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1. INTRODUCTION

The Middle Atlantic River Forecast Center (MARFC) has received numerous requests from customers including emergency managers, the public, and National Weather Service (NWS) Weather Forecast Offices, for historical flood information. MARFC has answered these requests by compiling and analyzing more than 7900 flood events from 1687 to 2011.

Customers have utilized the historical flood data in different ways. Design engineers have used the data to determine if a project's location will be subject to flooding. Climatologists have analyzed trends in seasonal, annual and decadal flooding. Other scientists have investigated trends in flood events and the corresponding weather patterns. Weather Service forecasters and emergency managers have compared the current or predicted flood event to past flood events.

Flood climatology data is available for all 173 forecast points in the MARFC area. As shown in Figure 1, MARFC's forecast area includes the Susquehanna, Delaware, Passaic, Raritan, Potomac, James and Appomattox River Basins.

All of MARFC's flood climatology data is available by request in an Access database or online (http://www.weather.gov/marfc/Rivers/FloodClimo).

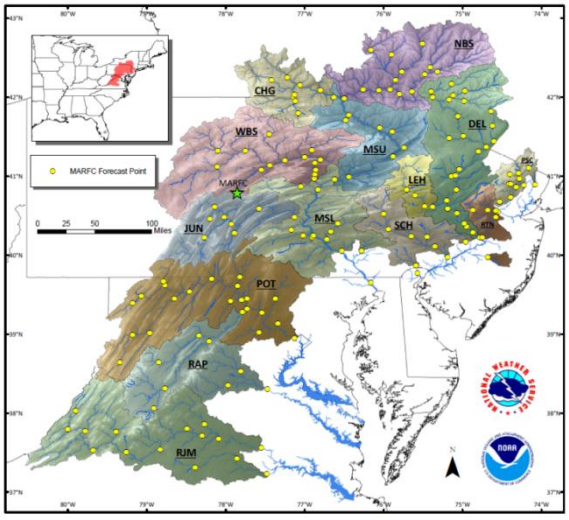

Figure 1: Map of MARFC's basins and forecast locations.

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2. METHODOLOGY

Extensive flood and meteorological information was gathered from National Weather Service (NWS) hydrologic reports, United States Geological Survey (USGS) website, county managers, books (Bell 1868, Gelber 2002, Hain 1922, Schwartz 2007, Watson 2005, Watts 1906, Meginness 1895), newspaper clippings (Lowell Sun 1950), websites (Roth and Cobb 2001, HPC, Miller 2009) and analysis of historical weather maps (NOAA Coastal Service Center 2011).

To account for changes in datum or discontinuous records, each flood event is categorized as either a historical event or a flood frequency event. Historical events include every known flood regardless of changes in datum, flood stage, or lack of continuous record. Flood frequency events only include floods that have occurred at the same datum and flood stage as the current datum and flood stage, and the gauge has a continuous record.

2.1 *Flood Frequency Analysis*

Return period, frequency of flood occurrence, flood frequency percentages and flood stage exceedence values are calculated only for flood frequency data. For these calculations, each flood event is assumed to be independent of all other flood events at the same location.

A return period is the estimated interval of time between two flood events (Linsley et al 1982). For MARFC's flood climatology, the return period is calculated by

$$Return\ Period = \frac{Period\ of\ Record+1}{n_{floods}} \quad (1)$$

where the period of record is the length of time in years of the flood frequency data record and n_{floods} is the number of flood frequency events that have occurred. Flooding is expected to occur more often at locations with smaller return periods. Statistically, a flood is expected to occur every year if the return period is less than one.

Probability of exceedence is the probability that a flood greater than a particular magnitude will occur in a specific time interval. For flood frequency data, the probability of exceedence is calculated for minor, moderate and major flood stages for 1-year, 5-year, 10-year and 20-year intervals. The probability of exceedence is calculated by

$$P_{Exceedence} = \left(\frac{n_{floods} t_{interval}}{Period\ of\ Record+1}\right) \times 100 \quad (2)$$

where n_{floods} is the number of minor, moderate or major floods, $t_{interval}$ is the year associated with the time interval (e.g. 1, 5, 10 or 20) and the period of record is length of time in years of the flood frequency data record.

The final calculations in the flood frequency section are the frequency of flood occurrence and percentage of flood occurrence. Frequency of flood occurrence is the number of times a location has flooded for a particular month. The percentage of flood occurrence is the percentage of floods that have occurred in a particular month as compared to the total number of flood events. The percentage of flood occurrence is calculated by

$$Percent\ of\ Flood\ Occurrence = \left(\frac{n_{month}}{n_{total}}\right) \times 100 \quad (3)$$

where n_{month} is the number of floods that have occurred in a specific month and n_{total} is the total number of floods that have occurred.

2.2 *Forecast Point Analysis*

A more in-depth data analysis of flood frequency data and historical data was completed for each MARFC forecast point. Flood data were categorized by minor, moderate and major flood levels, the month of occurrence, the year of occurrence and the category of flood stage exceedence for each month and meteorological season.

A list of top ten floods by crest height, and a list of the top five lowest stages have been established for each location. Both of these analyses contain a section listing the corresponding weather conditions at the time of the measurement.

The height above flood stage calculation, a list of floods caused by tropical events and mean daily and monthly discharges for each forecast point are also available.

2.3 *Flood Event Analysis*

Meteorological and hydrologic information is available for individual flood events. Meteorological information includes surface maps, a weather summary of the conditions before and during the event, maps of observed precipitation, and the top 15 largest precipitation amounts in 24-hours for each day that flooding was occurring. Hydrologic data includes a list of the flooded locations and the category of each flood, the date and time when flooding started and ended, and the flood crests at each location. In addition, the flood information is summarized for each river basin and weather forecast area affected by the flood.

In the past, MARFC flood events were compared by the number of flooded locations, without accounting for the severity of each flood. A power ranking system was developed in an attempt to also account for the severity of each flood. The power ranking is computed by

$$Power\ Ranking = (n_{minor}) + (5)(n_{moderate}) + (10)(n_{major}) + (n_{unknown}) \quad (4)$$

where n_{minor} is the number of minor floods, $n_{moderate}$ is the number of moderate floods, n_{major} is the number of major floods and $n_{unknown}$ is the number of unknown floods.

3. RESULTS AND DISCUSSION

Most of the flood climatology calculations are available as charts and tables in the Access database and on the flood climatology website, but there are a few exceptions. Results of the flood frequency analysis are only available as tables on the website and in the database. Daily and monthly mean discharge tables are only available on the website.

Table 1: Return period and probability of exceeding minor flood stage for MARFC forecast points in the Raritan River basin.

Site	Blackwells Mills	Bound Brook	Manville	Raritan	Stanton
Stream	Millstone River	Raritan River	Raritan River	Raritan River	Raritan River
Flood Stage	9	28	14	10	8
Period of Record	8/17/1928 - 1/1/2012	10/1/1966 - 1/1/2012	8/15/1923 - 1/1/2012	10/17/1936 - 1/1/2012	8/17/192 - 1/1/2012
Years	83.33	45.17	88.33	75.17	86.33
Number of Floods	139	66	115	48	93
Return Period					
Return Period	0.6	0.68	0.77	1.57	0.93
Floods per year	1.67	1.46	1.3	0.64	1.08
Probability of Exceeding Minor Flood Stage					
1 Year	100%	100%	100%	64%	100%
5 Years	100%	100%	100%	100%	100%
10 Years	100%	100%	100%	100%	100%
20 Years	100%	100%	100%	100%	100%

Table 2: Percentage of flood occurrences by month for MARFC forecast points in the Raritan River basin.

Site	Stream	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Total
Blackwells Mills	Millstone River	12%	6%	21%	11%	3%	4%	6%	6%	6%	4%	6%	14%	139
Bound Brook	Raritan River	11%	5%	17%	15%	5%	5%	5%	5%	11%	6%	3%	15%	66
Manville	Raritan River	13%	10%	14%	10%	3%	3%	5%	7%	7%	5%	10%	14%	115
Raritan	Raritan River	8%	8%	12%	12%	4%	6%	6%	15%	10%	6%	2%	8%	48
Stanton	Raritan River	6%	13%	13%	10%	2%	4%	10%	9%	10%	6%	9%	9%	93

3.1 *Flood Frequency*

Results for the flood frequency analysis for the Raritan River basin are shown in Tables 1 and 2. This analysis includes the return period, probability of exceeding flood stage and percentage of monthly flood occurrences.

Table 1 contains the return period and probability of exceeding flood stage results. The return period values illustrate why one cannot rely on the number of past floods to predict the likelihood of a flood. For example, Manville has flooded almost twice as many times as Bound Brook; however, the period of record at Bound Book is less than the period of record at Manville. Therefore, the return period at Bound Brook is less than the return period at Manville. Statistically, this means Bound Brook will flood more often than Manville.

Table 2 contains the percentage of flood events each month as compared to the total number of floods for each location. These results can be used to observe trends in monthly flood events. For example, more than half of the floods in the Raritan River basin occurred from December to April. Typically, ice effects or rain and snowmelt cause these flood events.

3.2 *Forecast Point*

MARFC's flood climatology data contains several calculations that can be used to analyze trends in flood events for a specific forecast point. This analysis includes the severity of floods for each month and meteorological season, number of floods that have occurred each year, and the top ten highest crests.

Historical and flood frequency events have been categorized as minor, moderate or major floods for the location at which the flood occurred. Any flood where the height of the crest is unknown, likely due to a gauge malfunction, is categorized as missing.

Figure 2 shows the severity of flood events for Raritan, NJ on the Raritan River by month and meteorological season for both historical and flood frequency events. In this example, historical floods include any flood from 1896 to 2012; flood frequency events include only floods with a known crest height from 10/17/1936 to 1/1/2012.

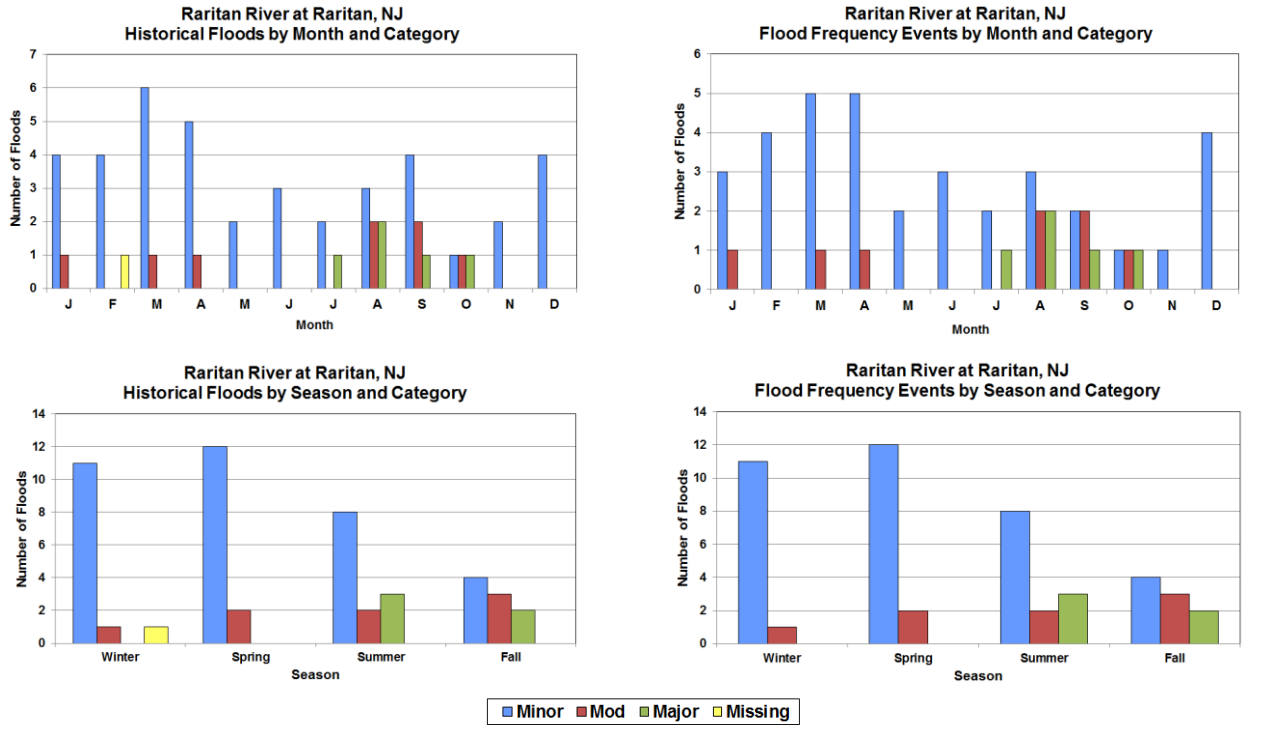

Figure 2: Number of minor, moderate, major and floods of unknown magnitude for each month and meteorological season for the Raritan River at Raritan, NJ for historical and flood frequency events.

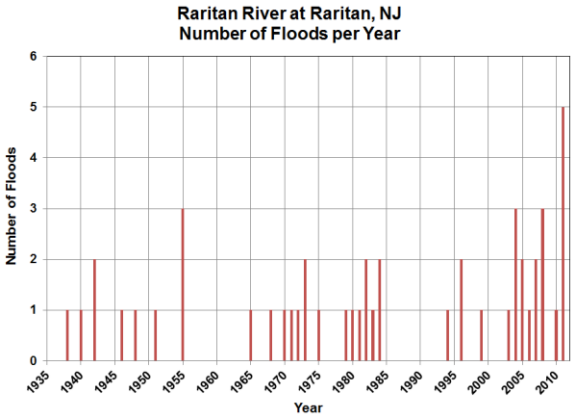

Figure 3: Number of flood frequency events that ocurred each year from 1936 to 2011 for the Raritan River at Raritan, NJ.

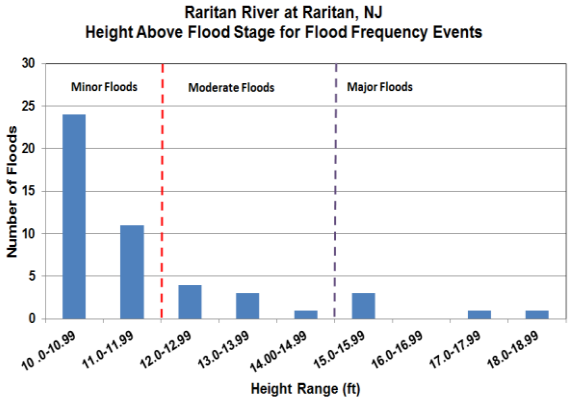

Figure 4: The crest height for each flood frequency event for Raritan River at Raritan, NJ. Minor flood stage is 10 feet, moderate flood stage is 12 feet and major flood stage is 15 feet.

Several trends are presented in this figure. The majority of the flood at Raritan, NJ occurred in the winter and spring; however, these floods tended to be minor. In fact, no major floods have occurred in from November to June. Six of the top ten highest crests for this location have occurred from July to October. The large flood events were caused by tropical systems or strong thunderstorms that produced heavy rain.

The number of flood events per calendar year is another calculation that is useful for observing the number of flood events per year. Figure 3 shows the number of flood frequency events per calendar year for the Raritan River at Raritan, NJ. The highest number of flood frequency events in a single year occurred in 2011, which had five flood events. The most active decade for flood frequency events was 2000-2009, with 12 flood events. This is almost double the number of flood events that have occurred in any other decade during the period of record. Most of the 2000-2009 flood events were caused by rainfall from tropical systems, convection, short wave systems or frontal passages. Additional information regarding flood events caused by tropical systems can be found in the tropical floods section of this analysis.

Another calculation that can provide insight as to the height at which a flood crest is likely to occur is the height above flood stage calculation. Figure 4 shows the height above flood stage reached by each flood for the Raritan River at Raritan, NJ. Most flood events crest less than one foot over minor flood stage. This is consistent with the results depicted in Figure 2, which show that the majority of flood events are minor floods. Very few moderate floods have occurred and only four floods have been major.

For customers who want drought-related information, MARFC's flood climatology also includes a list of the five lowest recorded stages for each location. The low stage values for most locations include a reading of 0.00 feet or a negative value. Negative stage values occur when the height of the stream drops below the zero value of the gauge. The lowest recorded stage for the Raritan River at Raritan, NJ has a discharge of 3 cfs, but the stage height is missing. The data is missing due to ice effects. The second lowest recorded stage was 2.23 feet, which occurred after months of drought.

3.3 *Flood Events*

Results from the MARFC power ranking calculation are very useful when comparing different flood events. Prior to the development of power rankings, only the number of flooded locations were used to compare flood events. As shown in Table 3, the largest number of flooded locations occurred during the 1/19/1996 – 1/23/1996, also known as the

Table 3: Top 10 highest power ranking floods in the MARFC forecast area from 1687 – 2012.

Flood Event Dates	Total	Minor	Moderate	Major	Unknown	Power Ranking	Tropical System
6/21/1972 - 6/27/1972	118	21	18	79	0	901	Agnes
1/19/1996 - 1/23/1996	140	34	47	58	1	850	
3/17/1936 - 3/20/1936	92	12	15	64	1	728	
9/06/2011 - 9/15/2011	107	34	41	32	0	559	Lee
6/26/2006 - 7/01/2006	92	29	27	36	0	524	
9/17/2004 - 9/20/2004	83	18	31	34	0	513	Ivan
8/17/1955 - 8/21/1955	71	17	19	34	1	453	Diane
4/01/2005 - 4/04/2005	86	32	31	23	0	417	
9/25/1975 - 9/29/1975	69	22	24	22	1	363	Eloise
3/06/2011 - 3/18/2011	112	71	31	10	0	326	

“January 1996” flood event; however, Hurricane Agnes caused more major floods than January 1996. Therefore, the Hurricane Agnes flood event has a higher power ranking than the January 1996 flood event.

4. CONCLUSIONS AND FUTURE WORK

MARFC’s flood climatology data addresses the need for historical flood information. During large flood events, emergency managers, hydrologic forecasters, river basin commissions and the media want to know how the current event ranks compared to historical flood events. The flood climatology analysis provides the necessary information.

The flood climatology data has been used by MARFC forecasters as historical event analogues during large flood events. For example, Hurricane Irene was predicted to have similar rainfall amounts and rainfall duration as Hurricane Floyd. MARFC forecasters used the floods from Hurricane Floyd as a guideline for expected flooding from Hurricane Irene.

MARFC forecasters have noticed that the spring snowmelt floods seem to be occurring earlier each year. Trends in floods caused by snowmelt will be analyzed to determine if the flood climatology data support this hypothesis.

In recent months, the MARFC’s Flood Climatology website has undergone major upgrades. During the next year, the website will allow the user to view data specific to his or her request. By making the website more dynamic, the amount of lag time between a flood event and the appearance of the event on the website will be greatly reduced.

5. ACKNOWLEDGEMENTS

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