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METEOROLOGIC, HYDROLOGIC, AND GEOGRAPHIC CHARACTERIZATION OF HISTORIC FLOODS IN THE DELAWARE RIVER BASIN

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ABSTRACT: *The nature of historic floods in the Delaware River Basin (DRB) can provide resource managers insights into how best to prepare for future flooding under changing conditions of climate and land cover. Floods exceeding a 10-year recurrence interval were investigated at 33 sub-watersheds in the DRB where U.S. Geological Survey gages provide 50 or more years of discharge data. Those sites span a wide range of drainage area, land cover, and soil conditions. Each of 282 flood events was assessed with regard to flood magnitude, the meteorology of flood-generating precipitation events, antecedent rainfall, snow melt, land cover, soil type, basin scale, and geographic location. Tropical cyclones generated the most floods, including the majority of "major floods" that exceeded a 50-year recurrence interval, while multi-day events characterized by stalled cyclonic systems were the second most common driver of floods. Wet antecedent moisture conditions were often, but not always, associated with floods. Snow cover existed for only 20% of flood events, with substantial snowmelt less common and very rare for major floods. Snow influenced flooding somewhat more frequently at sites north of 40.2° latitude and rarely further south. Greater watershed forest cover was associated with more, rather than less, runoff production, a result that likely reflects rugged topography and more frequent snow cover in those northern watersheds. The sites with the highest percentage of developed land and those with predominantly low-infiltration soil types also produced greater peak discharges.*

Keywords: *Floods hydrology, meteorology, Delaware River Basin, land cover, soil type*

INTRODUCTION

Flood magnitude and frequency may change in response to shifts in weather events, snowmelt, antecedent soil moisture, and land cover change. Slater and Villarini (2016) describe substantial regional variation in recent U.S. flood frequency trends, with increasing risk in some areas and decreasing risk elsewhere. They describe flood risk in the Delaware River Basin (DRB) as increasing, although not at a statistically significant ($p<0.05$) level. Recent major floods in the DRB have generated questions about watershed management and the potential to redress the impact of future floods (Smith et al., 2010). This paper examines the meteorology, hydrology, and geography of large historic floods across the DRB. An improved understanding of common flood-generating characteristics will help resource managers guide future decisions with regard to flooding under changing land cover, climate, and watershed management.

Smith and others (2010) review floods in the DRB and emphasize three primary meteorological drivers: tropical cyclones, late winter or early spring extratropical systems, and warm season convective systems. The largest floods were most commonly generated by tropical cyclones, but those systems account for relatively few smaller floods. Winter–spring extratropical systems were the largest contributor to annual flood peaks in the DRB. The importance of warm season convective systems to floods in the DRB depends on basin scale, with the greatest frequency in smaller basins. Their study also addressed the role of snowmelt in flood hydrology, concluding that because the largest floods are warm season events associated with tropical cyclones, snowmelt influence is generally limited to smaller, more frequent flood events. Orographic effects also influence DRB flood climatology. Smith et al. (2010) describe storms that generated large flood events as having maximum rainfall over the highest elevation mountains and headwater catchments in those areas producing the largest runoff values.

DRB flood processes are clearly influenced by changes in climate and land cover. Much of the focus on how climate change may alter DRB flood hydrology has emphasized patterns of snow accumulation and melt (Wolock et al., 1993) and would thus appear to affect primarily high frequency, low-magnitude floods. The potential for changing frequency of tropical and extratropical systems has also been addressed, but with little consensus on how such changes would affect the northeastern United States (Smith et al., 2010). Urban development has affected flooding in some smaller DRB sub-watersheds, but those effects are not detectable at larger basin scale along the main stem of the Delaware River (Smith et al., 2010).

Berghuijs and others (2016) examined regional differences in flood-generating mechanisms and the roles of factors other than event precipitation. They note the role of antecedent soil moisture in runoff generation, as affected by antecedent precipitation, snowmelt, and seasonal differences in evapotranspiration. In reviewing watersheds across the U.S., they find the dominant flood generating processes at a given location to be strongly linked to the time of the year that major floods occur. In the northeast U.S., including the DRB, most maximum annual precipitation events occur during late summer, but precipitation excess is generally highest during late winter and early spring (Berghuijs et al., 2016). In the Catskills region of the DRB, this is borne out by the highest probability of flood occurrence during March, followed by April and December (Weller et al., 2000).

Much of the prior work addressing DRB flood hydrology has considered floods ranging in magnitude from annual events, which have a key role in fluvial geomorphic processes, to the largest events, which can cause extensive damage and economic impact. This study focuses on large flood events with recurrence intervals exceeding 10 years. The meteorologic, hydrologic, and geographic characterizations made here will thus differ from prior studies, as the roles of those factors vary depending on the flood event scale considered (Smith et al., 2010).

METHODS

This study examined sub-watersheds within the Delaware River Basin (DRB), which drains 35,075 km^2 in New York, New Jersey, Pennsylvania, Delaware, and Maryland (Figure 1) and includes a 2010 population of approximately 8.2 million people (Williamson et al., 2015). Landscapes across the DRB vary considerably with regard to topography, land cover, climate, and hydrology. The northern headwaters are in the Catskill Mountains in southeastern New York, a landscape of steep slopes and dominantly forested land cover. Further south, the local relief diminishes as the river crosses the Ridge and Valley Province, the Reading Prong, the Piedmont, and the Atlantic Coastal Plain where the river discharges into Delaware Bay (Fenneman, 1917). The central portion of the watershed supports significant agricultural land cover while the lower watershed is influenced by urban areas, including Allentown-Bethlehem, Philadelphia, Trenton, and Wilmington.

The climate of the DRB ranges from humid subtropical (Köppen Cfa) in the Delaware Bay region to humid continental upstream of Philadelphia (Köppen Dfa and Dfb) (Kottek et al., 2006). Average annual precipitation in the DRB ranges from 1050 mm in the south to 1270 mm in the higher elevation north (Jenner and Lins, 1991). The general hydrology is dominated by rainfall-runoff processes, with snowmelt of increasing importance in the northern, higher elevation headwaters (Jenner and Lins, 1991). Flood control efforts include several dams and reservoirs built largely in the 1950s and 1960s, affecting reaches of the East and West Branches of the Delaware River, and the Lackawaxen, Neversink, Mongaup, Lehigh, and Schuylkill Rivers and Brandywine Creek (Smith et al., 2010, Williamson et al., 2015). The effects of reservoir regulation do not extend far downstream of the source of regulation and there are minimal impacts on flood peaks in the main stem Delaware River (Smith et al., 2010).

U.S. Geological Survey (USGS) river discharge gages were selected to include watersheds draining at least 50 km^2 and including a historic record of at least 50 years of discharge data. Impacts of reservoir regulation on flood flows were not considered, as the goal was to examine floods under actual watershed conditions. The sites meeting those criteria were reviewed to insure that they represent a broad range of geographic conditions, including location, scale, land cover, and climate (e.g. potential snowmelt influence on hydrology). The selected sub-watersheds include 72% of the DRB drainage area. Annual flood peak data (instantaneous maximum discharge) for the full historic record were obtained (USGS, 2016) and the recurrence interval of each event was calculated using the log Pearson type III distribution (Interagency Advisory Committee on Water Data, 1982). The peak discharges equaling or exceeding a 10-year recurrence interval were included in the data set for further examination and are referred to as “flood events,” while discharges exceeding a 50-year recurrence interval are termed “major flood events.”

Sub-watershed land cover and soil cover were calculated using the wiki watershed GIS tool (Stroud Water Research Center, 2016). Land cover was based on the National Land Cover Database (Homer et al., 2015) and included percentages of forest (including shrub/scrub), agriculture, developed land, and wetlands (including open water). Sub-watershed soil cover was mapped from gSSURGO 2016 data (USDA-NRCS, 2016) categorized into Hydrologic Soil Groups based on infiltration rates (USDA-NRCS, 2007). Group A soils have the greatest infiltration capacity while group D soils have the least. When assessing the influence of watershed scale, land cover, and soil type on flood magnitude, peak discharge was normalized for drainage area and precipitation totals that include the flood event plus seven days antecedent to generate a “peak water yield” (i.e. peak discharge per area per precipitation depth) for each event. Total precipitation was defined as such in this analysis, as it was more strongly correlated with peak flood discharge than calculations based on other durations of antecedent precipitation.

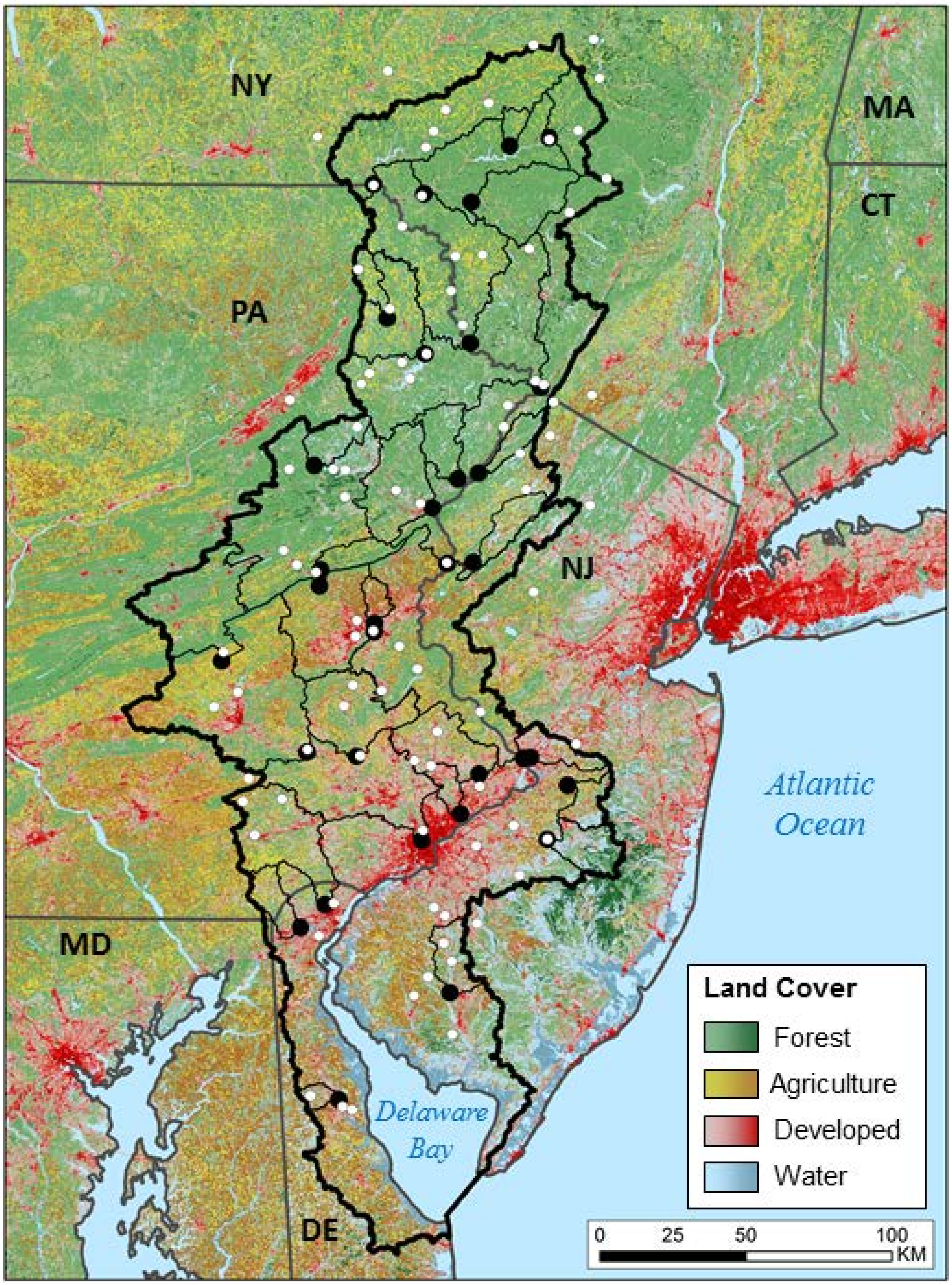

Figure 1. The Delaware River Watershed with USGS stream gages (black circles), corresponding watershed boundaries for study sites, weather stations (white circles) and 2011 land cover (National Land Cover Database; Homer et al., 2015).

The flood events were classified based on the meteorology of the flood-generating weather event as indicated by visual inspection of daily weather maps (NOAA, 2016a) and available studies describing key historic flood events (Mangan, 1942; Bogart, 1960; Lumia, 1998; Perry et al., 2001; Reed and Protz, 2007; Suro et al., 2009; Lumia et al., 2014; Watson et al., 2014). Floods were considered as generated by independent weather events if they were separated by at least seven days. Daily weather data were compiled for NOAA observation stations in and near the DRB, including precipitation, snowfall, snow depth, and minimum and maximum temperatures (NOAA, 2016b). Data from 93 weather stations were used to maximize spatial coverage across the selected sub-watersheds for the historic flood events (Figure 1). Sub-watershed mean daily precipitation values were calculated as an arithmetic average of weather stations located within 20 km of the sub-watersheds, using between 1 and 12 stations depending on drainage area and available data for each historic flood event. For cases in which data were available from two or more weather stations located in close proximity (<20 km), the daily values for those stations were averaged and included in the sub-watershed mean precipitation calculation as a single value.

A number of summary statistics were calculated for the daily weather conditions immediately prior to the flood event. Event precipitation was defined as the total precipitation recorded on the date of peak discharge and the following day, which was included since many weather stations report 24-hour totals that include precipitation on the preceding calendar day that may have occurred prior to the flood peak. Antecedent precipitation totals were calculated for three, five, seven, 14, and 30 days to characterize soil moisture and streamflow conditions prior to the flood event. The antecedent moisture condition (AMC) was calculated following USDA-NRCS classes (USDA-SCS, 1964) of dry, average, and wet (AMC I, II, and III) defined by five-day antecedent precipitation amounts that are greater for the growing season (May – October) than the dormant season (November – April).

The contribution of snowmelt to runoff was assessed in two ways to categorize flood events. A simple Boolean function was used to note if any snow was on the ground within three days prior to the flood event and the snow melt prior to the flood event (as a simple depth) was assessed by subtracting snow depth on the date of the flood event from that which existed seven days prior. Snow water equivalent values were not available for the majority of weather stations and were not assessed. Flood events influenced by significant snowmelt were defined as those with seven-day reduction in snow depth exceeding 250 mm.

RESULTS AND DISCUSSION

A broad range of geographic conditions is represented in the 33 sub-watersheds selected for examination (Table 1). Watershed scale (drainage area), land cover, and soil conditions all vary substantially between the watersheds, providing a useful dataset to evaluate the influences on historic flood magnitude and frequency. Elevation and local relief were not quantitatively evaluated, but the sampled sub-watersheds are distributed across all DRB physiographic provinces and include a wide range of topography. The dataset of floods with recurrence intervals greater than 10 years includes 282 events from 1902 to 2016. Flood magnitudes for some of the historical data series may have been affected by reservoirs at six of the 33 sites, as indicated by USGS (2016) notation and examination of historical flood series (Smith et al., 2010; Williamson et al., 2015).

Table 1. Characteristics of the 33 Delaware River Basin sub-watersheds for which historic flood events were analyzed.

Variable	Min	Median	Mean	Max	St Dev
Drainage area (km^2)	82.6	543.9	2061.7	17560.1	3778.5
Record (years)	51.0	84.0	84.8	112.0	15.5
Forest (%)	8.5	61.5	55.2	91.4	24.8
Agriculture (%)	0.3	18.0	18.2	51.9	12.4
Developed (%)	2.2	11.2	17.5	77.6	17.0
Water and wetlands (%)	0.6	5.2	8.7	32.4	8.6
HSG A (%)	1.2	8.4	13.3	63.8	14.5
HSG B (%)	0.1	11.2	19.4	59.7	17.6
HSG B/D (%)	0.3	2.6	4.2	38.5	6.8
HSG C (%)	10.8	29.9	30.5	73.6	13.7
HSG C/D (%)	0.0	5.9	6.3	24.2	5.8
HSG D (%)	0.0	28.6	26.2	65.5	19.3

Note: HSG refers to the USDA Hydrologic Soil Groups.

Meteorology of flood-generating weather events

A total of 79 independent weather events generated the 282 floods examined. The majority (85%) of weather events generated floods at five or fewer stream gage locations while a few events affected 11-18 sites. The meteorology of flood-generating weather events included five storm types (Table 2, Figure 2). Tropical cyclones are the most common cause of large flood events in the DRB, generating 117 of 282 events (41%) and were responsible for the majority of major floods (29 of 46 floods (63%) with recurrence interval >50 years). The other major floods were caused by multi-day stalled cyclones (eight events), extra-tropical cyclones (seven events), and convective cold fronts (two events). Examination of the largest floods ever recorded (the "flood of record") at the 33 stream gages further illustrates the significance of tropical cyclones in the DRB, which generated 26 of the 33 events, including Hurricanes Diane (1955, 10 events), Agnes (1972, 4 events), and Irene (2011, 7 events). Tropical cyclones caused 22 of 27 major floods (82%) on smaller watersheds (<1,000 km^2) and 7 of 19 major floods (37%) on larger watersheds. Hurricane Connie preceded Diane by 10 days, but did not generate DRB floods exceeding the 10-year event, while Lee, following 10 days after Irene, generated >10 year floods at six of the sampled DRB stations.

Table 2. Meteorology of floods exceeding a 10-year recurrence interval for the 33 sub-watersheds of the DRB.

Type of event	Number of weather events (n, %)	Number of stream gage events (n, %)	Average number of sub-watersheds impacted per event
Tropical cyclone	20 (25%)	117 (41%)	5.9
Convective thunderstorms	4 (5%)	5 (2%)	1.3
Convective cold front	11 (14%)	20 (7%)	1.8
Extra-tropical cyclone	20 (25%)	63 (23%)	3.2
Multi-day events (stalled cyclones)	24 (30%)	77 (27%)	3.2

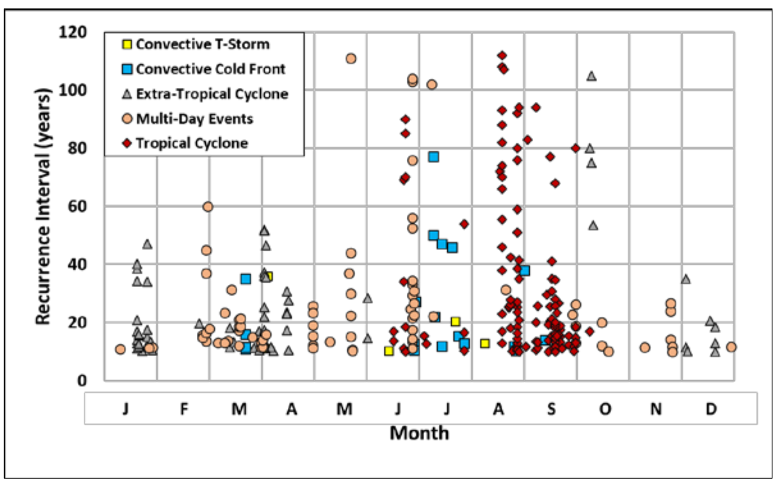

Figure 2. Distribution of DRB flood events by month and meteorology category.

Seasonality of flooding

The majority of flood events occurred in the warm season of May to October, with 185 of 282 (66%) events in that period and only 34% in the other six months (Figure 2). A higher percentage of major floods were in the warm season (43 out of 46 events, 93%) with only three major events (7%) in the cool season. All 33 flood-of-record events were in the warm season, with 26 of 33 events (79%) occurring in the summer (June-August) and none affected by snow.

Cool season events generally generate less total precipitation over the event and the preceding seven days (n = 97; mean = 103 mm) than warm season storms (n = 185; mean = 186 mm). Almost all warm season flood events were associated with at least 100 mm precipitation (94%) while many cold season events had less than 100 mm precipitation (53%). Warm season precipitation events are capable of producing very high rainfall amounts, with 11 floods generated by over 300 mm of total precipitation. These results are consistent with the important role of seasonality in soil moisture conditions antecedent to the flood-generating storm (Berghuijs et al., 2016).

Snowmelt influence

Snow was not a common characteristic of large flood events, with only 57 of 282 (20%) events having measureable snow on the ground within three days prior to the peak flow and only 24 of those events (9%) having snowmelt over seven days prior to the flood date exceeding 250 mm of snow depth (Figure 3). Of the major flood events, only two of 46 (4%) had snow on the ground within three days prior to the flood and only one (2%) had a seven-day snowmelt of more than 250 mm. Snow had a slightly more frequent influence on flooding in large watersheds (>1,000km^2), affecting 26% of floods compared to 17% of events on smaller watersheds. Floods in the 24 watersheds north of 40.2° latitude were affected by snow more frequently (26% of events) than the nine more southerly watersheds (3%).

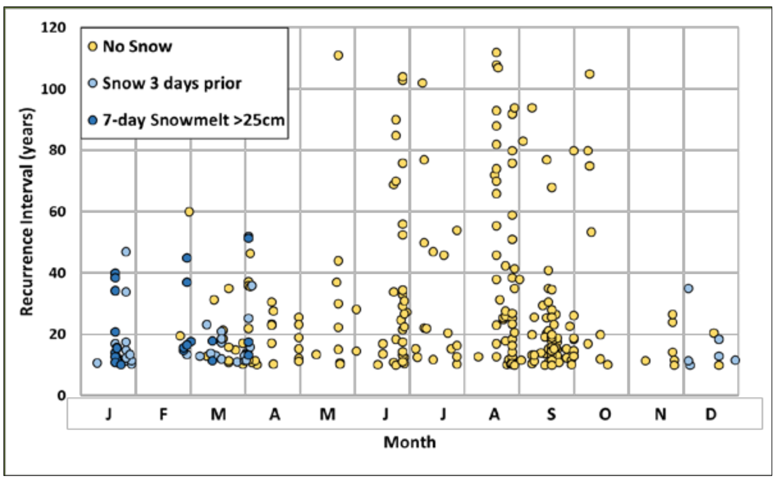

Figure 3. Distribution of DRB flood events by month and snow influence.

Berghuijs and others (2016) found that many annual floods in the northern DRB and nearby watersheds are generated by rain-on-snow events. Given the infrequent influence of snowmelt on larger magnitude floods identified in this study, the stronger influence of snowmelt that they report is likely limited to lower magnitude (<10 year) flood events.

Antecedent moisture

Antecedent moisture is a key driver of most, but not all, DRB floods (Figure 4). Of the 282 flood events, 176 (62%) were under "wet" conditions (USDA Antecedent Moisture Condition III), with 106 events (38%) under "dry" or "average" conditions (AMC I or II). Of the major flood events, 34 of 45 events (76%) were in wet antecedent conditions. Most flood-of-record events (24 of 33, 73%) occurred with wet antecedent conditions. While pre-flood soil moisture conditions clearly influence runoff generation and flooding, it is significant that major floods are not uncommon in periods with dry or average antecedent moisture.

Total precipitation

Flood magnitude (recurrence interval) was correlated with various measures of precipitation including the two-day event total as well as that value plus antecedent precipitation falling over three, five, seven, 14, and 30 days prior. The strongest correlation was with event precipitation plus seven days of antecedent precipitation (R^2 = 0.22). Using that nine-day precipitation total, the percentage of flood events is fairly evenly split between precipitation of less than 150 mm (143 events) and more than 150 mm (139 events). Most of the major floods (40 of 46, 87%) were generated by precipitation totals in excess of 150 mm.

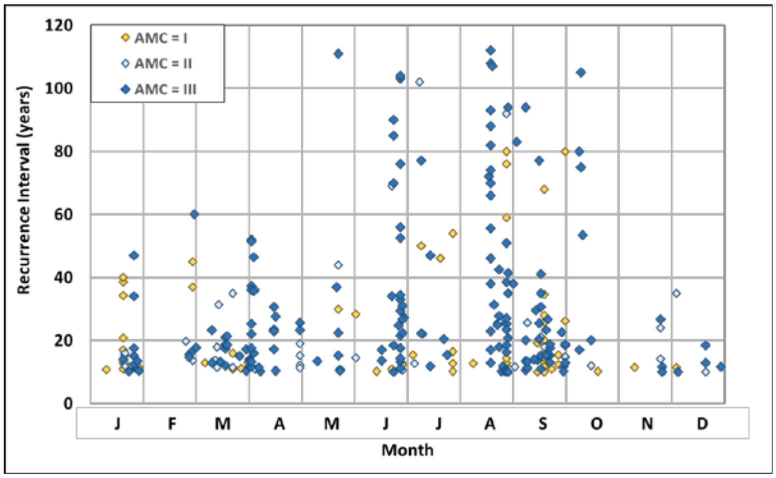

Figure 4. Distribution of DRB flood events by month and antecedent moisture condition.

Combined effects of precipitation and land cover

Peak water yield values ($m^3 s^{-1} / km^2 /100$ mm precipitation) were averaged for each of the 33 watersheds and evaluated with respect to watershed land cover and soil conditions (Table 3). Greater sub-watershed forest cover does not reduce the generation of flood flows (Figure 5). In fact, the highest peak water yields occur in watersheds with the greatest (>75%) forest cover. This counterintuitive result likely reflects the fact that those watersheds are located in the highest elevation and steepest topography of the northern Delaware River Basin, a landscape conducive to high runoff production (Smith et al., 2010). Those northern, forested watersheds are also more frequently affected by snow, with pre-flood seven-day snowmelt totals exceeding 250 mm for 11% of flood events compared to only 7% in the other watersheds. Perhaps more importantly, the watersheds with the least forest cover (<50%) and thus greater agricultural and/or urban land cover, do not show increased runoff production, illustrating that land cover has relatively little influence on the large magnitude DRB floods examined in this study.

Table 3. Peak flood flows normalized for drainage area and precipitation amount ("peak water yield") for all floods exceeding a 10-year recurrence interval across the 33 sub-watersheds of the DRB subdivided by watershed land cover and soil type.

Land cover or soil type	Watershed coverage (%)	Mean peak water yield ($m^3 s^{-1} /km^2/100$ mm precipitation)
Forest	9 - 50	0.60
Forest	50 - 75	0.61
Forest	75 - 91	0.74
Developed	2 - 10	0.72
Developed	10 - 20	0.43
Developed	20 - 40	0.68
Developed	40 - 78	0.84
Low infiltration soils (C and D)	11 - 50	0.54
Low infiltration soils (C and D)	50 - 95	0.71

Note: Land cover based on NLCD 2011 data. Soil groups C and D refer to NRCS hydrologic soil groups.

Watersheds with the greatest percentage of developed land (>40%) had somewhat higher runoff production than less developed watersheds and generated the greatest peak water yields of any land cover class (Figure 6). Watersheds with very little developed land also generated high peak water yields. Many of those are the same watersheds that are heavily forested and located in the northern, topographically rugged part of the DRB. Similarly, watersheds dominated by low-infiltration soils (>50% area in hydrologic soil groups C and D) had slightly higher runoff production than watersheds with higher infiltration soils (<50% C and D soils) (Figure 7).

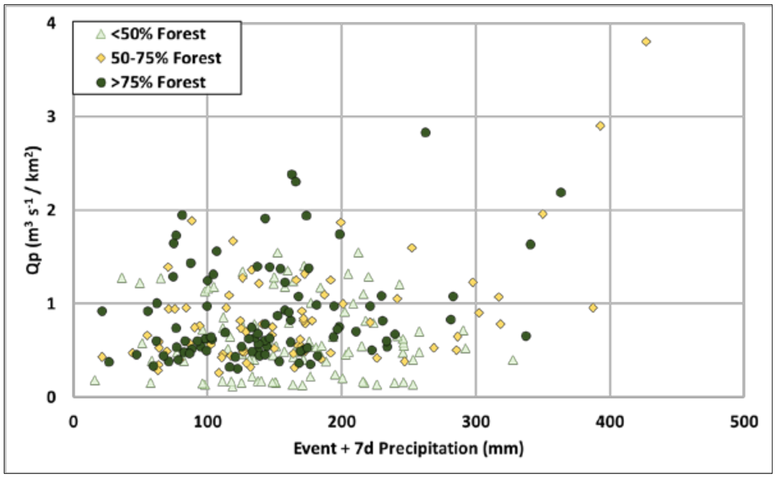

Figure 5. Relationship of normalized peak discharge to precipitation and forest land cover.

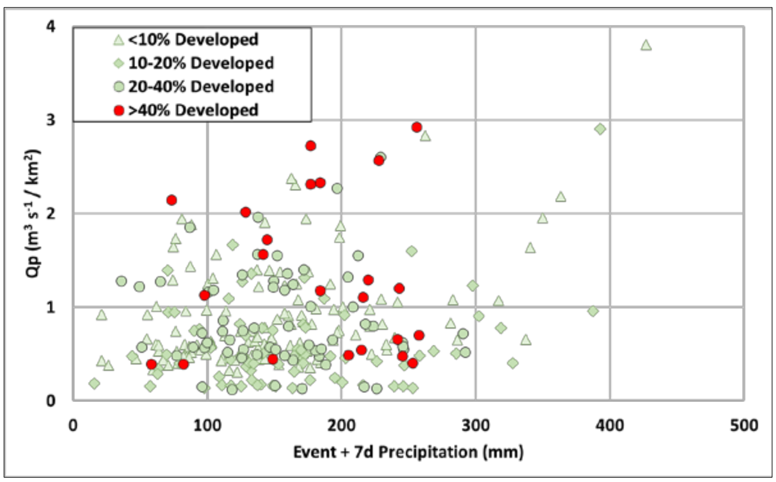

Figure 6. Relationship of normalized peak discharge to precipitation and developed (urban) land cover. Sub-watersheds with >40% developed land cover are shown in red to highlight the comparison with less developed sub-watersheds.

The relatively minor differences in peak water yield documented do not rule out the possibility that land cover and/or soil cover are important influences on DRB flooding. Land and soil cover differences would be expected to have a greater effect on small magnitude flood events (e.g. <10-year events) than on the larger flood events examined here (Schopp and Firda, 2008). It is important to recognize that the results of this study are limited to characterizing the hydrology of large flood events that exceed a 10-year recurrence interval. This explains some differences with prior studies that examined a wider range of flood magnitudes (Weller et al., 2000; Smith et al., 2010; Berghuijs et al., 2016) and found a greater role of snowmelt and winter-spring conditions than is the case for larger floods.

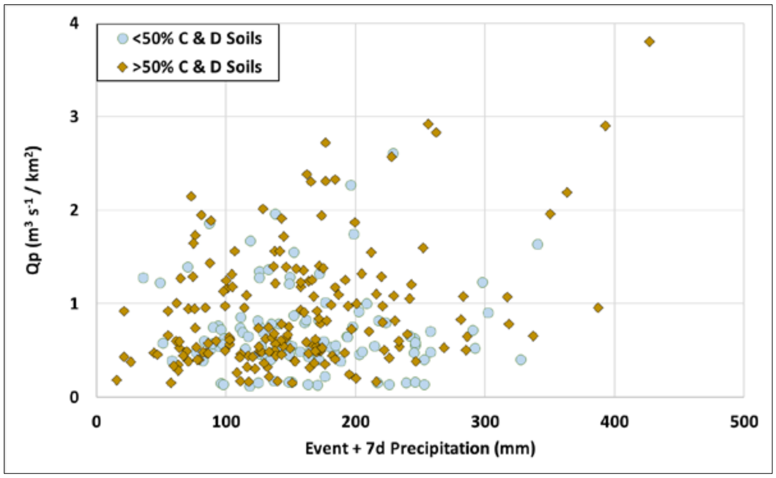

Figure 7. Relationship of normalized peak discharge to precipitation and soil type.

CONCLUSIONS

As resource managers face an uncertain future in which climate and land cover will continue to change, the results of this study help identify key factors that influence large magnitude floods in the DRB. Changes in the magnitude and frequency of tropical storms that move into the DRB would have a large influence on flooding, as these storms generate many large (>10-year) floods and the majority of major (>50-year) floods. Future climate changes that affect the amount and timing of snowmelt would appear to have a minor influence on larger floods, although those changes could affect the magnitude and frequency of smaller (<10-year) floods. Similarly, land cover differences, which would be expected to have a large influence on smaller floods, have a relatively minor influence on larger magnitude events.

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