottoes, VA	24.5	15.8	18.0	20.3	2.7	0.8	1.5	1.4	0.2	0.7	0.3	0.4
Basin Average	24.0	22.6	26.5	24.7	2.1	0.8	1.5	1.5	0.3	0.7	0.2	0.3
Storm Average	19.4	19.2	21.0	18.2	2.8	0.7	3.5	2.8	0.2	0.6	0.1	0.2
Storm Standard Deviation	8.7	9.6	7.6	8.1	1.4	0.3	1.8	1.1	0.1	0.2	0.1	0.1

Tropical Storm: Isabel, Frances, Ivan, Jeanne

Table 21. Rainfall-runoff ratios September 2003 and 2004

Gauge Location	Isabel	Frances	Ivan	Jeanne
	Tropical Storm			
	North Branch Potomac River			
Wills Creek Cumberland, MD	0.21	0.17	0.31	0.02
Headsville, WV	0.41	0.06	0.05	0.23
Franklin, MD	0.45	0.40	0.30	0.06
NB Potomac Cumberland, MD	0.39	0.20	0.18	0.04
Basin Average	0.37	0.21	0.21	0.09
	South Branch Potomac River			
Moorefield, WV	0.56	0.16	0.14	0.53
Brandywine, WV	0.57	0.30	0.36	0.62
Petersburg, WV	0.34	0.19	0.17	0.31
Springfield, WV	0.38	0.12	0.13	0.28
Basin Average	0.49	0.22	0.22	0.49
	North Fork Shenandoah River			
Strasburg, VA	0.29	0.14	0.18	0.27
Mount Jackson, VA	0.43	0.12	0.15	0.31
Cootes Store, VA	0.57	0.18	0.11	0.52
Winchester, VA	0.41	0.10	0.31	0.40
Buckton, VA	0.44	0.09	0.28	0.46
Basin Average	0.43	0.13	0.21	0.39
	South Fork Shenandoah River			
Front Royal, VA	0.34	0.15	0.10	0.30
Lynnwood, VA	0.34	0.14	0.09	0.35
Grottoes, VA	0.25	0.08	0.03	0.27
Basin Average	0.34	0.14	0.10	0.32
Millville, WV	0.37	0.18	0.21	0.18
Storm Average	0.40	0.16	0.18	0.31
Storm Standard Deviation	0.05	0.04	0.04	0.04

September 2003 Rainfall

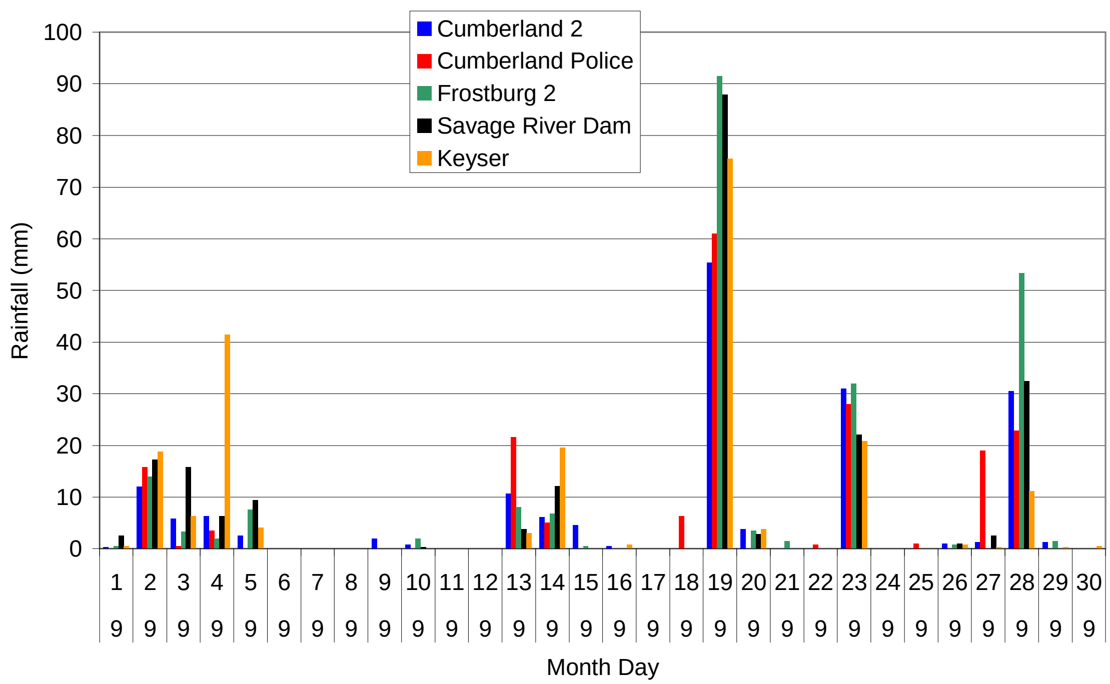


Figure 45. September, 2003 precipitation - North Branch Potomac River basin.

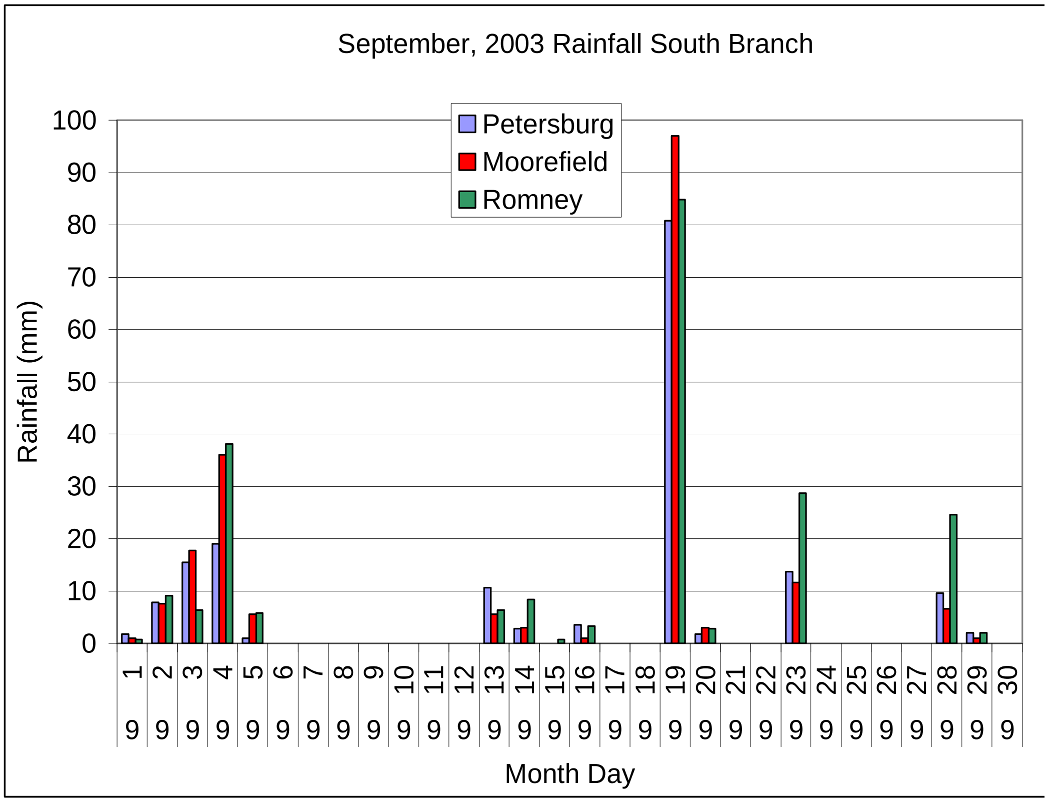


Figure 46. September, 2003 precipittaion – South Branch Potomac River Basin

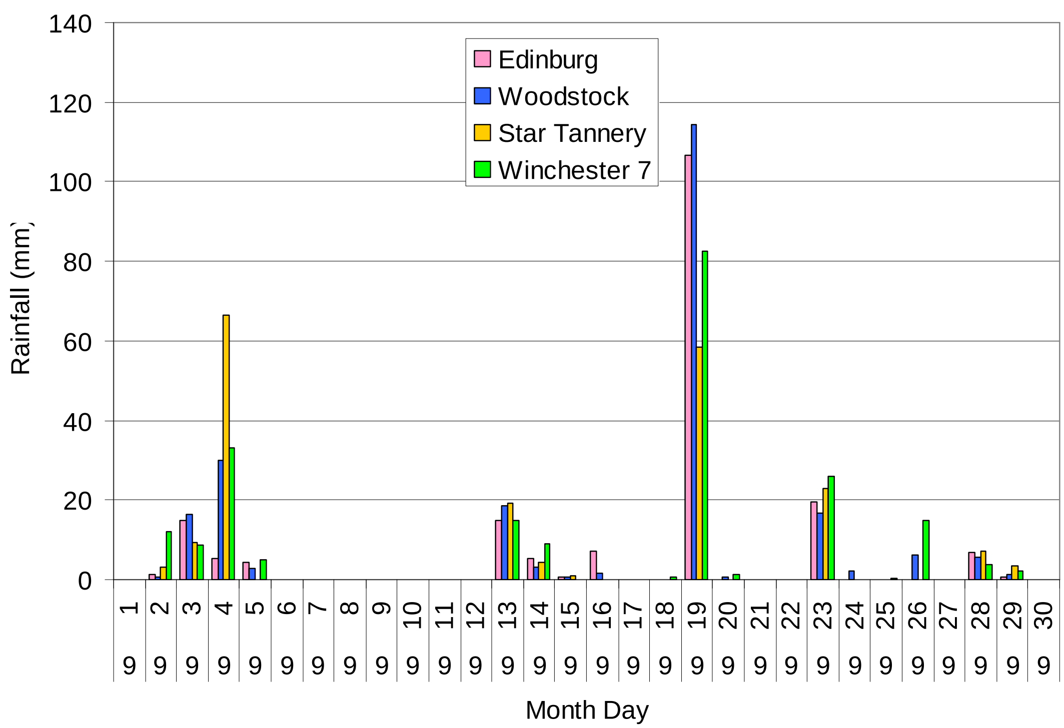


Figure 47. September, 2003 precipitation - North Fork Shenandoah River basin.

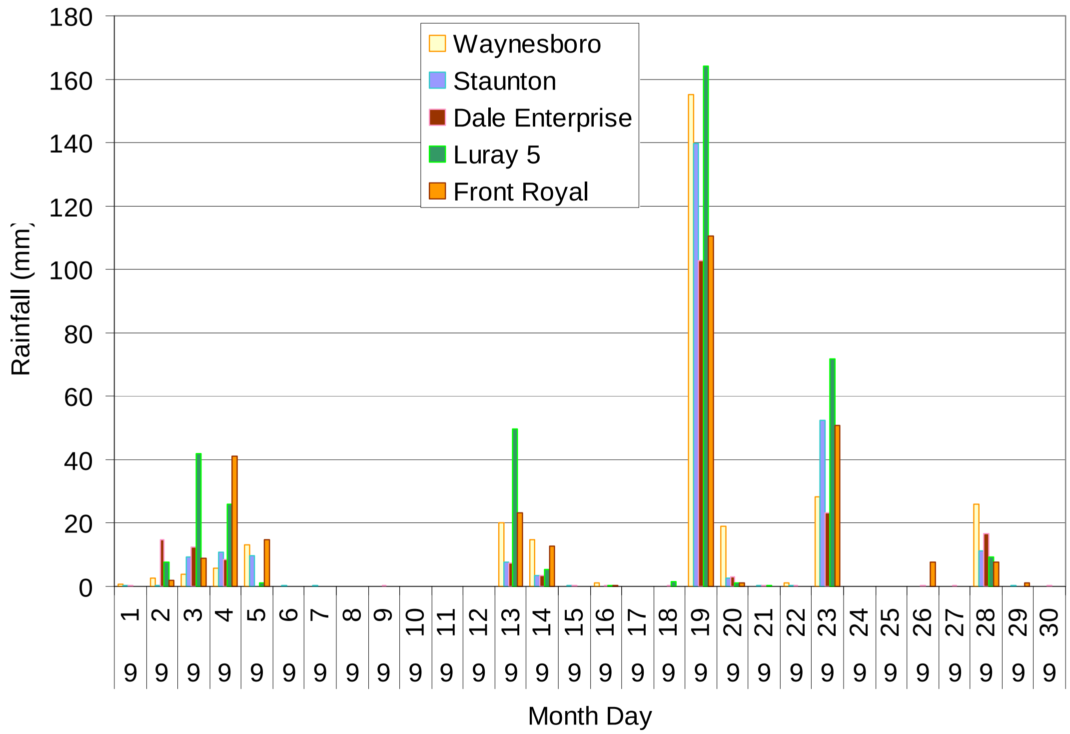


Figure 48. September, 2003 precipitation - South Fork Shenandoah River basin.

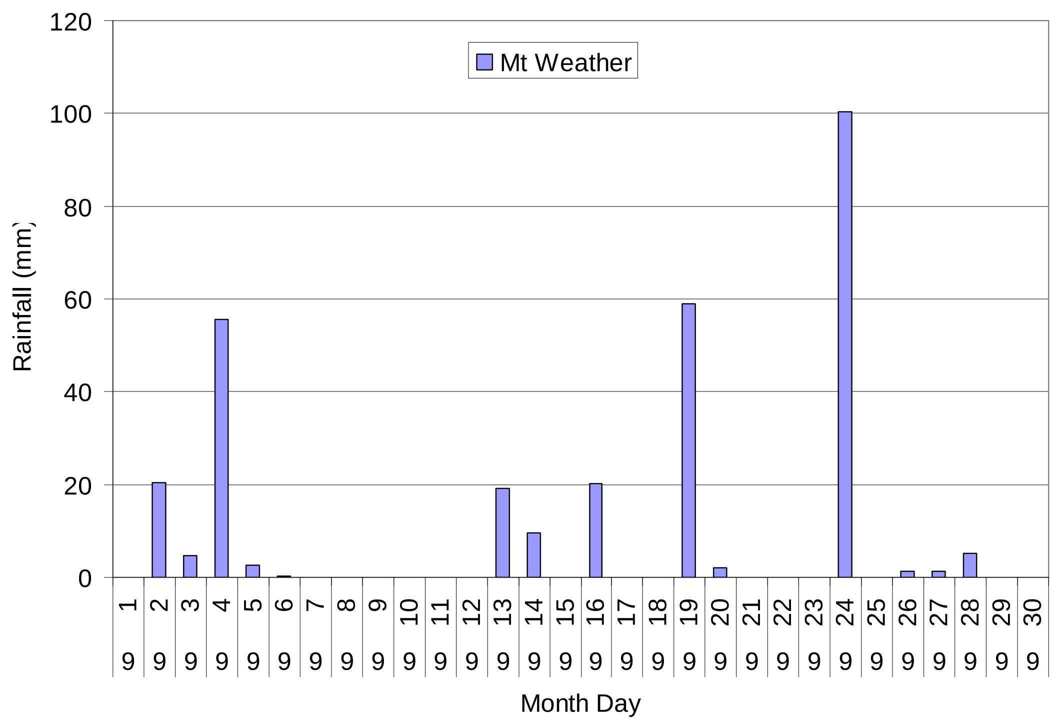


Figure 49. September, 2003 precipitation - Shenandoah River mainstem.

September 2004 Rainfall

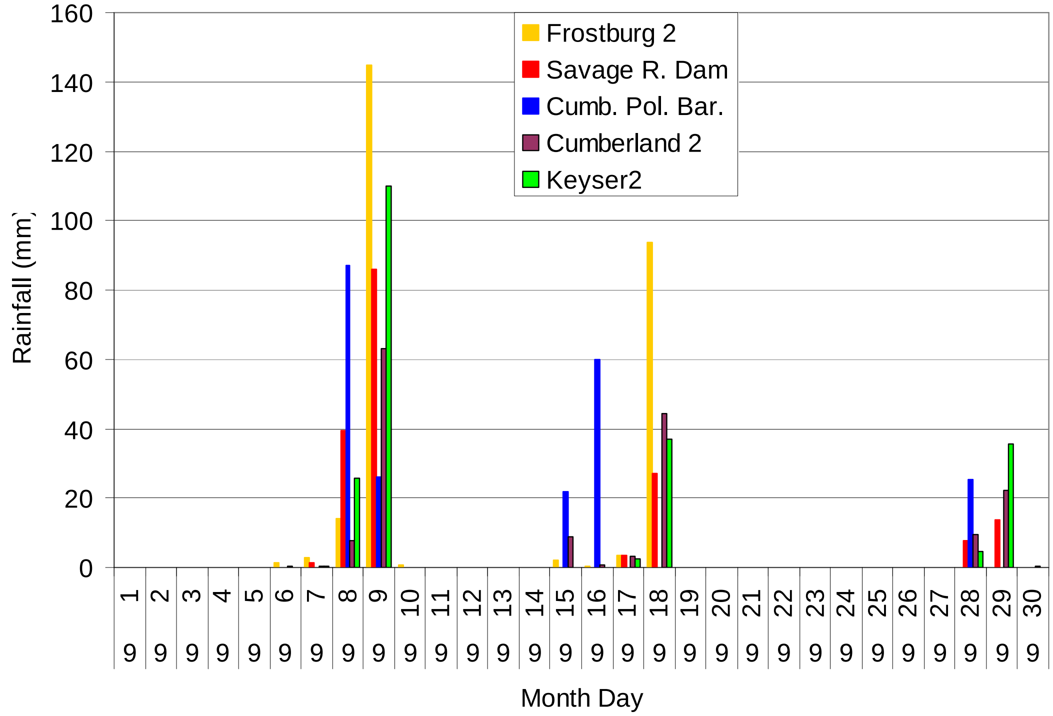


Figure 50. September, 2004 precipitation - North Branch Potomac River basin.

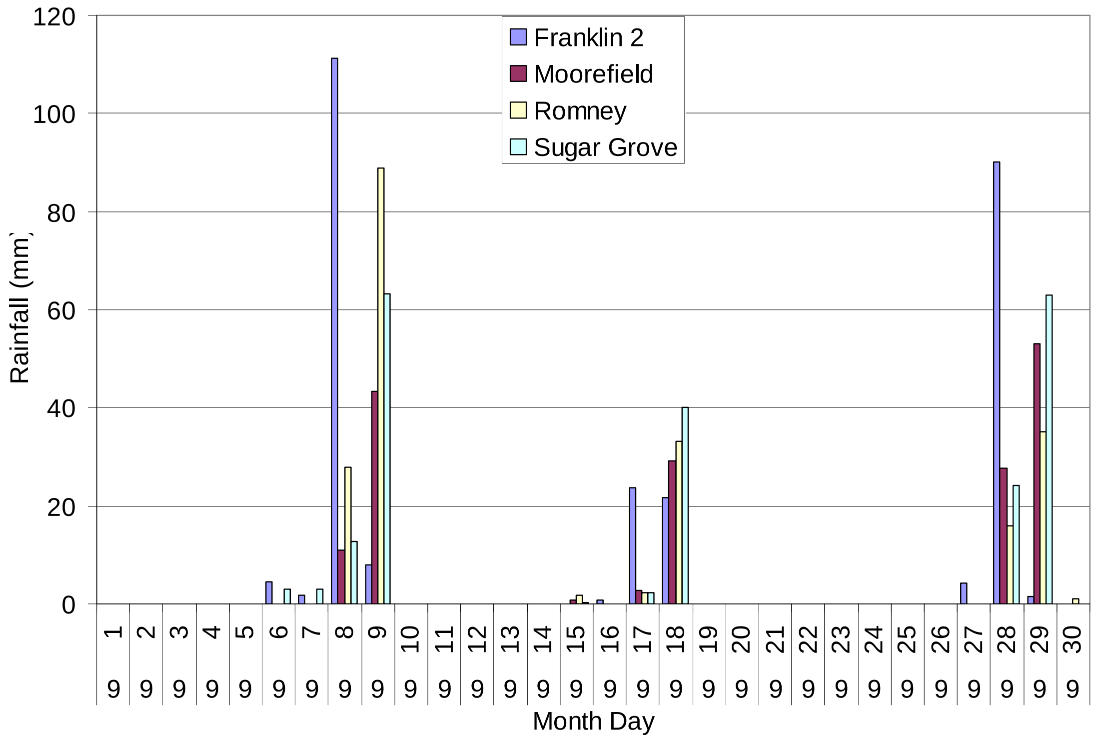


Figure 51. September, 2004 precipitation - South Branch Potomac River basin.

Figure 52. September, 2004 precipitation - North Fork Shenandoah River.

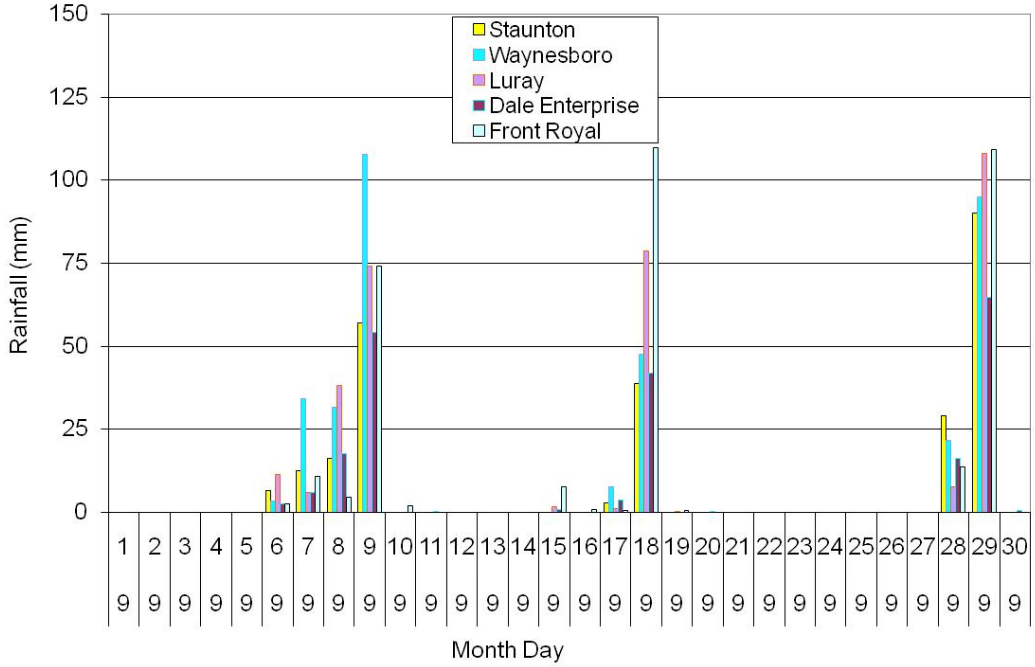


Figure 53. September, 2004 precipitation - North Fork Shenandoah River basin.

Select Hydrograph September 2003

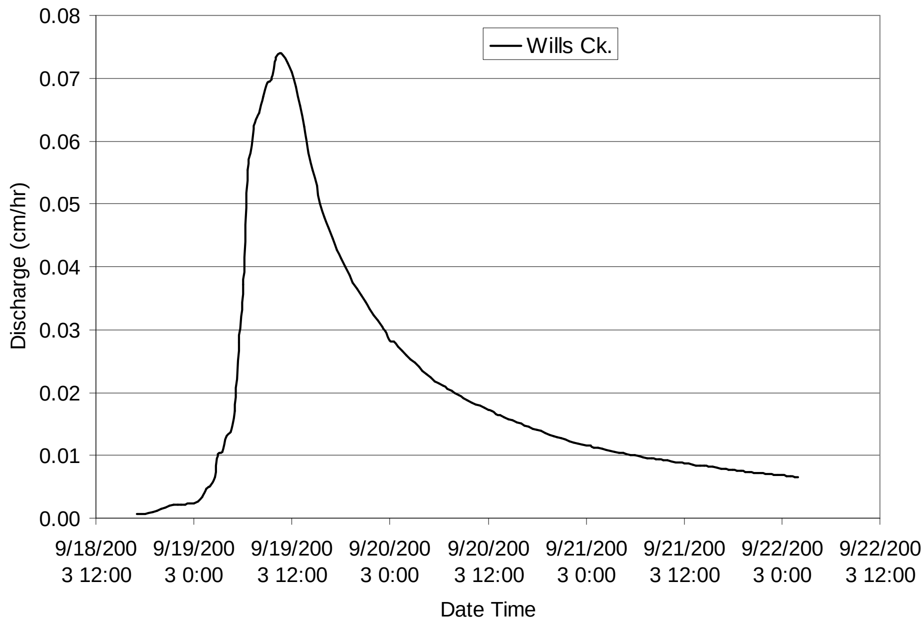


Figure 54. September 18-22, 2003 (Hurricane Isabel related) instantaneous discharge reported by the gauge on Wills Creek near Cumberland, MD. This hydrograph shape is representative of all hydrographs with the exception of ones for gauges at Millville, WV, all study sites in the South Fork Shenandoah River, Point of Rocks, MD and Little Falls Pumping Station near Washington, DC.

Select Hydrographs September 2004

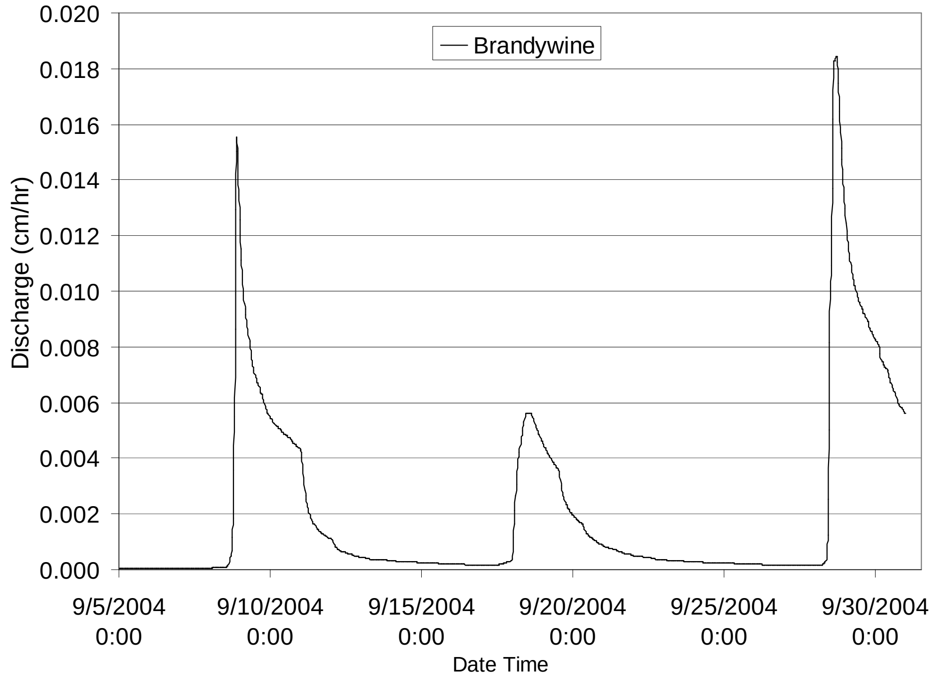


Figure 55. September 5-September, 2004 (sequential tropical storm related) instantaneous discharge reported by the gauge on the South Fork South Branch Potomac River near Brandywine, WV. This hydrograph is representative of hydrographs for gauges at Moorefield, WV, Springfiled, WV, Cootes Store, VA, Mount Jackson, VA, Strasburg, VA, Grottoes, VA, Lynnwood, VA, Front Royal, VA and Millville, VA.

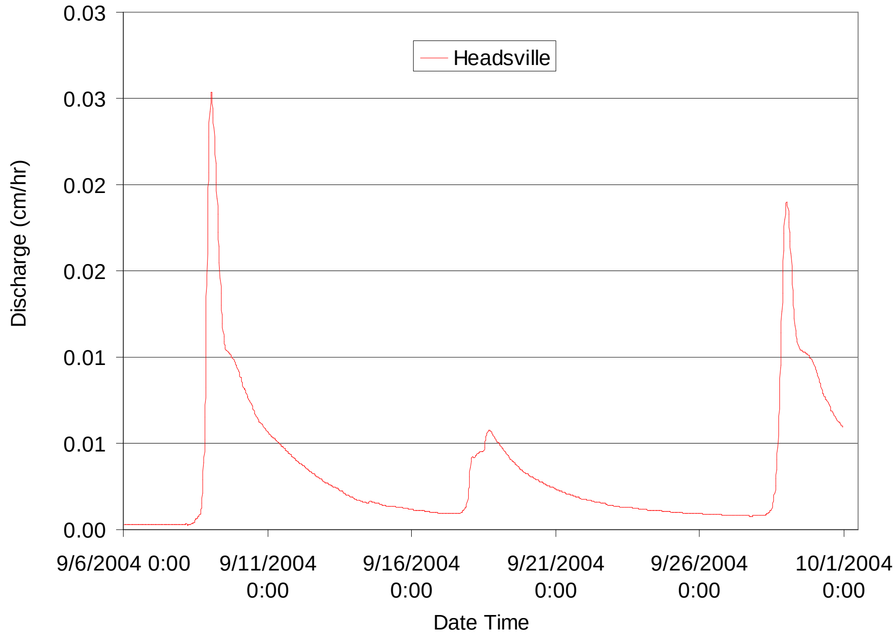


Figure 56. September 6-October, 2004 (sequential tropical storm related) instantaneous discharge reported by the gauge on the South Fork South Branch Potomac River near Headsville, WV. This hydrograph shape is representative of the hydrograph for the gauge at Petersburg, WV,

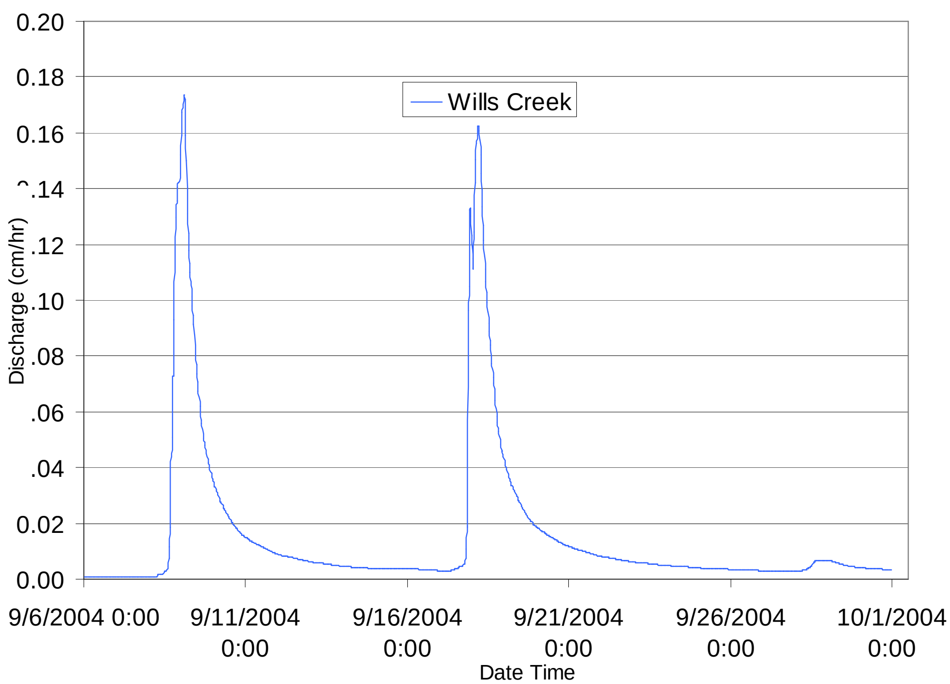


Figure 57. September 6-October 1, 2004 (sequential tropical storm related) instantaneous discharge reported by the gauge on Wills Creek near Cumberland, MD. This hydrograph is representative of hydrographs for gauges at Georges Creek near Franklin, MD and North Branch Potomc River near Cumberland, MD.

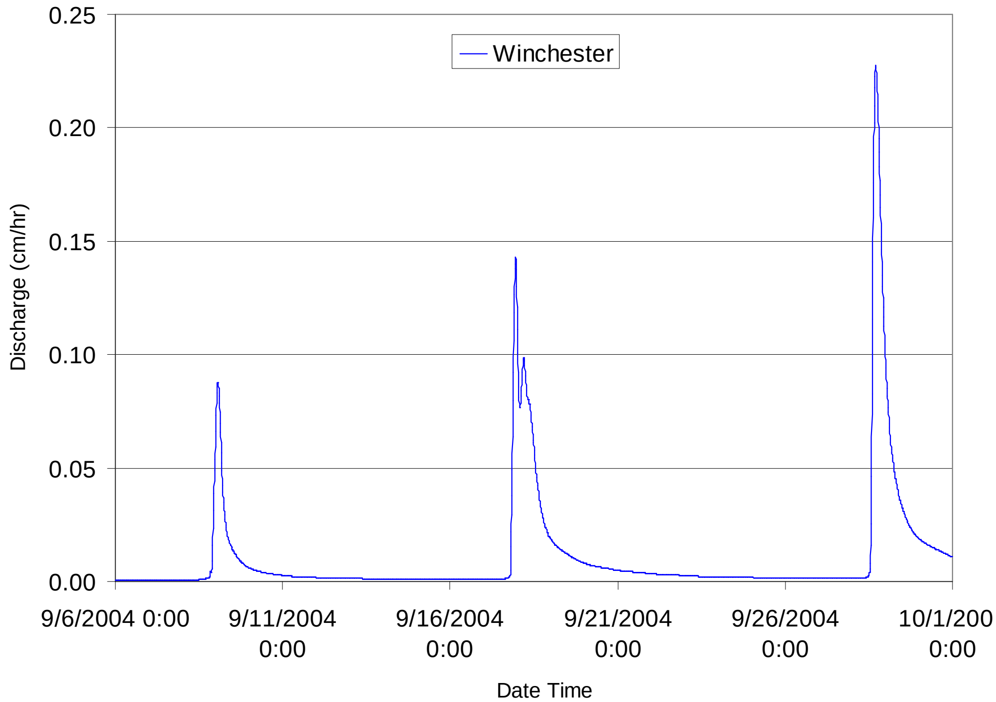


Figure 58. September 5-September, 2004 (sequential tropical storm related) instantaneous discharge reported by the gauge on Cedar Creek near Winchester, VA. This hydrograph shape is representative of the hydrograph for the gauge on Passage Creek at Buckton, VA.

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