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Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed

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Abstract

Aerial photography provides a historical vehicle for determining long-term urban landscape change and, with concurrent daily streamflow and precipitation records, allows the historical relationship of anthropogenic impervious surfaces and streamflow to be explored. Anthropogenic impervious surface area in the upper Accotink Creek subwatershed (near Annandala, Virginia, USA) was mapped from six dates of rectified historical aerial photography ranging from 1949 to 1994. Results show that anthropogenic impervious surface area has grown from approximately 3% in 1949 to 33% in 1994. Coincident to this period, analysis of historical mean daily streamflow shows a statistically significant increase in the streamflow discharge response (per meter of precipitation) associated with ″normal″ and ″extreme″ daily precipitation levels. Significant changes were also observed in the frequency of daily streamflow discharge at given volumes above and below the historical daily mean. Simultaneously, the historical magnitude, frequency and pattern of precipitation values $\geqslant$ 0 mm, $\geqslant$ 6.0 mm and $\geqslant$ 35.0 mm show either no statistically significant change or influence on streamflow. Historical changes in streamflow in this basin appear to be related to increases in anthropogenic impervious surface cover. Historical aerial photography is a viable tool for revealing long-term landscape and ecosystem relationships, and allows landscape investigations to extend beyond the temporal and spatial constraints of historical satellite remote sensing data.

Introduction

Environmental protection of water quality is evolving from the detection of end-of-pipe sources of water pollution, such as sewage and industrial waste, towards a watershed management approach based primarily upon detection of non-point-source (NPS) pollution (US Environmental Protection Agency (USEPA) 1994). In generally urbanized watersheds, NPS pollution is related to human habitation and the subsequent build-up of impervious surfaces on the landscape. In this study, these features specifically include roads, rooftops, parking lots, driveways, and sidewalks. The amount of impervious surface in a watershed is a landscape indicator integrating a number of concurrent interactions that influence a watershed's hydrology (Schueler 1994). The direct hydrologic effect of impervious surfaces occurs as a change in the magnitude and variability of velocity and volume of surface flow. Within landscapes under the influence of impervious surfaces, precipitation that would normally be part of natural infiltration instead falls on and flows over impervious surfaces. The runoff is then channeled and released via storm sewers directly into the receiving stream. This alteration of the natural hydrologic process reduces runoff lag time, increases the peak rate of streamflow discharge, increases the resulting number of bankfull/sub-bankfull values and brings about subsequent increases in the scouring and incision of the stream channel (Leopold 1973; Booth 1990). In this way, the channeled runoff from anthropogenic impervious surfaces influences the morphological structure of the stream and thereby alters the in-stream and riparian ecology.

The impact of impervious surfaces on hydraulic change and stream stability has been discussed in Hammer (1972) and Leopold (1973), Booth (1990), and Henshaw and Booth (2000). Klein (1979) and Galli (1991) related increases in impervious surfaces to increases in stream temperature. Jones and Clark (1987) and Kennan (1999) discussed the lack of benthic diversity associated with urban environments. Studies by Limburg and Schmidt (1990) and Weaver and Garman (1994), May et al. (1997) and Wang et al. (2001) related changes in fish communities to increases in urbanization. Anderson (1968) and Hollis (1975), and Rose and Peters (2001) discussed the impacts of urbanization and impervious surfaces on streamflow, while Biggs (1995) and Poff and Allen (1995) specifically related disturbance from streamflow variability to significant changes in aquatic habitat structure. Schueler (1994) observed that imperviousness of a watershed is the primary gauge of urban stream ecosystem health, and hypothesized that a threshold for urban stream stability and habitat quality exists at approximately 10% to 20% watershed impervious surface area. While the biological effects of altered hydrologic regime have been quantified, few empirical studies have attempted to discriminate and relate the relative historical impacts of precipitation and landscape change on streamflow rate at the daily temporal scale. In addition, although continuous hydrologic modeling efforts such as Dinicola (1989) and James (1994), and Leitch and Harbor (1998) are numerous, there have been no empirical studies that specifically utilized daily precipitation as an input for determining changes in long-term streamflow response. In light of current climate change investigations (Karl and Riebsame 1989; Karl et al. 1995; Karl and Knight 1998), historical precipitation data are necessary for discriminating long-term causes of streamflow rate change in urbanized basins.

In their review of remote sensing for the detection of impervious surfaces, Slonecker et al. (2001) reported on such uses as aerial photography, satellite multi-spectral imagery, and airborne multi-spectral imagery to map impervious surfaces. In general, they found that most uses of remote sensing have emphasized general land use mapping and single-date conditions as inputs into hydrologic models or tax assessment structures. Of note are Hammer (1972) and Graf (1975), and Moscript and Montgomery (1997). These studies employ historical approaches but rely upon secondary geo-spatial sources and/or generalized land cover mapping to determine the area and extent of impervious surfaces. Concerning historical landscape change and streamflow investigations, there has been little scientific effort placed on the accuracy, resolution, and consistency of explicit impervious surface area calculation across time.

In this study, we related the impact of anthropogenic impervious surfaces upon daily streamflow discharge, independent of precipitation variables, over a 51-year period (October 1947 through September 1998) in the upper Accotink Creek subwatershed of Fairfax, Virginia, USA. Six dates of rectified aerial photography were utilized to map historical changes in total impervious surface area (TIA). Impervious surface area data were then compared with coincident mean daily streamflow discharge data and daily precipitation records to determine historical trends between impervious surface growth and changes in the amount and pattern of mean daily streamflow discharge.

Study area

The area of interest for this study is the upper Accotink Creek subwatershed. This sub-watershed is bisected from the larger Accotink Creek watershed at the pour point location of the Virginia Department of Environmental Quality (VDEQ) Stream Gage 01654000, Accotink Creek, near Annandale, VA (Figure 1). Located 15 km west of Washington D.C., within Fairfax County, Virginia, Accotink Creek flows in a generally southeasterly direction from its source in Fairfax City and empties directly into the Potomac River at Gunston Cove. The upper Accotink Creek sub-watershed drains 61 km^2 with a stream length from headwater to gauging station of 18 km and an average slope of 3.6 m km^{-1} (Anderson 1968). The basin lies in the Piedmont region of Northern Virginia and has a geologic composition of crystalline rock and saprolite with an overburden primarily of clay and silt (Froelich and Zennone 1985). The instantaneous peak discharge for stream gage 01654000 was initially set by VDEQ as 11.34 m^3 s^{-1} in 1947, and modified to 22.67 m^3 s^{-1} in 1961 and to 39.67 m^3 s^{-1} in 1966. The changes in the reporting of instantaneous peak discharge are related to the consistent increases in bankfull discharge as observed by the stream gage (Figure 2). This is further borne out

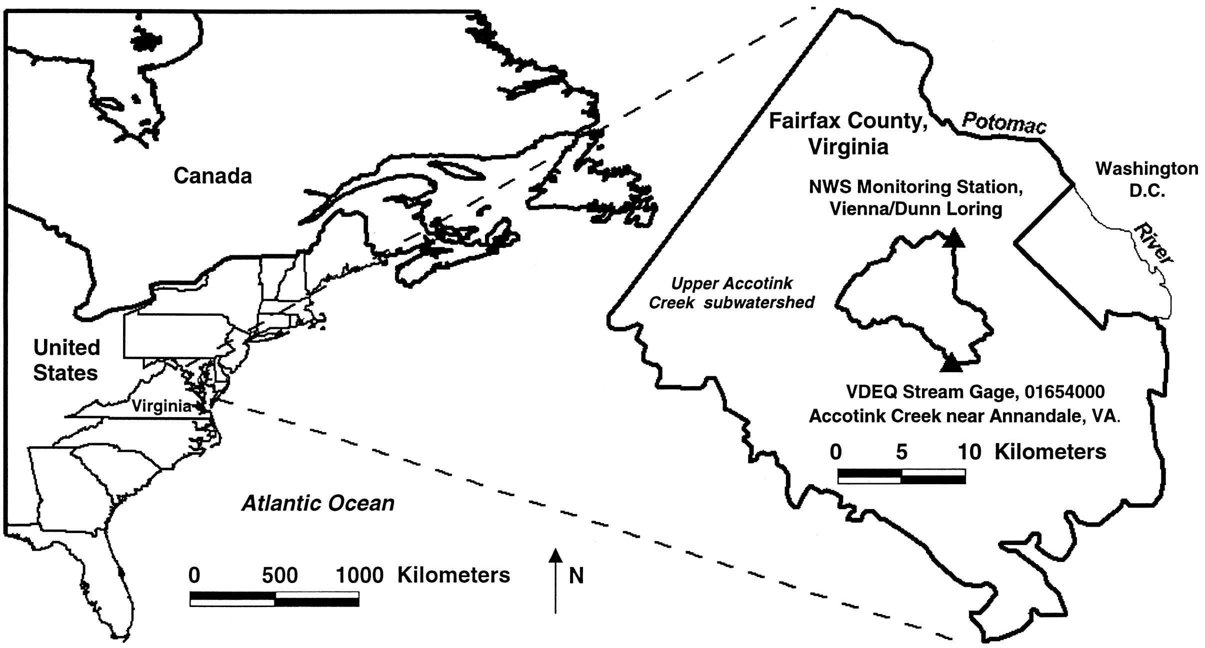

Figure 1. Location of the upper Accotink Creek subwatershed.

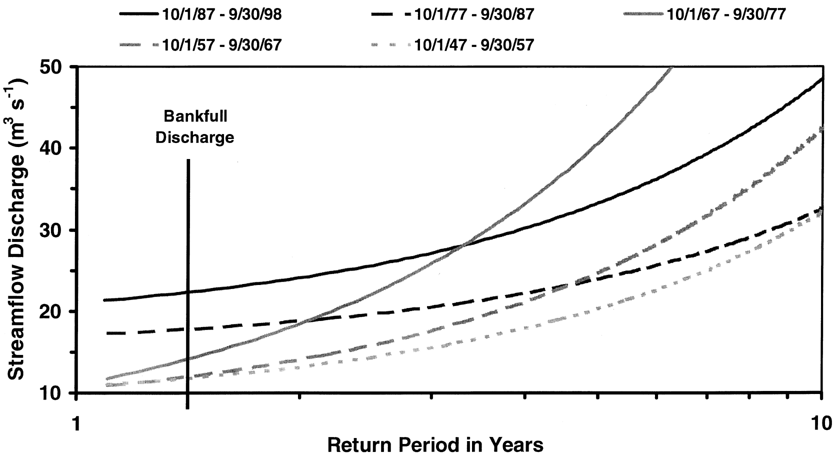

Figure 2. Bankfull discharge per decade utilizing yearly-peak mean daily streamflow data. Return Period derived as per Leopold (1968).

by the historical increases in the mean frequency per year (6.0 to 20.6) and mean streamflow rate per year (23.16 $m^3 s^{-1}$ to 27.40 $m^3 s^{-1}$) of instantaneous discharge values $\geqslant$ 11.34 $m^3 s^{-1}$ observed between the first and last decade of record for the gage.

Methods

Calculation of impervious surface area

This study makes use of hardcopy film and digital rectified historical aerial photographs to map impervious surfaces from six dates ranging from 1949 to 1994 (Table 1). USGS digital orthophoto quarter quads (DOQQ, U.S. Geological Survey (USGS) (1996)) derived from 1994 National Aerial Photography Program (NAPP) data (Light 1993) were utilized as a base to rectify all historical aerial photographs

Table 1. Aerial Photographic Data. #USGS - United States Geological Survey, ASCS - Agricultural Soil Conservation Service, VDOT -Virginia Department of Transportation. ##Also Acquired in USGS DOQQ format.

Date	Photo Scale	Film Type	Source#
3/94##	1:40,000	Color Infra-Red	USGS
4/88##	1:40,000	Color Infra-Red	USGS
10/79	1:40,000	Black + White	ASCS
4/71	1:24,000	Black + White	VDOT
4/63	1:24,000	Black + White	USGS
4/49	1:24,000	Black + White	USGS

not commercially available in digital rectified format (years 1979 and earlier). The unrectified historical photographs were scanned and converted to digital format at 1 m^2 pixel resolution. These data were subsequently rectified to the 1994 orthoimagery utilizing image-to-image registration techniques and second order polynomial transformation algorithms (Jensen 1996). The use of rectified digital imagery allowed impervious surfaces to be compiled in a digital mapping environment. This enabled the compiled impervious surface data to have ″real world″ areal extent that could be concisely tabulated as TIA.

Impervious surface areas were analyzed and compiled through the composite means of analog stereoscopic visual analysis and ″heads-up″ digital collection procedures. Impervious surface boundaries were delineated using standard photographic interpretation techniques as put forth in Jensen (1983) and Haack (1997). The five categories chosen for compilation (roads, parking lots, sidewalks, rooftops, and driveways) were representative of the predominant anthropogenic cover types in the basin. The minimum mapping unit set for this project was 1 pixel or 1 m^2. This resolution corresponds to the spatial resolution necessary to discern and compile sidewalks, the smallest spatial unit of the five impervious surface categories. Where features were not clearly discernable on the photograph and the scanned image, they were not compiled. Photographic resolution (Table 1) limited our ability to discriminate the degree of compaction of soil in order to determine infiltration and runoff capability. Based on the compacted nature of bare soil transportation networks (″dirt roads″), a decision rule was employed to compile bare soil areas related to road features only. If a ″dirt road″ pattern could be distinguished then it was compiled as an impervious surface.

The map compilation of the various impervious surface components was broken down into two categories: 1) *direct compilation* (Figure 3) in which a unique area feature was mapped with a unique polygon, thus allowing an individual area assessment for each unique polygon; and 2) *indirect compilation* (Figure 4) in which sampling procedures were introduced to assign probable area assessments to point features. Direct compilation methods were utilized for the analysis and mapping of roads, parking lots, sidewalks, multi-family rooftops as well as commercial rooftops and institutional rooftops (schools, churches, etc.). Indirect compilation of single-family detached rooftops employed a sampling strategy based on the number of residential parcels/rooftops contained within 2 km^2 grid areas. For each given grid, a point theme denoting the total number of single-family dwellings was created. Area assessments were then derived for a sample set of five percent (5%) of these single-family dwellings for each respective grid. Rooftops, driveways, and walkways from the single-family parcel sample set were delineated with polygons, and a resultant sampled mean for the impervious surface area per parcel was derived. The sample set mean was then multiplied by the number of total rooftops – per respective grid – such that impervious surface area related to single family houses could be calculated. Derived impervious surface area data from the two approaches (direct and indirect) were combined and a TIA for the watershed was calculated. The TIA was then divided by the total watershed area to compute an impervious surface percentage for each separate year of imagery. No efforts were made to distinguish between the TIA and the Effective Impervious Area (EIA) as defined in Alley and Veenhuis (1983).

Precipitation/streamflow data

Historical mean daily streamflow data from the VDEQ stream gage 0165400, Accotink Creek near Annandale, VA (U.S. Geological Survey (USGS) 2001), were obtained for the water-year period of 1948 through 1998. Water year is defined as October 1st of the previous year through September 30th of the current year (e.g., water year 1950 = 10/1/49 – 9/30/50). Historical daily precipitation records coincident with the streamflow records were acquired from the National Weather Service (NWS) monitoring station Vienna/Dunn Loring (National Climatic Data Center (NCDC) 1998). The NWS station is located approxi-

Figure 3. Direct impervious surface compilation method. Delineated roads, parking lots and commercial/institutional rooftop areas are mapped in red. The Accotink Creek is mapped in blue.

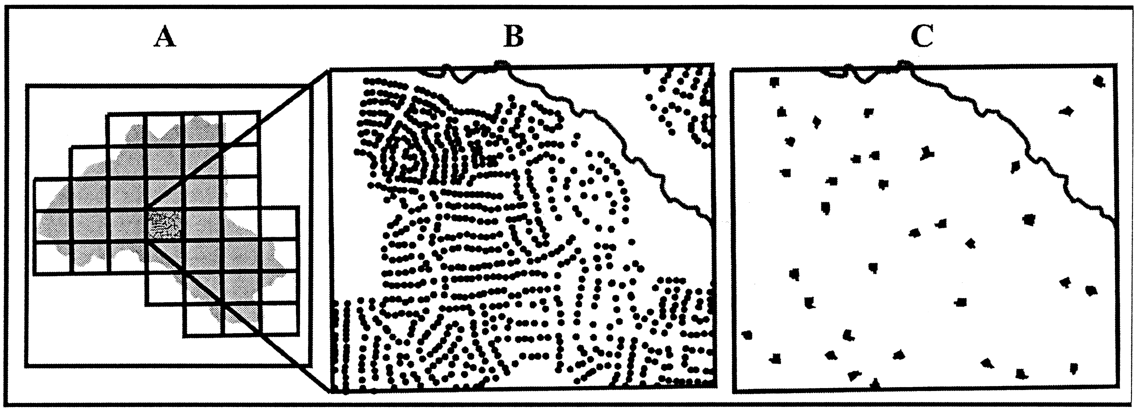

Figure 4. Indirect compilation based on: **A.** 2 km^2 sampling grid network overlaid on the basin. The highlighted area in the center of the sampling grid is the identical 2 km^2 area referenced in Figure 3 above. **B.** The compiled point theme representative of parcel/rooftops. **C.** An area sample displaying 5% of the parcel/rooftop point theme compiled as polygons from rooftop, driveway and walkway impervious surface features associated with each parcel. The mean of the polygonal areas then became the mean area for all residential rooftops in that particular grid.

mately 10 kilometers north of the VDEQ streamflow gage (Figure 1) and provided the best historical estimate of overall precipitation amount and distribution in the upper Accotink Creek basin. The streamflow dataset was 100% complete while the precipitation dataset was missing 434 total records – primarily from the first two years of data. No attempt was made to interpolate values for the missing precipitation records.

Coincident daily precipitation/streamflow data pairs were formed from the individual data sets and grouped into categories based on measurable daily precipitation cutoff values at 1) > 0 mm, 2) $\geqslant 6.0$ mm, and 3) $\geqslant 35.0$ mm. The precipitation cutoff > 0.0 mm included all daily occurrences of measurable precipitation and allowed the general relationship of precipitation and streamflow to be explored. The precipitation cutoff $\geqslant 6.0$ mm included approximately 45% of the data pairs with measurable precipitation (6.0 mm was viewed as a ″normal″ precipitation occurrence). The precipitation cutoff $\geqslant 35.0$ mm included approximately 5% of the data pairs with measurable precipitation (35.0 mm was viewed as ″extreme″ precipitation occurrence).

The precipitation/streamflow data pairs were further binned into temporal categories as: 1) 10-year bins to examine the overall historical precipitation/streamflow discharge trend; and 2) 3-year bins, around each date of photographic coverage, to examine the relationship of a specific percent impervious surface area on streamflow discharge. Due to missing precipitation data and a single ″decade″ that consisted of more than 10 years (10/1/87 – 9/30/98), we used a sample year (365 days) and sample decade (3,650 days) to standardize the number of data pairs per year for 10-year and 3-year bins.

Streamflow frequency pattern

We grouped the counts of mean daily streamflow discharge rates ranging in volume from 0.25 $m^3\ s^{-1}$ to 14.0 $m^3\ s^{-1}$ into 10-year bins to develop a frequency analysis that would characterize historical variability in given levels of streamflow discharge.

Calculation of a streamflow response value

For the streamflow-precipitation data pairs related to the precipitation cutoff groupings of $\geqslant 6$ mm and $\geqslant 35$ mm, a daily streamflow response value (per meter of precipitation) was produced. The streamflow response ($m^3\ s^{-1}\ m^{-1}$) metric is the product: [mean daily streamflow ($m^3\ s^{-1}$) / daily precipitation (in meters)]. ″Streamflow response″ provided a unifying term for the data pair whereby historical changes in streamflow response to per unit of precipitation could be tracked and reported over time.

The streamflow response value is similar to a daily runoff coefficient (RC) in that the variables of streamflow and precipitation are utilized to derive a runoff ratio. The terms of area and time are constants in this study, so that the relative change in the daily relationship of the streamflow response value and the RC are identical. With respect to change over time in single watershed studies, there is no difference between the streamflow response value and the RC. However, we feel that as a metric, streamflow response provided a more intuitive stream ecology relationship than the RC and better captured the changing magnitude of streamflow as an ecological disturbance event.

Historical precipitation pattern

As part of the data pair approach, precipitation data was tested for differences in frequency and amount per 10-year and 3-year bins for the categories > 0 mm, $\geqslant 6$ mm and $\geqslant 35$mm.

Additionally, we tested for changes in historical precipitation pattern that could influence historical streamflow discharge patterns. Precipitation data for the categories > 0 mm and $\geqslant 6$ mm were grouped into 10-year bins based on occurrences of 1-day, 2-day, 3-day and > 3-day precipitation duration by decade. The categories > 0 mm and $\geqslant 6$ mm were also grouped into 10-year bins based on the seasonal categories of winter, spring, summer and fall to test for changes in seasonal patterns. The ″continuous daily precipitation duration″ and ″daily precipitation by season″ groupings were tested for changes in the frequency and mean amount of daily precipitation per decade.

Statistical analysis

Normality of data was tested utilizing Kolmogorov-Smirnov One Sample Tests using a Normal (0.00, 1.00) distribution and 2-tail Lilliefors probabilities. All statistical tests were run with SAS 7.0 and SYSTAT 9.0 on a Windows NT platform.

Results

Both the streamflow and precipitation data were not normally distributed and this condition was not correctable via data transformations. Therefore, we used the non-parametric Kruskal-Wallis One-Way Analysis of Variance for the tests of differences in amount of the streamflow and precipitation variables. One-Way Crosstabs using Pearson chi-square were used to test for differences in the frequency of variable values.

Mapping of impervious surfaces

Figure 5 is a set of image mosaics, produced from rectified digital photographs, overlaid with compiled impervious street networks and commercial/institutional areas. These images reveal the changing nature of the landscape in the basin over the study period. The percentage of impervious cover in the basin grew from approximately 3% in 1949 to 33% in 1994. Root Mean Square (RMS) error for the image-to-image registration was < 2.5 pixels for all coverages while post-rectification check points showed that registration errors were in the 2–4 pixel range. Individual map accuracy assessments were achieved via simple random sampling procedures as set forth by Congalton and Green (1999). Total map accuracy for the six impervious surface maps ranged from 97% in 1949 to 91% in 1994 (Table 2).

10-year bins (general streamflow and precipitation trends)

Figure 6 is a graph of the regression lines from the scatterplots of the streamflow-precipitation data pairs related to precipitation values > 0 mm, grouped in 10-year bins. The graph represents a general historical characterization of streamflow-precipitation relationship. A rising slope over time is observed indicating an increasingly direct relationship between precipitation and runoff. The data appear to form two distinct groupings of slopes over time, with the precipitation/streamflow response curves for the first two decades showing a lower streamflow response to increasing precipitation than the last three decades.

Table 3 is a set of historical streamflow discharge frequencies, in 10-year bins, ranging in volume from 0.25 $m^3\ s^{-1}$ to 14.0 $m^3\ s^{-1}$. The table reflects streamflow data only and does not refer to coincident precipitation values. The frequency of flows for the three cutoff values above the historical mean (0.80 $m^3\ s^{-1}$) have significantly increased over time, while the frequency of flows for the three cutoff values at or below the mean have significantly decreased over time.

Figure 7 compares the streamflow response value and precipitation for precipitation values $\geqslant$ 6.0 mm by 10-year bin. Two trends emerge from the data: 1) mean precipitation volumes show no significant variation over time, while 2) the streamflow response value shows a significant change over the same period.

Table 4 is a compilation of 10-year bin statistics of precipitation and streamflow for data pairs associated with the daily precipitation cutoff values of $\geqslant$ 6.0 mm (Figure 7) and $\geqslant$ 35.0 mm. There was no significant difference among bins for the frequency of precipitation occurrences or in the mean amounts of precipitation per value at either cutoff value. There was a significant difference among decades found for the streamflow response value at both cutoff values.

3-year bins (impervious surface and streamflow relationship)

Figure 8 compares the streamflow response value and precipitation for precipitation values $\geqslant$ 6.0 mm by 3-year bins centered on aerial photography acquisition dates. As in Figure 7, two trends emerge from the data: 1) mean precipitation volume show no significant variation over time, while 2) the streamflow response value shows a significant difference over the same period. The transition in streamflow, previously observed in Figure 6 and Figure 7 is now generally present between the 3% to 21% impervious surface levels (years 1949, 1963 and 1971 respectively). Impervious surface percent for the years 1988 and 1994 were both mapped at 33%. Pair-wise testing revealed no significant difference in their respective streamflow response values; therefore, these years were combined into a single category.

Table 5 is a compilation of 3-year bin statistics of precipitation and streamflow for data pairs associated with the daily precipitation cutoff values of $\geqslant$ 6.0 mm (Figure 8) and $\geqslant$ 35.0 mm. There was no significant difference among bins for the frequency of precipitation occurrences or in the mean amounts of precipitation per value at either cutoff value. There was a significant difference among decades found for the streamflow response value at the cutoff value $\geqslant$ 6.0 mm but not at the cutoff value $\geqslant$ 35.0 mm.

Precipitation frequency, magnitude, and pattern

No statistically significant differences were found in the amounts or frequency of the daily precipitation data, per 10-year bins, associated with the cutoff values of > 0 mm (Kuskal-Wallis test statistic = 3.24, df = 4, p = 0.518; $\chi^2 = 1.45$, df = 4, p = 0.835), $\geqslant$ 6mm (statistics in Table 4) and $\geqslant$ 35 mm (statistics in Table 4).

The pattern of daily precipitation $\geqslant$ 6mm revealed a statistically significant increase for the fre-

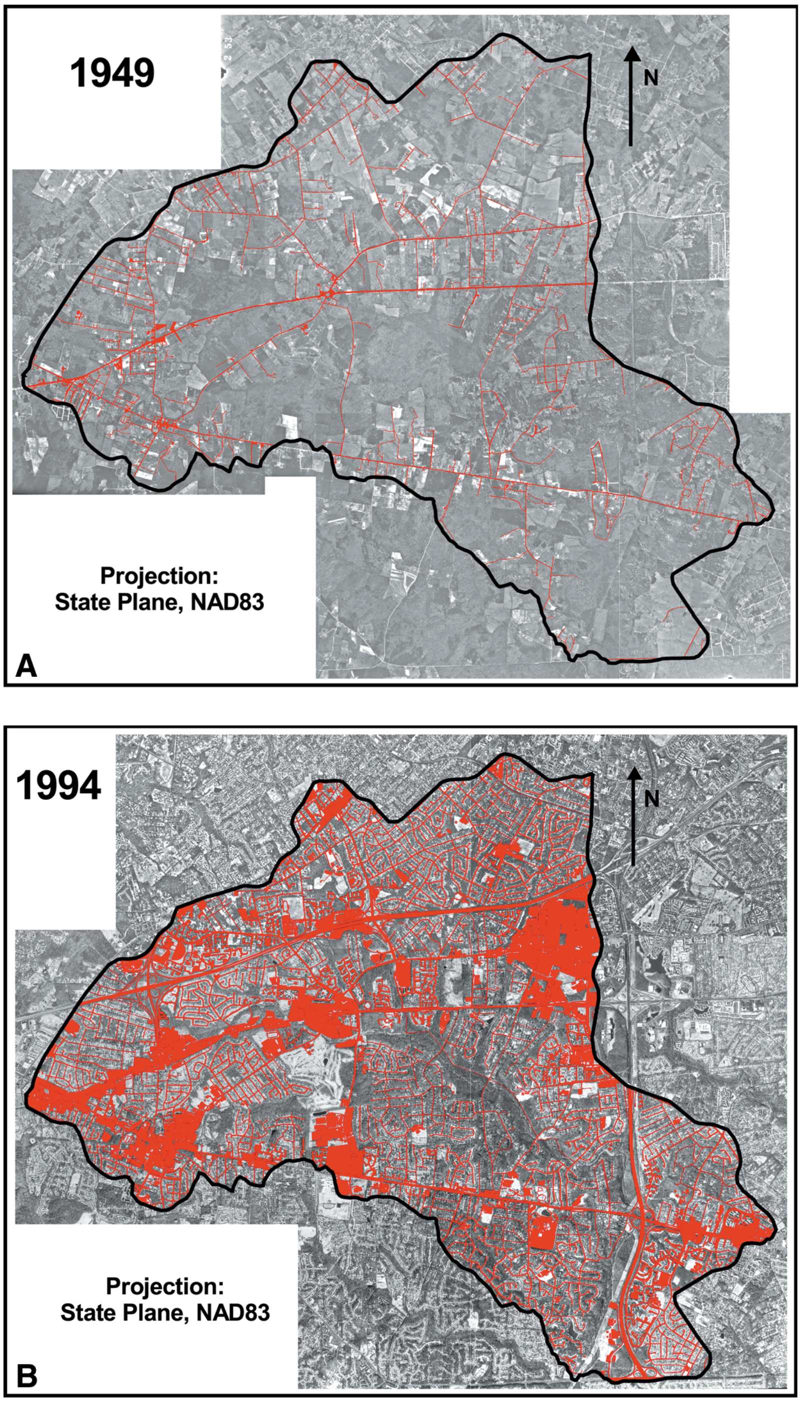

Figure 5. Image mosaics of 1949 (A) and 1994 (B) where roads and commercial/institutional areas are mapped in red. Anthropogenic impervious surface area has increased from 3% in 1949 to 33% in 1994.

quency of precipitation occurrences > 3-days in duration ($\chi^2 = 27.47$, df = 12, p = 0.007) by 10-year bin. We tested of the frequency of >3-day duration occurrences and found that for the first 4 decades, when the predominant increase in streamflow response value occurred, no significant change in the

Table 2. Registration error, percent impervious surface area and total map accuracy assessment per photographic coverage. Registration error is based on the mean of four post-rectification check points per coverage.

Year of Imagery	Registration Error (in Pixel Units)	Approximate TIA (%)	Total Map Accuracy (%)
1949	X = 2.1 Y = 3.4	3	97
1963	X = 1.1 Y = 2.7	13	95
1971	X = 2.9 Y = 2.9	21	96
1979	X = 1.9 Y = 1.5	27	93
1988	N/A	33	92
1994	N/A	33	91

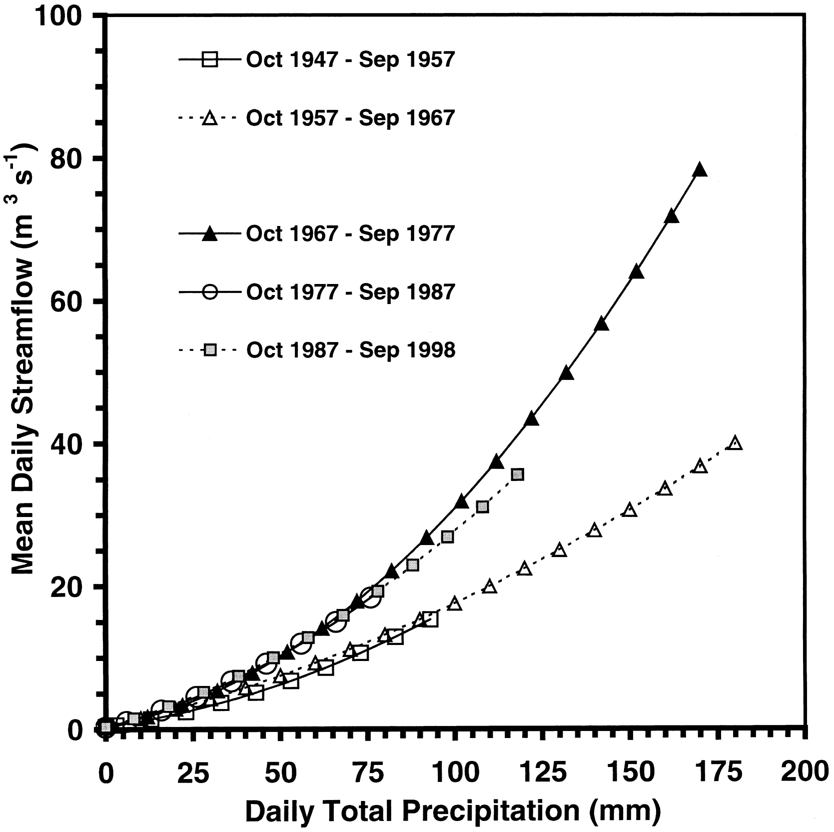

Figure 6. 1947–1998 Streamflow vs. Precipitation for days of measurable precipitation. A decade-by-decade series of regressions illustrating the general historical curvilinear relationships of daily precipitation and streamflow. Figure includes all streamflow-precipitation data pairs where precipitation values > 0, N = 5865. The regression lines for the first two decades follow a similar path while the curves for the last three decades form a second group.

Regression equations and sample n per decade:

- 1st decade (10/47 – 9/57): $y = 0.001x^2 + 0.0678x + 0.3595$, $R^2 = 0.4609$, n = 1051;
- 2nd decade (10/57 – 9/67): $y = 0.0005x^2 + 0.1259x + 0.1366$, $R^2 = 0.5429$, n = 1076;
- 3rd decade (10/67 – 9/77): $y = 0.0022x^2 + 0.0811x + 0.4803$, $R^2 = 0.7139$, n = 1159;
- 4th decade (10/77 – 9/87): $y = 0.0013x^2 + 0.1372x + 0.1425$, $R^2 = 0.5406$, n = 1199;
- 5th decade (10/87 – 9/98): $y = 0.0014x^2 + 0.1297x + 0.4052$, $R^2 = 0.4849$, n = 1380.

frequency of > 3-day occurrences was observed ($\chi^2 = 5.09$, df = 6, p = 0.532). It is not until we include the final decade of the > 3-day duration data that a significant difference in frequency is observed. The *frequency* of all other duration periods related to the

Table 3. Differences in streamflow frequencies by decade. The darker middle column denotes historical mean (0.8 m^3 s^{-1}). Significant differences were found among decades at $\alpha = 0.05$ for all mean daily streamflow occurrence cutoff levels. One-way crosstabs (χ^2) statistical tests used were for the number of values per sample decade, results reported as (test statistic value, df, p-value).

Decades	Number of days with mean daily streamflow ≥ 0.25 m^3 s^{-1} per sample decade	Number of days with mean daily streamflow ≥ 0.5 m^3 s^{-1} per sample decade	Number of days with mean daily streamflow ≥ 0.8 m^3 s^{-1} per sample decade	Number of days with mean daily streamflow ≥ 1.5 m^3 s^{-1} per sample decade	Number of days with mean daily streamflow ≥ 9.0 m^3 s^{-1} per sample decade	Number of days with mean daily streamflow ≥ 14.0 m^3 s^{-1} per sample decade
10/1/47 - 9/30/57	2450.0	1525.7	816.3	281.8	22.0	6.0
10/1/57 - 9/30/67	2360.7	1265.3	722.6	305.8	23.0	13.0
10/1/67 - 9/30/77	2691.8	1397.9	738.4	360.7	46.0	19.0
10/1/77 - 9/30/87	2102.8	1125.4	684.6	362.8	38.0	19.0
10/1/87 - 9/30/98	2204.7	1143.7	672.2	447.8	49.1	25.4
Results	(90.051, 4, < 0.001)	(88.231, 4, < 0.001)	(17.81, 4, 0.001)	(46.74, 4, < 0.001)	(17.94, 4, 0.001)	(13.04, 4, 0.011)

cutoff values > 0 mm and ⩾ 6 mm were not statistically significant.

We did factor analysis of streamflow and related precipitation duration values. These results showed that streamflow significantly increased with an increase in the duration of precipitation (four levels: one-day, two-day, three-day, and ⩾ three-day; ANOVA F-Ratio = 35.05, df = 12, p < 0.001) and the decade of occurrence (ANOVA F-Ratio = 15.95, df = 12, p < 0.001). However, the interaction of streamflow to precipitation duration among 10-year bins was not significantly different (ANOVA F-Ratio = 1.05, df = 12, p = 0.402). This means that the increase in streamflow with increasing duration of precipitation was the same across decades.

The pattern of daily precipitation ⩾ 6mm also showed a statistically significant change in the mean *amount* of 3-day precipitation duration occurrences (Kruskal-Wallis test statistic = 10.65, df = 4, p = 0.031) by 10-year bin. This however is due to a declining trend in 3-day duration amounts. A declining precipitation amount trend should have no positive impact on an increasing streamflow trend. The *amounts* of all other duration periods related to the cutoff values > 0 mm and ⩾ 6 mm were not statistically significant.

We observed no significant change in seasonal data, by 10-year bin, in mean amount or frequency related to the daily precipitation cutoff values of > 0 mm and ⩾ 6 mm.

Discussion

We feel that historical climate data analysis is a required component for any analysis of change in historical streamflow discharge rates, particularly at the daily temporal scale where changes in streamflow pattern would have the greatest observable impact on stream ecology. Climate change research by Karl and Knight (1998) reported historical precipitation increases for the frequency of days with precipitation as well as the frequency of extreme precipitation values (50 mm) across the United States. We did not find this result for the precipitation station in our study area. Our results suggest that the historical frequency, magnitude, and temporal pattern of precipitation values at multiple cutoff levels were generally unchanged for the period of the study. Where we did observe a statistically significant change in pattern (frequency of precipitation values > 3-days in duration, amount of precipitation per 3-day duration value), we found no concurrent increases in historical

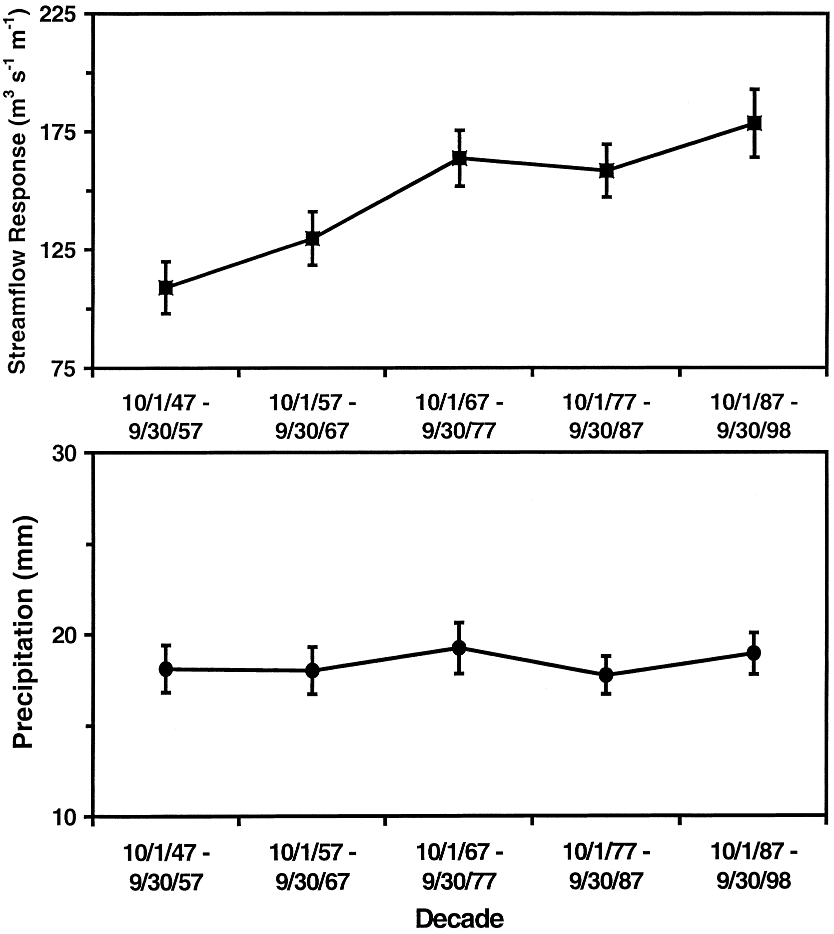

Figure 7. Comparison of decade averages of daily precipitation (mm) and daily streamflow response value ($m^3\ s^{-1}\ m^{-1}$). Daily streamflow response values were calculated for days where daily precipitation value $\geqslant$ 6.0 mm. Error bars show the ± 95% confidence interval for the means. N = 2,681 streamflow-precipitation pairs. Data related to Hurricane Agnes (June 21–22, 1972 were excluded from the analysis as outliers.

streamflow response. It is understood that wet and dry climate patterns may have short-term impacts upon streamflow rate; however, we found no long-term precipitation trend that would alter streamflow discharge over time.

Three historical trends emerge from our data: 1) mean precipitation volume and the frequency of precipitation show no significant variation 2) both the daily streamflow response per unit precipitation and the daily streamflow frequency pattern show significant change, and 3) the landscape trend is characterized by increasing impervious surface area. These results suggest that hydrologic changes in daily streamflow have occurred due to landscape changes, specifically, the buildup of impervious surfaces. From the historical trend, several possible inter-relationships and transitions emerge related to landscape pattern and streamflow discharge.

We found a statistically significant shift in mean daily streamflow rate in the 10-year bins associated with daily precipitation values $\geqslant$ 6.0 mm and $\geqslant$ 35.0 mm and in the 3-year bins associated with daily precipitation values $\geqslant$ 6.0 mm. The streamflow response trend for the 3-year bins associated with precipitation values $\geqslant$ 35.0 mm, while not statistically significant, showed consistent increases over the study period. The lack of statistical significance for the trend in the 3-year bin data is due to fewer observations than the 10-year bin data.

Our results imply that the amount of precipitation required to produce a given level of streamflow has decreased over time. The amount of precipitation necessary to produce a streamflow of 12 $m^3\ s^{-1}$ (bank-

Table 4. Statistics for October 1947 through September 1998 precipitation and streamflow response value. The data are binned by decade. * = significant difference found among decades at $\alpha = 0.05$. Statistical tests used for number of values = one-way crosstabs (χ^2), tests for amounts = Kruskal-Wallis one-way analysis of variance, results reported as (test statistic value, df, p-value). N = 2,681 streamflow-precipitation pairs for precipitation values $\geqslant$ 6.0 mm, 259 streamflow-precipitation pairs for precipitation values $\geqslant$ 35.0 mm. Data related to Hurricane Agnes (June 21–22, 1972) were excluded from the analysis as outliers.

Decades	Number of daily precipation values $\geqslant$ 6 mm per sample year	Mean precipitation amount (mm) per value $\geqslant$ 6 mm ± 95% C.I.	Streamflow response (m^3 s^{-1} m^{-1}) per precipitaion value $\geqslant$ 6 mm ± 95% C.I.*	Number of daily precipation values $\geqslant$ 35 mm per sample year	Mean precipitation amount (mm) per value $\geqslant$ 35 mm ± 95% C.I.	Streamflow response (m^3 s^{-1} m^{-1}) per precipitaion value $\geqslant$ 35 mm ± 95% C.I.*
10/1/47 – 9/30/57	54.7	18.1 ± 1.3	108.9 ± 10.9	5.3	53.7 ± 5.3	119.5 ± 28.3
10/1/57 –9/30/67	49.9	18.0 ± 1.3	129.6 ± 11.3	4.9	50.6 ± 6.7	172.3 ± 34.0
10/1/67 – 9/30/77	53.6	18.8 ± 1.3	161.8 ± 11.8	5.8	51.7 ± 5.0	191.7 ± 27.3
10/1/77 – 9/30/87	56.2	17.7 ± 1.0	158.3 ± 11.2	4.6	49.2 ± 3.6	274.1 ± 39.3
10/1/87 – 9/30/98	54.6	18.9 ± 1.1	178.9 ± 14.5	5.4	51.5 ± 4.9	223.1 ± 38.5
Results	(0.42, 4, 0.981)	4.08, 4, 0.395)	(176.07, 4, < 0.001)	(0.16, 4, 0.997)	(1.53, 4, 0.821)	(24.17, 4, < 0.001)

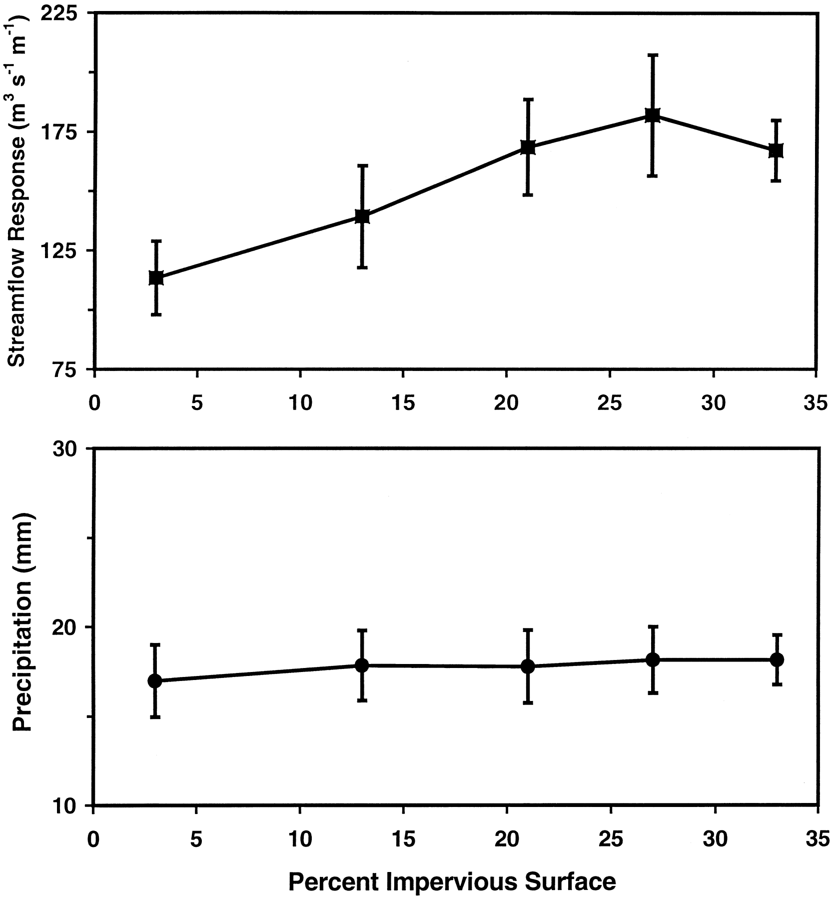

Figure 8. Comparison of averages of daily precipitation (mm) and daily streamflow response value (m^3 s^{-1} m^{-1}) for the percentages of impervious surface found over time in the watershed. The 3-year bin periods are centered on the acquisition date of aerial photography used to determine the percentage of impervious surface. Daily streamflow response values were calculated for days where total precipitation $\geqslant$ 6.0 mm. Error bars show the ± 95% confidence interval for the means. N = 990 streamflow-precipitation pairs. Data related to Hurricane Agnes (June 21–22, 1972 were excluded from the analysis as outliers.

full discharge for the first decade, Figure 2) dropped from approximately 80 mm in the first decade to approximately 55 mm in the final decade (Figure 6). An increase in the frequency of large flows is a consequence (Table 3). The increase in frequency of larger discharge streamflows over time implies a change in the stream's disturbance regime related to the volumes. We found that it was four times more likely to record a mean daily streamflow $\geqslant$ 14.0 m^3 s^{-1} in the last decade of our study than in the first. The altered flow regime is further illustrated by Figure 9 (derived from Table 3) where percent cumulative changes in specific streamflow cutoff levels reflect the historical change in streamflow pattern. Henshaw and Booth (2000) observed that increasing urbanization was related to decreases in the frequency of flows above the mean. A similar pattern is noted here, where a decreasing frequency of daily flows above the historical mean (0.8 m^3 s^{-1}) is observed. Further, observations show an increase in hydrologic variability at all given streamflow frequency ranges during the study period. The impact is most pronounced at higher volumes but is also evident at low flow levels. The hydrologic alteration of lower flow volumes agrees with Rose and Peters (2001) where a transition to shorter recession periods was related to urbanizing basins. This altered flow regime is indicative of an increasingly ″flashy″ streamflow prone to short-term high flows and a quick recession back to base flow. The changing stream ecology impacts the benthic and aquatic habitat as: 1) larger and more frequent pulse events in the form of peak discharges well above the historical mean and 2) less frequent sustained flows at or below the historical mean.

Table 5. Statistics for precipitation and standardized streamflow per percentage of impervious surface found over time in the watershed. 3-year bins centered on the aerial photography acquisition dates. * = significant difference found among decades at $\alpha = 0.05$. Statistical tests used for number of values = one-way crosstabs ($\chi 2$), tests for amounts = Kruskal-Wallis one-way analysis of variance, results reported as (test statistic value, df, p-value). N = 990 streamflow-precipitation pairs for precipitation values $\geqslant$ 6.0 mm, 85 streamflow-precipitation pairs for precipitation values $\geqslant$ 35.0 mm. Data related to Hurricane Agnes (June 21-22, 1972) were excluded from the analysis as outliers.

Impervious surface % related to 3-year bin	Number of daily precipitation values $\geqslant$ 6 mm per year	Mean precipitaion amount (mm) per value $\geqslant$ 6 mm ± 95% C.I.	Streamflow response value ($m^3\ s^{-1}\ m^{-1}$) per precipitaion value $\geqslant$ 6 mm ± 95% C.I.*	Number of daily precipation values $\geqslant$ 35 mm per sample year	Mean precipitation amount (mm) per value $\geqslant$ 35 mm ± 95% C.I.	Streamflow response ($m^3\ s^{-1}\ m^{-1}$) per precipitaion value $\geqslant$ 35 mm ± 95% C.I.
3	62.2	17.0 ± 2.0	113.4 ± 15.4	5.5	51.2 ± 7.9	130.3 ± 41.1
13	49.3	17.8 ± 2.0	139.2 ± 21.5	4.3	49.3 ± 6.0	162.3 ± 42.9
21	56.3	17.8 ± 2.0	168.4 ± 20.1	5.0	52.0 ± 6.8	205.2 ± 63.6
27	60.6	18.1 ± 1.9	181.9 ± 25.5	4.6	52.5 ± 4.9	238.1 ± 62.5
33	53.7	18.1 ± 1.4	167.1 ± 12.7	4.6	48.3 ± 6.2	227.2 ± 53.4
Results	(1.93, 4, 0.748)	(4.18, 4, 0.383)	(54.51, 4, > 0.001)	(0.51, 4, 0.973)	(5.00, 4, 0.292)	(8.38, 4, 0.079)

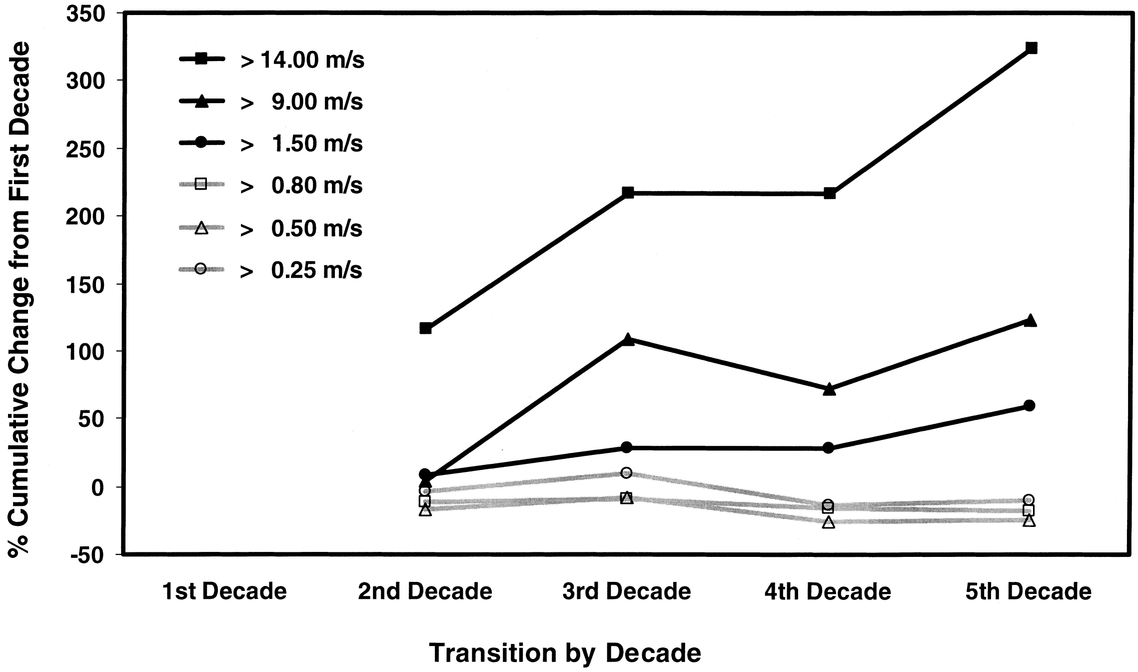

Figure 9. Historical streamflow frequency patterns as derived from data in Table 3. Categories defined the number of daily streamflow (m^3 s^{-1}) occurances above a given level. Change is reported per flow category as cumulative percent change in the frequency of streamflow occurances from the first decade. The historical daily mean streamflow for the upper Accotink Creek is 0.8 m^3 s^{-1}.

As illustrated in Figure 6, the data appear to form two groupings of slopes over time – suggesting a shift in the streamflow discharge pattern during the study period. Under ″normal″ precipitation conditions, the level at which significant change in historical mean daily streamflow response first occurred was between 13% and 21% impervious surface area (Mann-Whitney U test statistic = 10028.50, df = 1, p = 0.002) for the 3-year bins, and between the 1st and 2nd decades (Mann-Whitney U test statistic = 107649.00, df = 1, p = 0.002) for the 10-year bins. The 13% impervious surface category and the 1st decade category appear to be transitional zones, above which permanent alteration of streamflow discharge is observed. A more precise relationship of impervious surface area and streamflow response might be obtained if the study were expanded to include photographic coverage between 1963 and 1971. However, we can generally state that a change in mean daily streamflow response in this basin occurred in the mid-1960s time-period. This trend is observed at all precipitation cutoff values used in our investigation: > 0 mm (Figure 6), $\geqslant$ 6.0 mm (Figures 7 and 8) and $\geqslant$ 35.0 mm (Tables 4 and 5). In addition, during the period of rapid impervious surface growth (1949–1979), there is a corresponding rise in daily streamflow response. In the subsequent period (1980–1994), slower impervious surface growth corresponds to a slower rise in streamflow response. It is also possible that this later period was influenced by detention basins that were widely introduced into Fairfax County in the mid-to-late-1970s (Rayyan 2001).

Ecological studies such as Klein (1979) and Limburg and Schmidt (1990), Weaver and Garman (1994) and Wang et al. (2001) utilized land use/land cover information to derive an impervious component and found that significant ecosystem change occurred at approximately 10% –15% impervious surface area. The results presented here (significant hydrological change between 13% and 21% impervious surface area) agree with these investigations. However, the reasons for agreement are unknown. As speculated in Wang et al. (2000), it is possible that instream changes in species composition noted in urban studies are primarily due to changes in the variability of frequency and magnitude of streamflow disturbance brought about by impervious surfaces. However, the connection between the change in stream disturbance regime and changes in stream species composition is not supported by this investigation or by the current science. While the literature is abundant with investigations that have related impervious surface and

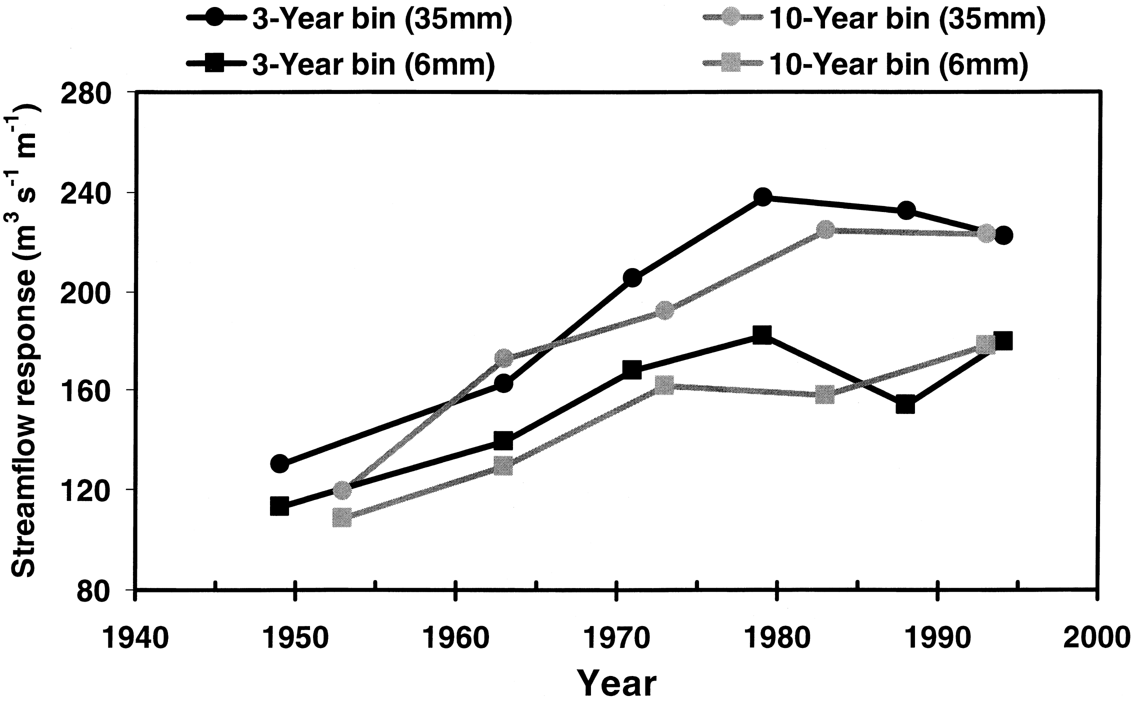

Figure 10. Trends of streamflow response value (m^3 s^{-1} m^{-1}) at 3-year and 10-year bins associated with precipitation cutoff values $\geqslant$ 6 mm and $\geqslant$ 35 mm. Data points for 10-year category are plotted at approximate mid-decade (1953, 1963, 1973, 1983, 1993). Data points for the 3-year category are plotted per photo year.

stream biota there have been few investigations that specifically relate the historical relationship of impervious surface area, streamflow and stream biota (Moscript and Montgomery 1997) and none that specifically address this issue at the daily temporal scale. We did not have a long-term biota data set from which to assess this issue and suspect that, with few exceptions, consistent long-term stream sampling data in urban environments (coincident with stream gages) are rare. An issue for future research would be capturing and analyzing fine temporal-scale, long-term stream data (streamflow and biota) along with explicit impervious surface data to determine specific linkages between changes in historical hydrologic pattern and in-stream biological communities in urbanizing watersheds. The production of streamflow pattern metrics based on the de-construction of historical daily streamflow variability in urbanizing basins, as simply illustrated in Figure 9, might be a step towards determining the exact mechanisms by which impervious surfaces and hydrologic change impact stream biota.

Ecological change due to hydrological disturbance has been addressed in Biggs (1995) and Poff and Allen (1995). These studies, while not specifically addressing an impervious surface issue, reveal the biological impacts related to altered flow regimes and changing hydrologic pattern. Cairns (1995) discussed the concept of ecological elasticity and urban runoff and concluded that ″ The effects of closely spaced pulses of urban runoff, which do not permit full recovery to occur, undoubtedly have a cumulative impact ... but the cumulative impact of multiple, closely spaced pulses is not well understood″.

Figure 10 illustrates the general agreement on streamflow response value between the 3-year and 10-year bins. We assumed that high variance associated with the 3-year windows (wet-year/dry-year impacts and smaller sample sizes) would necessitate a decade bin analysis to accurately characterize an overall streamflow trend. However, the agreement between the differing temporal resolutions suggests the 3-year window has been minimally influenced by wet-year/dry-year precipitation phenomena and accurately characterizes the landscape, precipitation, and runoff relationship. This agreement between the two temporal scales allowed us a higher level of confidence in the relationship of impervious surface percent and streamflow response.

Manual analysis and compilation proved to be a highly accurate method for the mapping of impervious surfaces. However, there were three areas subject to interpretation confusion. ***Sidewalks*** were not always compiled due to a lack of clearly definable edges. This was due primarily to the spatial resolution of the scanned imagery. Pixel size (1 m^2) was based on USGS DOQQ standards, which provided a standard mapping methodology across all years of coverage. In many areas however, the resolution precluded discrimination of smaller features such as sidewalks that often are imaged at sub-pixel resolutions. ***Open compacted soils*** related to construction zones were possibly mis-classified due to the inability of aerial photography to determine a measure of imperviousness for these soil areas. ***Single-family rooftops*** were subject to confusion due to the density of canopy cover over portions of the residential areas. In numerous cases, the density of woody overgrowth precluded clearly delineating impervious polygon boundaries at the parcel level. Due to the number of rooftops increasing over time, this source of confusion could possibly lead to an increasing amount of error in the TIA per photographic coverage over time.

Conclusion

Using an empirical approach, we have attempted to characterize the long-term impact of impervious surface growth on mean daily streamflow discharge. Results show that, over the study time period, daily streamflow response values coinciding with ″normal″ and ″extreme″ precipitation occurrences have increased approximately 50% and 100% respectively, while the percent of anthropogenic impervious surface area has increased 10-fold. Results suggest that a statistically significant change ($p < 0.05$) in streamflow response occurred between the 13% (1963) and 21% (1971) impervious surface levels for the 3-year bins and between the 1st (1948–1957) and 2nd (1958–1967) decades for the 10-year bins. Results also indicate that a statistically significant ($p < 0.05$) disturbance in the frequency of mean daily streamflow levels has occurred between the flow range of $\geqslant 0.25$ $m^3\ s^{-1}$ and $\geqslant 14\ m^3\ s^{-1}$. This particular alteration of the physical ecology is suggestive of an urbanizing basin prone to ″flashy″ flows that bring about an increased variability in streamflow at the daily temporal scale.

Anthropogenic impervious surface, as a landscape variable, is not the only driver of changes in streamflow response in urbanizing basins. More research is necessary to determine the historical relationship that streamflow has with other individual landscape variables such as forest patches, grasslands and agricultural areas, riparian area as well as the effects of integrated landscape pattern. In addition, in historical investigations, there is a need to further define historical precipitation patterns and their possible impacts on streamflow rate. However, there is historical evidence, in the upper Accotink Creek subwatershed, to suggest that anthropogenic impervious surface growth is an indicator of statistically significant response in streamflow discharge.

The methodologies utilized in this investigation offer a means to discern the historical relationship between landscape, precipitation, and streamflow. Utilizing these to formulate historical integrated assessments can be a research mechanism for determining the relative health of evolving stream ecosystems. However, in order to implement this method over larger landscape areas, a more efficient method of accurately measuring impervious surfaces is required. To that end, the mapping portions of this investigation will be used to study the classification accuracy of coarser resolution remote sensing data such as LANDSAT MSS and TM data, and such evolving image classification methods as data fusion and sub-pixel analysis. As noted by Booth and Jackson (1997), the lack of consistent methodology for determining impervious surface area as well as the lack of reporting of how the parameter was generated inhibits a thorough scientific comparison of results. A common mapping framework for impervious surfaces needs to be established before the myriad integrated impacts of this ecological indicator can be fully understood.

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