

SEASONALITY OF FLOODING IN NORTH CAROLINA

Scott A. Lecce

This paper examines spatial patterns in the timing of floods in North Carolina. Regions with distinctly different seasonal flood regimes were identified using cluster analysis of monthly flood frequencies for the annual and partial duration series. The partial duration series produced results similar to those using the annual flood series, which was used to delineate three regions: the Appalachian Region, the Piedmont Region, and the Coastal Plain Region. In the Appalachian Region, about three-fourths of all floods occur during winter and early spring (December–April), while less than one fourth occur from May to November. The Appalachian Mountains are an effective barrier to warm, moist air masses that influence the rest of the state during the summer and fall. The frequency of floods in summer and fall increases to the east in the Piedmont and Coastal Plain regions, where maximum frequencies (~25–30%) occur during August–October. Although flooding in summer and fall is greater than in the Appalachian Region, floods still occur most frequently from January to April in the Piedmont (44%) and Coastal Plain (55%) regions. The smallest watersheds tend to experience a larger proportion of floods in summer and fall.

Key words: floods, seasonality, spatial patterns, North Carolina.

A variety of different atmospheric mechanisms (e.g., convective thunderstorms, extratropical cyclones, tropical cyclones, and rapid snowmelt) produce flooding in river systems by delivering precipitation in excess of that which a watershed is capable of absorbing or storing (Hirschboeck, 1991). These flood-generating mechanisms have different duration and intensity characteristics and are often dominant during different seasons. Consequently, hydrologic time series may consist of mixed statistical populations (Hirschboeck, 1988; Knox, 1988). The existence of mixed distributions is recognized as a problem in flood frequency analysis (U.S. Water Resources Council, 1981) because one of the basic underlying assumptions in the determination of flood probabilities, homogeneity in the flood series, is violated (Hirschboeck, 1987a, 1987b, 1988; Knox, 1988; Magilligan and Graber, 1996). The most common approach used to identify mixed populations of floods involves separating the flood series into seasons (Waylen and Woo, 1982, 1983; Diehl and Potter, 1987; Knox, 1988). Although hydrologists can potentially improve flood frequency estimates by separating flood series into homogeneous, meteorologically defined subgroups (Hirschboeck, 1987b), it is not surprising that such research is relatively uncommon since it may require the painstaking review of daily weather charts for each event. It may be useful, therefore, to examine seasonal characteristics of floods in order to define regions or watersheds where mixed distributions are problematic before proceeding with more extensive analyses.

Dr. Lecce is an Assistant Professor of Geography, Tobacco Road Research Team, East Carolina University, Greenville, NC 27858. Internet: lecces@mail.ecu.edu.

Although recent studies have shown that the timing of floods may vary spatially in the Southeastern United States (Gamble, 1997; Lecce, 2000), the flood characteristics of this region are more often viewed as relatively homogeneous (Hayden, 1988; Hirschboeck, 1991). The purpose of this paper is to characterize spatial patterns in the tendency for floods to occur in particular seasons in North Carolina.

Data and Methods. Flood data were obtained from the 1994 EarthInfo Inc. CD-ROM. This database contains peak discharge values for the annual and partial-duration series acquired from the U.S. Geological Survey (USGS) WATSTORE peak flow file. The annual flood series consists of the largest flood event recorded during each year, while the partial-duration series includes all events that exceed a critical base discharge defined by the USGS. Station records were deleted if they were influenced by regulation, diversion, dam failures, mining, or urbanization. The remaining stations each contained a minimum of 30 years of record, resulting in 126 stations with annual flood records and 100 stations with partial floods.

Cluster analysis provided an objective method to identify regions with relatively homogeneous seasonal flood characteristics (Mosley, 1981; LeBoutillier and Waylen, 1993). The k-means clustering algorithm is a nonhierarchical clustering technique that defines distinct clusters by moving objects from cluster to cluster with the goal of minimizing the within-cluster variance and maximizing the between-cluster variance (StatSoft, 1996). This technique is appropriate for use with large data sets (Hartigan, 1975; Afifi and Clark, 1990). Because the algorithm would rely most heavily on the variable with the greatest range of values, the variables (percentage of floods occurring each month) were standardized to a mean of zero and a standard deviation of one (Afifi and Clark, 1990; StatSoft, 1996). Although no standard procedure exists for selecting the number of clusters, clusters were added until either the spatial homogeneity of the clusters decreased substantially, or the histogram of monthly flood frequencies for the additional cluster became difficult to distinguish from that of another cluster.

RESULTS AND DISCUSSION. Annual Floods. Figure 1 shows that the frequency of annual floods occurring in different seasons varies with drainage area. In particular, the smallest watersheds (<100 km²) have distinctly different seasonal characteristics (a higher frequency of annual floods in summer and/or fall for all cluster groups) from basins with larger drainage areas. Because this may influence the distribution of clusters, the small watersheds were eliminated from consideration. In the far western portion of the state (west of the crest of the Appalachian Mountains), the distribution of annual floods is strongly unimodal (Fig. 2, Cluster A1). Annual floods occur most frequently in winter and spring, while few occur from May–November. Low monthly frequencies in May to November and high flood frequencies in December distinguish these stations from those in Clusters A2 and A3. The stations in Cluster A2 are grouped on the eastern flank of the Appalachians and in

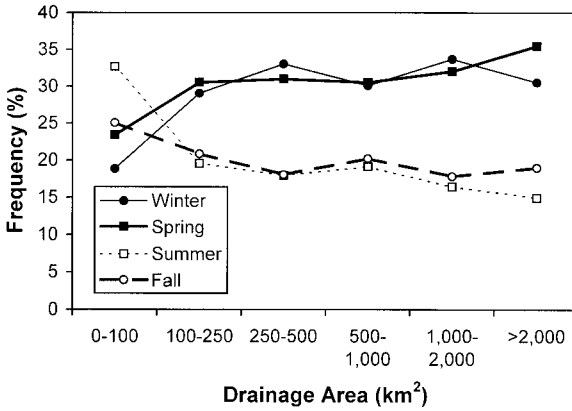


Fig. 1. Variations in flood seasonality with drainage area.

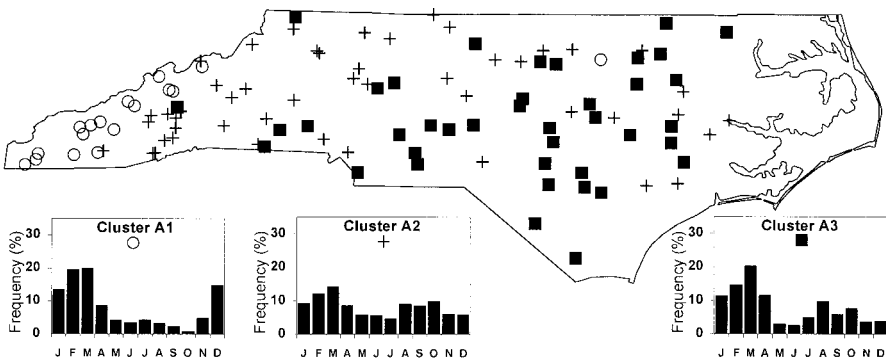


Fig. 2. Spatial distribution of clusters (annual floods) for stations with drainage areas >100 km² (n = 105). The histograms were calculated as the percentage of annual floods occurring in each month for all stations in each cluster.

the upper Piedmont. These stations display a more uniform distribution of floods through the year, with the highest frequencies occurring in late winter and early spring, and a secondary period of higher frequencies occurring from August to October. The seasonal distribution of annual floods for stations in Cluster A3 (lower Piedmont and Coastal Plain) is more bimodal, displaying the highest frequencies in late winter and early spring, as well as higher frequencies from August–October. Few floods occur in May–June and November–December.

Partial Floods. The spatial distribution of clusters and histograms of monthly frequencies for the partial duration series (Fig. 3) are similar to those for the annual

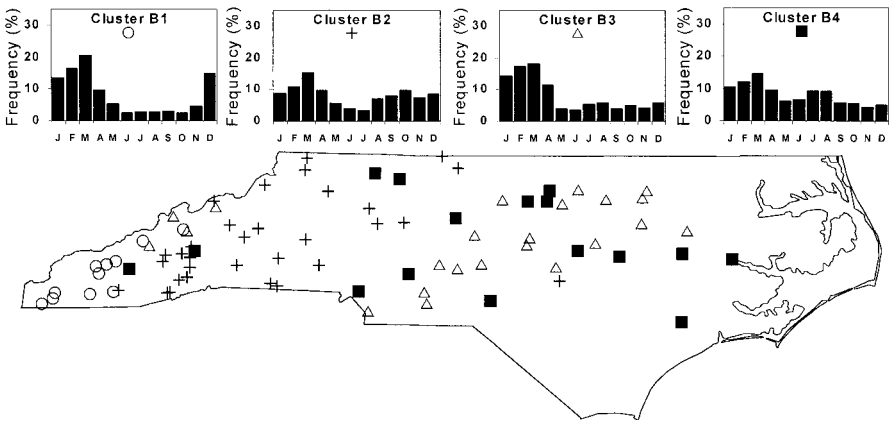


Fig. 3. Spatial distribution of clusters (partial floods) for stations with drainage areas $>100 \text{ km}^2$ ($n = 81$).

flood series (Fig. 2), except that the use of four clusters produces an eastern region divided between Clusters B3 and B4. In the Lower Piedmont and Coastal Plain, the dominant Clusters (B3 and B4 in Fig. 3) consist of watersheds with distinctly different drainage areas (Fig. 4). Almost half of the stations in Cluster B3 (Fig. 4a) have drainage areas $>500 \text{ km}^2$, whereas more than half of the stations in Cluster B4 (Fig. 4b) have drainage areas $<250 \text{ km}^2$. The larger watersheds in Cluster B3 display lower and more uniform flood frequencies from May–December than was the case for the annual floods (Cluster A3) in Figure 2. Small scale thunderstorms are less likely to generate flooding than frontal systems in these larger basins, and the occurrence of more than one partial flood each year in winter and spring may decrease the relative frequency of floods in summer and fall. Overall, however, these results suggest that the annual and partial-duration series display similar seasonal and spatial patterns. Given that it contains a larger number of stations with better spatial coverage, the annual-duration series was used to delineate flood regions.

Flood-Regime Regions. Based on spatial patterns of the clusters and their associated histograms for the annual flood series in Figure 2 ($>100 \text{ km}^2$), three flood-regime regions were identified in North Carolina: the Appalachian Region, the Piedmont Region, and the Coastal Plain Region (Fig. 5). Although the spatial homogeneity of the clusters within each region varies, one dominant cluster accounts for the majority of the stations in each region: 94% of the stations in the Appalachian Region, 85% in the Piedmont Region, and 64% in the Coastal Plain Region. Histograms of

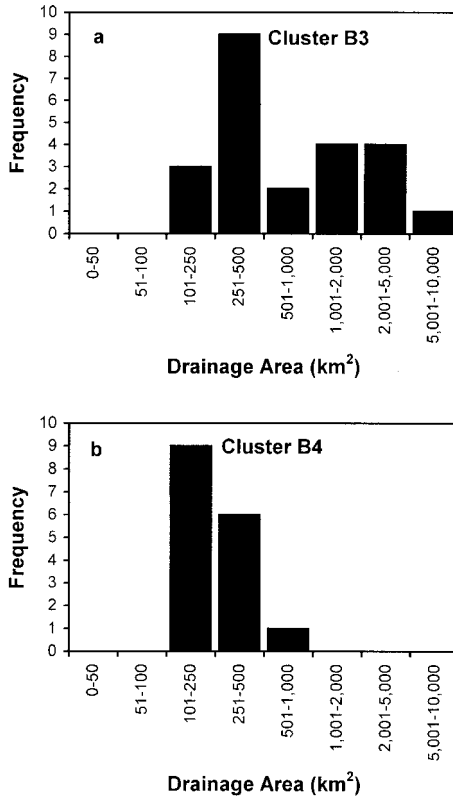


Fig. 4. Drainage area for clusters B3 and B4 in Fig. 3.

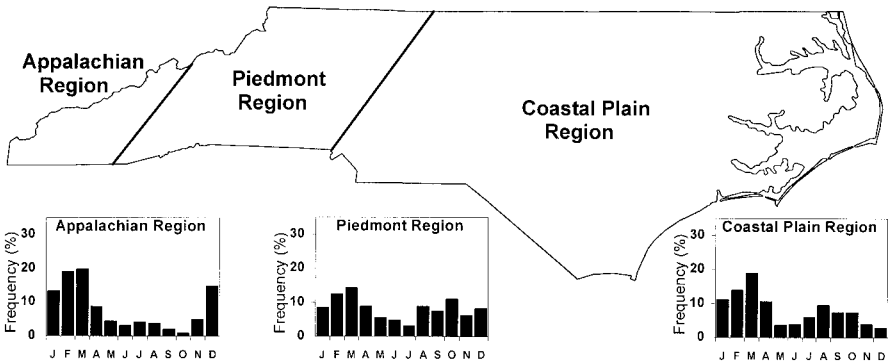


Fig. 5. Flood regime regions.

monthly flood frequencies show that 76% of the annual floods in the Appalachian Region occur in December–April. In the Piedmont Region, only 53% occur in December–April because of increased flood frequencies in August–October (28%). While the months of January–April have the highest flood frequencies in the Coastal Plain Region (55%), annual floods are also common in July–October (31%).

The boundaries among the three flood-regime regions are not equally distinct. Although these boundaries were located to maximize the internal homogeneity of the clusters within the regions, the delineation of boundaries is an inherently subjective process (Grigg, 1967; Mosley, 1981). The placement of the boundary between the Appalachian Region and the Piedmont Region is relatively straightforward. However, the boundary between the Piedmont and Coastal Plain regions is only an approximation. The intermixing of clusters and the similarity of the monthly histograms indicate that this boundary should be treated as a transitional zone and may be complicated by drainage area and the orientation of the major rivers in the region, which cross this boundary as they flow to the southeast. Errors may also be introduced because the gaging station locations are not necessarily representative of the areas surrounding them, particularly for large rivers in the Coastal Plain Region that drain areas located in the Piedmont Region and flow across the boundary between the two regions. Nevertheless, the boundaries between regions are intended as average, not exact, regional divisions.

Regional differences in flood seasonality in North Carolina may be explained, in part, by variations in topography and the dominant climatic processes that produce flood-generating precipitation. The timing of flooding in the Appalachian Region is distinct from the rest of the state because the Appalachian Mountains form an effective barrier to warm, moist air advected from the Atlantic Ocean (Konrad, 1994; Keim, 1996). The unimodal seasonal flood regime (winter/spring dominant) that characterizes the Appalachian Region is similar to, and contiguous with, a large area to the west encompassing most of Tennessee and the northern parts of Georgia, Alabama, and Mississippi (Lecce, 2000). Cyclones forming in the Gulf of Mexico (winter maximum) and along the Atlantic coast (March maximum) are active in winter and early spring, producing low-intensity, long-duration precipitation (Whittaker and Horn, 1981, 1984). Snowmelt in the higher elevations is also likely to generate some flooding in spring (Hayden, 1988).

The increased frequency of summer flooding in the Piedmont and Coastal Plain regions may be associated with heavy rainfall related to the clockwise circulation around the Bermuda High, which brings warm, moist air into the region (Konrad and Meentemeyer, 1994; Keim, 1996). Furthermore, the cyclogenesis center along the Atlantic coast remains active through the summer and fall (Whittaker and Horn, 1981, 1984). Tropical cyclones also contribute to the higher frequency of warm-season flooding in the Piedmont and Coastal Plain regions, particularly in September and October. Cry (1967) showed that the percentage of monthly precipitation

attributed to tropical cyclones in North Carolina during 1931–1960 was greatest east of the crest of the Appalachian Mountains in September (15–30%) and October (15–25%). Heavy rainfall events in the upper Piedmont and eastern flank of the Appalachians are enhanced by orographic uplift of moisture advected from the Atlantic Ocean during both warm and cool seasons (Konrad, 1994).

SUMMARY AND CONCLUSIONS. Cluster analysis identified three regions with distinctly different flood regimes: the Appalachian Region, the Piedmont Region, and the Coastal Plain Region. Seasonal and spatial patterns for the partial-duration series were similar to those for the annual flood series. In the southwestern corner of the state, the Appalachian Region displays a strongly unimodal flood regime dominated by frequent flooding in winter and spring and relatively few floods in summer and fall. The Appalachian Mountains shelter this region from moisture sources that influence the rest of the state during the summer and fall. In the Piedmont and Coastal Plain regions, the frequency of floods in summer and fall is twice that experienced in the Appalachian Region. The smallest watersheds tend to experience higher flood frequencies in summer and fall than the larger basins.

NOTE

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