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HYDROCLIMATOLOGICAL IDENTIFICATION OF FLOOD SEASONALITY AND GENERATING MECHANISMS IN THE UPPER ALLEGHENY RIVER BASIN

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Abstract: *Meteorological floods throughout the Appalachian region can occur during any month of the year and are generated by numerous mechanisms. Relatively unimpaired, and climate-sensitive, U.S. Geological Survey gaging stations (USGS-HCDN) at locations with upstream drainage areas > 30 mi^2 are used to develop a better understanding of flood processes within the upper Allegheny River Basin (uARB) of northwestern Pennsylvania. Dates of annual peak flows (floods) from USGS-HCDN gaging stations were used to evaluate seasonality and generating mechanisms. Flood-generating mechanisms were determined for the 1995-96 to 2014-15 water years using a manual environment-to-atmospheric circulation classification scheme. Composites of uARB USGS-HCDN station records show that 75% of peak flows occur during winter and spring, with 61% of flood events occurring between January and April. March events contribute the highest proportion of all floods (21.5%). Flooding is least common in August (< 2%). In the 20-year period covering the 1995-96 through 2014-15 water years, January peak annual flows were most common. Roughly 40% of top 10-ranked floods for all years of data occurred in March (21%) and January (19%). Annual peak flows during the 1995-96 through 2014-15 water years are dominated by snowmelt-related events (65%), primarily from December through March. Flooding from synoptic scale frontal passages, including convective precipitation and orographically enhanced events, are responsible for generating (26%) of floods throughout the uARB. The identification of flood seasonality and generating mechanisms, conducted here, are important pieces of information for flood forecasting, flood hazard assessment, and water resource studies within the uARB.*

Keywords: *Hydrology, Hydroclimatology, Synoptic Climatology, Floods, Eastern North America*

INTRODUCTION

Every year floods claim numerous lives and cause tremendous amounts of damage and economic loss throughout the United States (U.S.). The spatial distribution and timing of deadly flooding is not uniform throughout the U.S. with certain regions being more heavily impacted than others (LaPenta et al., 1995; Pielke and Downton, 2000; Ashley and Ashley, 2008a; Frei et al., 2015). The Appalachians are one such region that suffers from high flood related losses which, for example, resulted in 1024 lives lost and over $20 billion dollars in damage from 1955 through 1989 alone (LaPenta et al., 1995; Ashley and Ashley, 2008a). Meteorological floods within the Appalachian region can occur during any month of the year and can be generated by a mixture of causal mechanisms, which in turn creates a mixed peak annual flow (flood) time series (Miller, 1990; Hirschboeck, 1991; LaPenta et al., 1995; Villarini and Smith, 2010; Smith et al., 2011; Berghuijs et al., 2016). Temporal variations in regional flood magnitude and frequency are greatly influenced by large scale air mass trajectories and available low-level atmospheric precipitable water vapor that shift due to changing wind regimes throughout the year (Hirschboeck, 1991). However, meteorological conditions alone do not produce flooding, but combine with hydrological and geomorphological conditions, specifically the complex topography of the Appalachian region, to generate runoff that exceeds the capacity of stream channels within a watershed. In addition, monthly and/or seasonal variations in flooding occur due to multiple factors including the timing and type of meteorological event as well as antecedent conditions such as soil moisture, evapotranspiration, vegetation interception and frozen ground/snowpack, all of which influence rainfall-runoff relationships (Hirschboeck, 1991; Miller, 1990; LaPenta et al., 1995; Hirschboeck et al., 2000; Ashley and Ashley, 2008b; Shelton, 2009; Collins et al., 2014; Berghuijs et al., 2016).

To aid in understanding flood dynamics and hazards, spatial and temporal characteristics and variability of flooding can be evaluated and understood using methods and concepts of flood hydroclimatology (Hirschboeck, 1988; Hirschboeck et al., 2000). A primary goal of flood hydroclimatology is to explore relationships between atmospheric conditions at numerous spatial and temporal scales (storm scale through global scale) and how these conditions impact hydrological processes that may not necessarily be operating on the same scales (Hirschboeck, 1988; Hirschboeck et al., 2000; Shelton, 2009). Over small spatial scales and short temporal scales, storm scale meteorological events may include convectional precipitation and isolated thunderstorm cells that may only impact very small portions of a landscape, and typically only for a short period of time. At larger spatial and temporal scales, mesoscale and synoptic features such as mesoscale convective complexes (MCCs), mesoscale convective systems (MCSs), tropical storms, extratropical (mid-latitude) cyclones and tropospheric ridges and troughs may impact larger areas for several days to maybe as long as several weeks. Finally, macroscale atmospheric features associated with planetary long waves and ocean-atmosphere teleconnections are also known to impact large geographic areas (hemispheric scale), where flooding may persist for extended periods of time (Hirschboeck, 1988; Hirschboeck et al., 2000).

Pennsylvania lies within the Appalachian region and is particularly susceptible to severe flooding, including high incidences of flood-related deaths and damage (LaPenta et al., 1995; Yarnal et al., 1999), yet a recent and detailed examination of flood-generating mechanisms has not been conducted. This study aims to identify seasonal variations in meteorological flooding and flood-generating mechanisms within relatively unimpaired (free of anthropogenic disturbance) portions of the upper Allegheny River Basin (uARB) in Northwestern Pennsylvania (Figure 1). The Allegheny River Basin lies within the Allegheny Plateau Physiographic Province and drains portions of Pennsylvania and New York. Much of the uARB is covered in forest today (Figure 1) and includes the Allegheny National Forest (Allegheny National Forest, 1996). The results of this study may be important to a variety of water resource questions including flood frequency analysis and hazard assessment, flood forecasting, and water resource planning and management within the watershed.

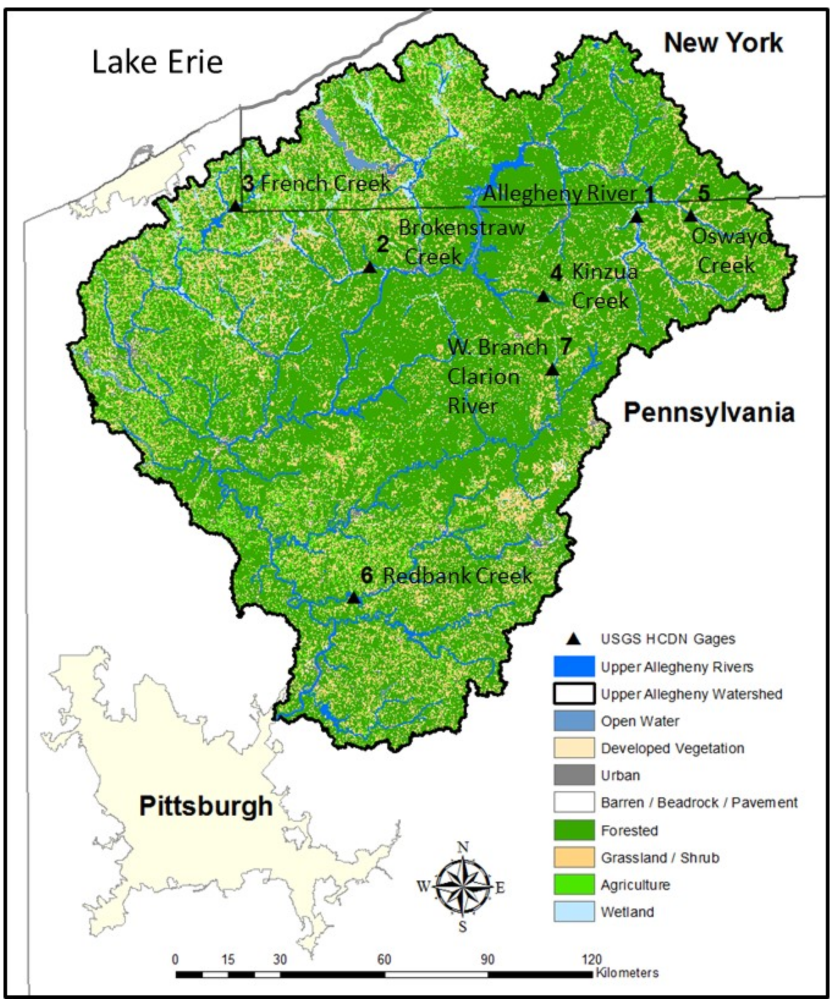

Figure 1. Geographic location of the Allegheny River Watershed in western Pennsylvania. Cartography by the author and Dr. Chris Schaney.

DATA AND METHODS

Annual peak streamflow datasets (annual flood series) of streams listed within the 2009 version of the US Geological Survey's Hydroclimate Data Network (USGS-HCDN) database (http://water.usgs.gov/osw/hcdn-2009/) were downloaded from the USGS website (http://waterdata.usgs.gov/pa/nwis/inventory/) and used to develop an understanding of flood seasonality, as well as spatial and temporal variability of flooding within the uARB. The USGS-HCDN consists of gaging stations with upstream drainage areas that are thought to be relatively unimpaired and therefore useful in climatological studies (Lins, 2012; Slack and Landwher, 1992). USGS-HCDN gaging stations with greater than 30 mi^2 upstream area were included in this study (Figure 1; Table 1). Two additional gaging stations with long streamflow records (Allegheny River and Redbank Creek) were included in this study because they are listed within a former version of the USGS-HCDN database (Slack and Landwehr, 1992), and because their streamflow records include two very intense orographically enhanced rainfall events that produced large floods: the July 1942 Smethport storm which impacted the upper Allegheny River, and the July 1996 storm which impacted Redbank Creek. For detailed analyses of Smethport and Redbank Creek events, the reader is referred to Yarnal et al. (1999) and Smith et al. (2011).

Table 1. USGS-HCDN gaging station information

Station Name	**Latitude**	**Longitude**	**Drainage Area**	**Gage datum**	**Yrs. of record**
Allegheny River at Eldred, PA	41° 57' 48"	78° 23' 11"	550 mi^2	1416.53'	100
Brokenstraw Creek at Youngsville, PA	41° 51' 09"	79° 19' 03"	321 mi^2	1186.92'	106
French Creek near Wattsburg, PA	42° 00' 55"	79° 46' 58"	92 mi^2	1304.00'	41
Kinzua Creek near Guffey, PA	41° 45' 59"	78° 43' 08"	38.8 mi^2	1540.00'	50
Oswayo Creek at Shinglehouse, PA	41° 57' 42"	78° 11' 54"	98.7 mi^2	1460.34'	41
Redbank Creek at St. Charles, PA	40° 59' 40"	79° 23' 40"	528 mi^2	973.14'	106
West Branch Clarion River at Wilcox, PA	41° 34' 31"	78° 41' 33"	63 mi^2	1502.02'	62

Annual peak flows (floods) from each of the seven USGS-HCDN gaging stations were first separated by month and then aggregated by meteorological season: Winter (December-January-February, DJF); Spring (March-April-May, MAM); Summer (June-July-August, JJA); and Fall (September-October-November, SON) for each gaging station. Monthly totals were used to identify the month with the most and least flood occurrences. In addition, all seasonal gaging station records were aggregated into a representative composite of the uARB so that seasonality and variability could be identified.

A decision tree approach to flood-generating mechanisms has been used in numerous studies (e.g Maddox et al., 1979; Hirschboeck, 1987; LaPenta et al., 1995; Gamble and Meentemeyer, 1997; Gaffin and Hotz, 2000; Ashley and Ashley, 2008b; Collins et al., 2014) and is used herein to develop a synoptic climatology of flood-generating mechanisms based upon atmospheric conditions immediately preceding and during each flood date recorded within the USGS annual flood series for each USGS-HCDN site. Synoptic classification of flood-generating mechanisms was performed on a sub-set of the annual flood series for water years 1995-96 until 2014-15 to ascertain flood-generating mechanisms operating in the uARB. The decision tree approach can be considered a type of manual classification system that employs an environment-to-circulation approach as described by Yarnal (1994), and focuses first on separating snowmelt vs. non-snowmelt flood events, and secondly on identifying more specific flood-generating mechanisms for non-snowmelt floods. Flood-generating mechanisms were identified as related to either snowmelt (e.g snowmelt or rain-on/after-snowmelt), synoptic scale frontal boundaries (e.g cold front, warm front, stationary front) which may include convective precipitation generated by atmospheric instability associated with the frontal boundary, tropical systems (e.g. hurricanes, tropical storms, tropical depressions or remnants of tropical systems), or "other" (e.g. upper air disturbances, lack of a defined surface front). Flood-generating mechanisms were manually interpreted from analyses of daily surface weather and upper air maps (e.g. 500 hPa) (http://www.lib.noaa.gov/collections/imgdocmaps/daily_weather_maps.html), NOAA-NWS Storm Data Publication (https://www.ncdc.noaa.gov/IPS/sd/sd.html), and during the winter months from snow cover extent maps (https://www.ncdc.noaa.gov/snow-and-ice/snow-cover/). Snow Cover Extent maps are only currently available in digital form since 2002, so snowmelt events that occurred prior to then were determined from NWS Cooperative Observer Program (COOPs) files, daily weather maps and Storm Data publication information so that a twenty (20) year record could be developed. Storm Data Publication information were examined for numerous days immediately preceding and the day of annual peak flow events to gather additional information pertaining to the flood events. Similar to the seasonality results, synoptic classifications are first identified for each individual gaging station and then aggregated into a composite summary for the uARB.

RESULTS AND DISCUSSION

Flood Hydrology

Meteorological floods throughout the uARB can occur during any month of the year. Under the humid temperate climate of the eastern United States all USGS-HCDN gaging stations used in this study are perennial. Although the Allegheny River has been regulated by numerous small dams and the large Kinzua Dam for flood control purposes since 1966 (Allegheny National Forest, 1996), low flows above and below the dam primarily occur from July through October based on USGS daily and monthly streamflow data (not shown). Summing and compositing the monthly totals for each of the studied USGS-HCDN station within the uARB (Figure 2) shows that the majority of floods recorded occur during the winter and spring (75%). Individual gaging station summaries are available upon request to the author. The majority of those floods occur during from January through April (61%). The largest monthly proportion of those peak annual flows occur during the month of March (21%), primarily in the middle and later part of the month and related to the passage of extra-tropical cyclones across the region (discussed in the hydroclimatology section below). All three gaging stations with > 100 years of record, Allegheny River, Brokenstraw Creek and Redbank Creek, indicate March is a favorable month for the generation of peak maximum flows in both the northern and southern portions of the uARB (see Figure 1 for gaging station locations). December (8%) experiences the least peak annual flows during the winter months and May (6%) the least during the spring months. Conversely, the summer and fall do not typically produce a large proportion of peak annual flows, even though the atmosphere typically contains high values of precipitable water vapor, especially during July (Hirschboeck, 1991). During the summer, June experiences the highest percentage of peak annual flows (6%) and during the fall, November peak annual flows account for another 6%. August (late summer) often experiences low flow conditions in the uARB, thus peak annual flows within the uARB tend to be rare, accounting for only 1.6% of the total. October peak annual flows are the second least common (3%). The lack of organized synoptic-scale systems (Mid-latitude Cyclones) passing over the uARB during the summer and fall may be related to the lack of peak annual flows that occur during June through November.

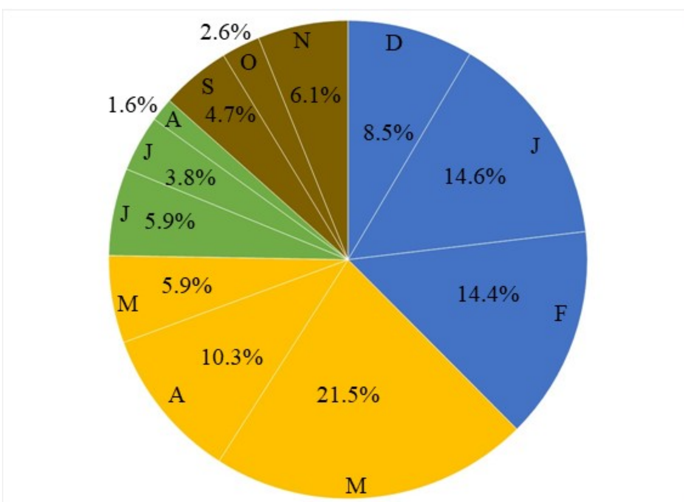

Figure 2. Seasonal distribution of annual peak flows for the uARB based on USGS-HCDN gage records. Note: for figures 2-4 DJF = Winter (blue); MAM = Spring (gold); JJA = Summer (green) and SON = Fall (brown).

When top-ten ranked floods are examined for the entire period of record at each of the USGS-HCDN gaging stations within the uARB, March and January combine to produce 40% of the largest floods (Figure 3). The winter season as a whole produces the most top-ten floods (40%), with spring recording the second most (26%). A relatively large percentage of top-ten floods occurs in June (14%), which is more than any other month during the summer and fall seasons (Figure 3). Fall as a whole produces the least number of top-ten ranked floods (11%).

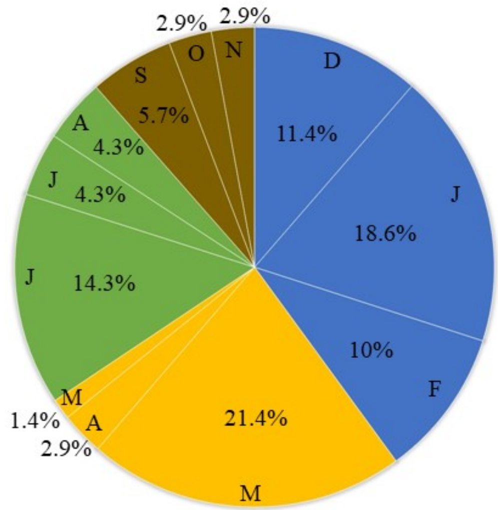

Figure 3. Seasonal distribution of the "Top 10" largest floods identified in this study.

Hydroclimatology

Flood-generating mechanisms for all peak annual flows for the seven USGS-HCDN gaging stations within the uARB were classified over a 20 year period covering the 1995-96 through 2014-15 water years. Out of 140 possible peak annual flow events that occurred during this 20 year period, 24 events (17%) fall within the top 10 flows for the entire period of record at each of the uARB USGS-HCDN stations (Figure 4). Thirteen of the 24 (54%) top-ten ranking peaks flows during the 1995-96 through 2014-15 water years in the uARB were generated by snowmelt or rain-on-snow processes (snowmelt-related), all of which occurred in either January or March (Figure 5). Large floods during February are conspicuously absent from top-ten ranking flows.

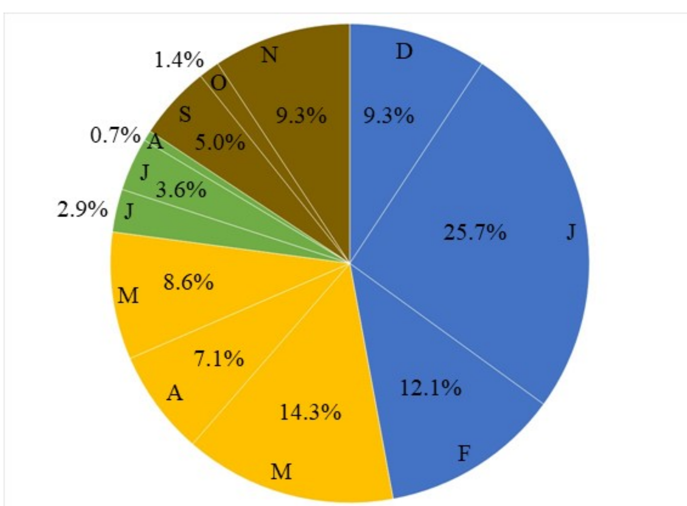

Figure 4. Seasonal distribution of peak annual flows during the 1995-96 through 2014-15 water years.

The impact of snowmelt flooding on the uARB should come as no surprise to many, as the study area lies within Northwestern Pennsylvania which receives some of the highest snowfall totals encountered anywhere in Pennsylvania due to "lake effect" snows produced by the Great Lakes. Snowmelt-related events over the classified 20 year period are the dominant flood-generating mechanism in the uARB and account for ~65% of all peak annual flows from December through early April (Figure 5). During most years, snowmelt-related peak annual flows occur on or within a few days of each other (e.g. January 24th-26th, 1999 and January 25th-27th, 2010). Winter flooding not related to snowmelt also does occur throughout the uARB, particularly in December, late March and April when frontal passages are associated with air temperatures above freezing and no snow pack is present. Ice-jam flooding may occur throughout northern Pennsylvania, including the uARB, concurrently with snowmelt and non-snowmelt flood events (e.g. Deck and Gooch, 1981; Leathers et al., 1998), but is not specifically addressed in this study.

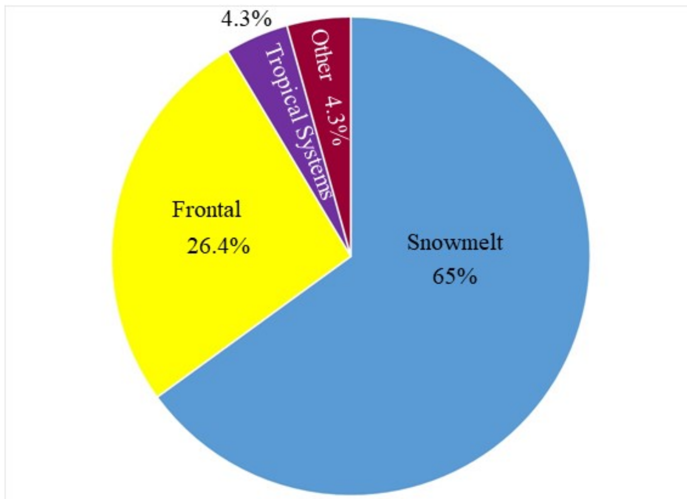

Figure 5. Flood-generating mechanisms manually interpreted for the uARB.

In contrast to years when snowmelt often leads to essentially contemporaneous basin-wide flooding, other years peak annual flows are generated on numerous dates and by several flood-generating mechanisms (data available upon request). For example, during the 1999-2000 Water Year peak annual flows were generated on November 3rd, 1999, February 27th-29th, 2000, April 4th and 8th, 2000, and August 16th, 2000. Snowmelt-related flooding was only present during the February event during the 1999-2000 Water Year, while warm season frontal passages were responsible for the other peak annual flow events. As a whole, frontal passages account for 26% of peak annual flows generated within the uARB (Figure 5). The 2000-2001 Water Year saw similar mixed flood-generating processes producing peak annual flows during Winter and Spring. Mesoscale convection is sometimes associated with frontal passages and the production of training storm cells, which are known to produce peak annual flows. The complex topography of the Appalachian highlands also lends itself nicely to orographic enhancement of precipitation (e.g. July 19th, 1996; see Smith et al., 2011 for a detailed discussion). On occasion tropical systems pass over the region and are responsible for producing the annual maximum flows (e.g. Hurricanes Frances and Ivan in 2004), but their scarcity in the overall flood record (4%) is easily recognized (Figure 5). However, the importance of orographic enhancement, training storm cells and hurricanes is evident within the Redbank Creek streamflow datasets where heavy precipitation from training thunderstorm cells produced the largest flow on record for Redbank Creek (July 19th, 1996) and Hurricane Ivan (September 19th, 2004) produced the second largest discharge, which was roughly half of the discharge generated by Ivan. Finally, 4% of the peak annual flows within the uARB were generated by "other" processes or the process could not be determined from the data sources examined in this study (Figure 5). "Other" flood-generating processes could include, but are likely not limited to: upper air disturbances or lack of a defined surface front shown on Daily Weather Maps.

CONCLUSIONS

Like other research throughout eastern North America (e.g. Ashley and Ashley, 2008b; Berghuijs et al., 2016; Collins et al., 2014; Villarini, and Smith, 2010; Frei et al., 2015; Berghuijs et al., 2016), this study has identified seasonal variations in flooding within a relatively small geographic area, and documented numerous meteorological flood-generating mechanisms contribute to the annual flow series. The dataset compiled in this study clearly demonstrates that snowmelt-related flooding is the dominant flood-generating mechanism in the uARB, primarily from December through early April over the period of 1995-96 through 2014-15. It should also be highlighted, that intense rainfall generated by frontal passages, tropical storms or other meteorological conditions can generate peak annual flows during the cold and warm seasons. Detailed information on flood seasonality and flood-generating mechanism presented in this study can be used to update and refine flood frequency analysis and flood forecasting, flood hazard assessment and water resource management in the uARB.

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