

3. Quantifying Long-term Hydrologic Response in an Urbanizing Basin*

Summary: This paper describes long-term hydrologic response within a rapidly developing watershed in the western suburbs of Washington, DC, within the Chesapeake Bay drainage basin. Data consist of up to 24 years of observed rainfall, basin discharge, and land use/land cover (LULC) from four headwater basins of the Occoquan River in northern Virginia. Basin outlets are monitored for storm and nonstorm flows, respectively, using flow-proportional, volume-integrating storm samplers and continuous stream gaging. Landsat-derived measures of impervious surface are supplemented with regional land use mapping to characterize LULC in each basin. Three of the four study basins, ranging in size from 67 to 400 km², are predominantly forest and/or mixed agriculture. The fourth basin, the 127 km² Cub Run watershed, has urbanized rapidly over the past 20 years with approximately 50 percent of current land area classed as urban (18 percent impervious surface). Results indicate a greater hydrologic response in the urbanizing Cub Run basin, compared to the three adjacent basins. Cub Run basin has higher annual and seasonal storm volumes per surface area than non-urban basins after 1983, when estimated impervious surface area in Cub Run basin reached approximately nine percent. In all four study basins, storm discharge per surface area is more responsive to rainfall during winter and spring due to generally denuded dormant season landscapes. Only during the summer and fall is long-term storm runoff in Cub Run basin higher than non-urban basins. This result is significant, as it supports expected biophysical reductions in interception, infiltration, and evapotranspiration during the growing season due to higher imperviousness. Results of this study also support literature regarding increased storm volumes in catchments above 10 percent imperviousness. Increased unit-area storm discharge in Cub Run basin during the growing season has important implications for seasonal NPS pollutant flux which are addressed in the following chapter.

KEYWORDS: storm runoff, urbanization, LULC, impervious surface

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3.1. Introduction

The American Society of Civil Engineers (ASCE, 1998) states that increased stormwater runoff is one means to analyze the hydrologic impact of urbanization, but that other impacts should also be considered, including reduction in infiltration to groundwater, increased flooding and erosion potential, and greater risk of water quality and habitat degradation. As early as 1968, Brater and Sangal reported the effects of urbanization on peak flows; and Rantz (1971) suggested that the location and characteristics of impervious areas be considered important criteria in reducing peak discharge in urban areas. In 1974, Stankowski developed flood frequency relationships using landscape characteristics, including impervious cover. Numerous authors, including Wheeler et al. (1982), Laenen (1983), Booth and Reinelt (1993), Schueler (1994a), and Arnold and Gibbons (1996) have quantified shorter times of concentration, higher peak flows, larger storm volumes, and potentially lower baseflow volumes associated with urbanization.

Increased runoff volumes and reduced infiltration would be expected to result in lower groundwater recharge, resulting in lower dry weather stream flows (ASCE, 1998). However, according to Schueler (1994a, 1994b) data demonstrating this effect are rare. Although Simmons and Reynolds (1982) noted a reduction of dry weather flows after development in several urban watersheds in Long Island, New York, Evett et al. (1994) did not find any statistical difference in low stream flows between urban and rural basins in 16 North Carolina watersheds. This leads to the conclusion that the impact of impervious surface (IS) on baseflow is site-specific (ASCE, 1998).

Numerous authors have cited the benefits of long-term, continuous watershed monitoring (Richards and Holloway, 1987; Swift et al., 1988; U.S.EPA, 1990; Loftis et al., 1991; Dixon and Chiswell, 1996; Longabucco and Rafferty, 1998; Correll et al., 1999b). Correll et al. (1999c), in their 25-year watershed study of a mid-Atlantic Coastal Plain agroecosystem, stated that a number of issues relating hydrology of small, headwater catchments can be adequately addressed only through long-term data. However, few studies have the combined long-term precipitation, discharge, and land use/land cover (LULC) data necessary to analyze basin discharge as a function of precipitation and LULC.

The linkage between storm runoff and nonpoint source (NPS) pollution delivery has been recognized since the late 1960s (Novotny, 1981). In recent years, mean watershed imperviousness has become an indicator for assessing water quality impacted by urban growth. Many analysts have argued that impervious surface (IS) coverage in a watershed is a good indicator of potential impact on stream health (Randolph, 2004). According to Schueler (1994a), when watershed development exceeds 10 to 15 percent impervious cover, the hydrologic impact of flooding on streams increases channel cross-sectional area, triggering streambank erosion, habitat degradation, and downstream pollutant loading.

The urbanizing Cub Run basin and three adjacent rural basins which are the focus of this paper, are part of the Occoquan watershed, which drains into the Occoquan reservoir, an important water supply and recreational resource for more than one million people. Since the 1950s, rapid population growth in the suburbs west of Washington, DC have made the northern Virginia region one of the most rapidly growing areas in the country. Urban and suburban growth has resulted in substantial changes in land use and ecology. This study quantifies hydrologic changes due to such rapid urbanization.

Objective of the Study

This purpose of this study is to investigate the relationship between basin characteristics and hydrologic response to precipitation, with a specific focus on urbanization. The objective is to quantify changing hydrologic response within the four headwater basins of the Occoquan River using long-term monitoring records of basin precipitation and discharge, with regional LULC observations.

Study Area

The study area consists of four headwater basins in the Piedmont physiographic province of the Chesapeake Bay drainage. The basins are part of the 1530 km² Occoquan River watershed in northern Virginia (Figure 3-1). The three western basins, ranging in size from 67 to 400 km², are predominantly forest and mixed agriculture. The fourth basin, the 127 km² Cub Run watershed, is rapidly urbanizing, with 18 percent impervious surface and 50 percent of current land use classed as urban.

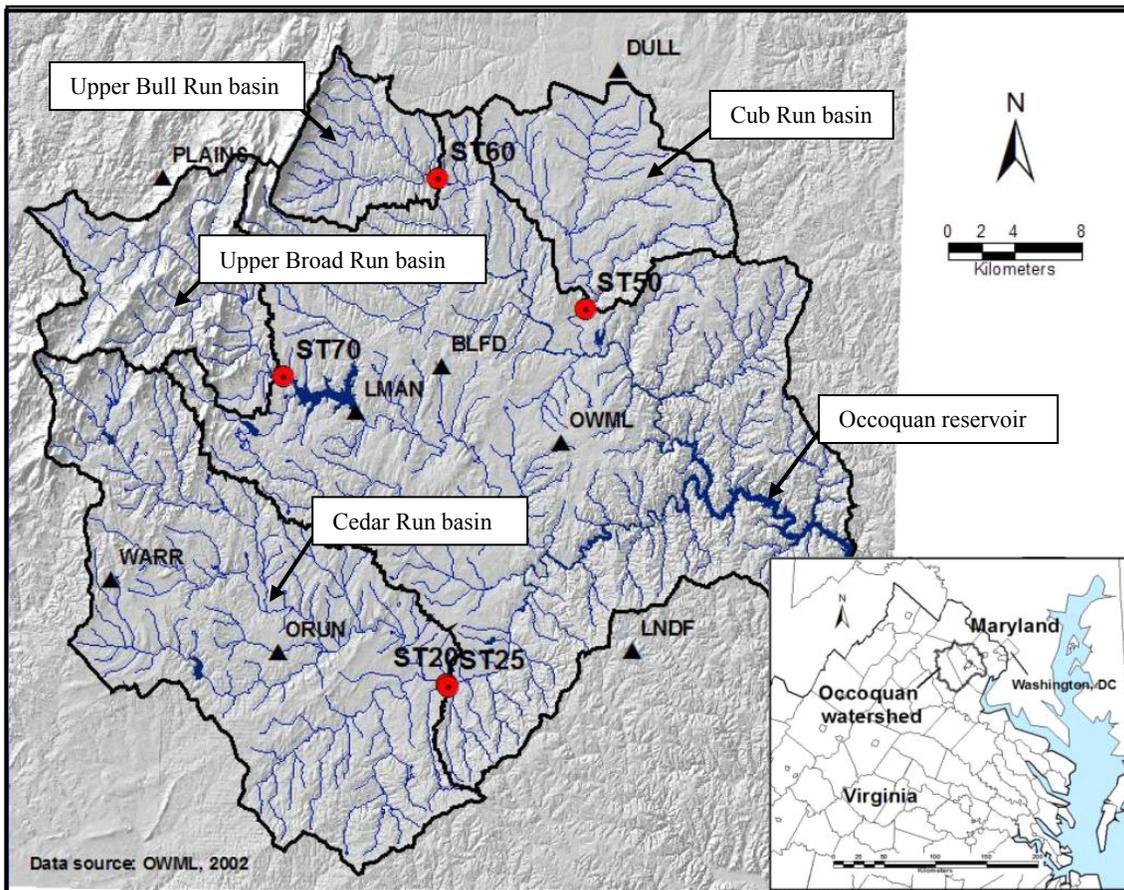


Figure 3-1. Occoquan River watershed study area, northern Virginia, USA.

Occoquan watershed (1530 sq. km) showing headwater basin water monitoring stations (red circles), rain gages (black triangles), and Occoquan reservoir. Insert: location map.

A summary of the physical characteristics for each basin (Table 3-1) reveals that Cub Run basin has the lowest average slope and elevation of all Occoquan headwater basins, and is most similar in area and stream density to Upper Broad Run basin. The

three rural basins in the study extend into the upland western section of the Occoquan basin and include areas of significant relief (Figure 3-1).

Table 3-1. Physical attributes of Occoquan headwater basins.

Basin	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
OWML monitoring station ¹	ST20/25 ²	ST50	ST60	ST70
Area, km ²	398	127	66.9	131
Ave. slope, %	5.3	3.4	6.9	10.3
Average elevation, m (range)	114 (53-416)	94 (48-154)	132 (75-387)	194 (87-417)
Stream length, km	389	112	66.4	107
Inverse drainage density, km [‡]	1.02	1.14	1.01	1.22

¹ Occoquan Watershed Monitoring Laboratory, Manassas, Virginia.

² Station 20 was replaced by station 25 on 8/20/91.

[‡] 1/DD = basin area/stream length (Reckhow et al., 1985).

3.2. Methods

The following section describes methods used to collect and summarize LULC and hydrologic data, as well as statistical procedures used to compare resulting summaries.

Basin Characteristics

Spatial data products available from Environmental Systems Research Institute, Inc. (ESRI®) and GeoLytics, Inc. (GeoLytics®), derived from U.S. Census data, are used to assemble decennial estimates of population density from 1980 to 2000 for each of the four Occoquan headwater basins (Appendix A). Building polygon locations linked to public tax assessment data (Figure A-6) are provided by county government agencies, providing an historic, spatial record of building activity within the urbanizing Cub Run basin. Annual population estimates for Cub Run basin are interpolated from decennial estimates using annual building numbers (Figure A-6). Annual population estimates for rural Cedar Run, Upper Bull Run, and Upper Broad Run basins are derived using simple linear interpolation of decennial estimates.

Land use analysis and summary is completed within a geographic information system (GIS) using rectified 1979 and 1989 land use maps (Figure Q-2) and pre-classified 1995 and 2000 land use shapefiles (Figure Q-3) from the Northern Virginia

Regional Commission (NVRC). Landsat-derived IS estimates for 1986, 1990, 1996, and 2000 (Figure A-5) are used as an indicator of urban land cover. Missing IS estimates for 1980 are synthesized using calibrated land use and IS relationships (Table A-1) derived from a previous study that evaluated IS estimation methods in Cub Run basin (Dougherty et al., 2004). Due to rapid growth rates, annual IS estimates for Cub Run basin are interpolated proportionately using annual building numbers, while IS estimates for the three rural basins are derived using simple linear interpolation of Landsat-derived IS estimates. Complete procedures for estimating population density and IS are found in Appendix A.

Basin Hydrology

Daily precipitation data from eight local rain gages (Figure 3-1) is provided by the Occoquan Watershed Monitoring Laboratory (OWML). Rainfall data for two of the eight gages is incomplete, and is supplemented with data from the National Oceanic and Atmospheric Administration (Figure B-1, Table B-1). Thiessen polygon analysis is used to synthesize daily rainfall estimates for the entire Occoquan basin and the four individual headwater basins (Figure D-1), with five successive time periods utilized to take advantage of rain gages that come in and out of service over the 24-year study period (Table B-1, Figure B-1). Two additional time periods from 1951 to 1978 are used to synthesize a complete 51-year rainfall record for the entire Occoquan basin.

Rain gages have from 0 to 29 percent missing data (Table B-2). Missing rainfall data is replaced through hot-deck infilling, which involves substitution of individual values from similarly responding units. A comparable method is recommended by Rantz et al. (1982) for infilling missing flow data during periods of fluctuating discharge. Selection of rain gages for infilling is based on Spearman's correlation of paired raw rainfall data (Figure B-2).

Stream Discharge Data

Average daily discharge data are tabulated from quarter-hour readings taken from stream-gaging equipment installed at OWML monitoring stations (Figure 3-1). Average daily discharge volume is estimated using the 15-min average flow. Missing stream discharge data comprises less than five percent of station data (Table F-1), which

compares favorably with nationwide streamflow data (Wallis et al., 1991). In his study of the Occoquan monitoring program, Johnston (1999) recommended linear regression infilling when missing data is less than 5 percent of total data. Consequently, regression flow relationships between adjacent basins are used to infill missing discharge data (Table F-1).

Storm Sampling

During storm discharge events, stream flow (and constituent concentrations) are measured automatically using flow-proportional, volume-integrating storm samplers. Before mid-1988, storm samples were collected by automatic triggering of samplers with a contact closure every 0.5 feet rise or fall in stream stage using magnets mounted on a float wheel which closed a reed switch mounted under the wheel (Grizzard et al., 1976). Since mid-1988, storm flows at each monitoring station are initiated through station-based micro-processors that test for the start of a storm every five minutes by comparing the stage of the past three five-minute intervals with the previous stage (Post and Grizzard, 1987). During a storm sequence, the computer tracks storm duration and flow volume at one-minute increments. Once storm flow starts, the program begins to test for the end of the storm using a modified version of the baseflow separation equation developed by Hewlett and Hibbert (1967) for small watersheds. In 1998, data intervals for storm flows were switched from a five- to a two-minute interval.

An important distinction is made in this study between nonstorm discharge and baseflow. Storm flow volumes reported in this study are based on an arbitrary rise in stream stage, with flow volumes not classed as storm flows reported as nonstorm flow volumes. These nonstorm volumes are likely to contain flows in excess of baseflow.

Excluded Data

Raw data consisting of storm and nonstorm flows are assigned to sequential water years running from October 1, 1978 to September 30, 2002. Water years are excluded if there are more than 90 consecutive calendar days without an integrated water quality sample (storm or nonstorm) collected in any basin, even though hydrologic data may be complete. Similarly, seasonal data periods are excluded if there are more than 30 consecutive calendar days (more than 45 days in the winter) without a sample collected in

any basin. As a result, three water years (1979, 1980, and 1982) are excluded from annual analysis, except where noted otherwise, and eleven seasonal intervals are excluded from seasonal analysis (Table L-1).

Statistical Approach

The study reported in this paper is observational, using long-term data to contrast hydrologic responses from four headwater basins under a variety of precipitation and LULC conditions. Hydrologic summaries generated by these data have non-normal distributions and contain significant outliers. Consequently, nonparametric Kruskal-Wallis rank sum and Wilcoxon two-sample tests which require no distributional assumptions are used to discern statistical differences between groups. Because of the possibility of data bias due to the change in storm sampling method in 1988 (Appendix H), statistical comparisons are limited to between-basin tests. Robust MM regression routines from S-Plus™ (Insightful Corp., 2001) are used to fit linear relationships (Appendix O). Resulting regressions are not intended to be predictive, rather are used to identify and explore linkages between annual/seasonal precipitation and discharge in the four mixed-land use basins. Local (Loess) regression, a nonparametric generalization of multivariate polynomial regression (Insightful Corp., 2001), is used to fit a general smooth surface to reveal the underlying structure of the data and encourage further exploration. Automatic (variable) span selection for the smooth surface is done by cross validation, with a reasonable span value between 0.3 and 0.5 (Insightful Corp., 2001).

3.3. Results

This section describes LULC and hydrologic summaries developed for this study, as well as important relationships identified by descriptive and comparative statistics, regression relationships, and graphical analysis.

Population Density and LULC Summaries

In 2004, Loudoun County, Virginia was identified as the fastest growing county in the United States (USA Today, 2004). From 1980 to 2000, the growth rate of Cub Run basin, located within rapidly urbanizing Loudoun and Fairfax counties, far exceeded the rate of the other three basins in this study. From 1980 to 2000, population in Cub Run

basin increased 380 percent, with nearly three times as much population growth occurring in the 1980s compared to the 1990s. Average land use summaries (Table 3-2, Figure Q-1) from 1980 through 2000 document differences in land use between the four basins. All have large percentages of forest or idle land, much of which has been converted to agricultural pasture or crop production. In the case of Cub Run basin, and to a lesser extent Upper Bull Run basin, agricultural land has subsequently been converted to urban uses. GIS analysis of historic land use in Cub Run basin confirms the rapid increase in urbanization between the years 1980 and 2000 (Figure Q-4). Before 1990, there was more than twice as much rural land as urban land. However, by 2000 there was more urban than non-urban land (Figure 3-2).

Table 3-2. Land use percentages, Occoquan headwater basins, 1980, 1990, and 2000.

Land use category	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
Forest/idle	44, 45, 52	51, 46, 45	57, 42, 49	39, 47, 57
Agriculture	53, 50, 41	27, 16, 4	33, 45, 33	58, 48, 38
Urban	3, 5, 7	22, 38, 51	10, 14, 18	2, 4, 6
Total	100, 100, 100	100, 100, 100	100, 100, 100	100, 100, 100

Source: Northern Virginia Regional Commission (NVRC) land use mapping, circa 1980, 1990, 2000.

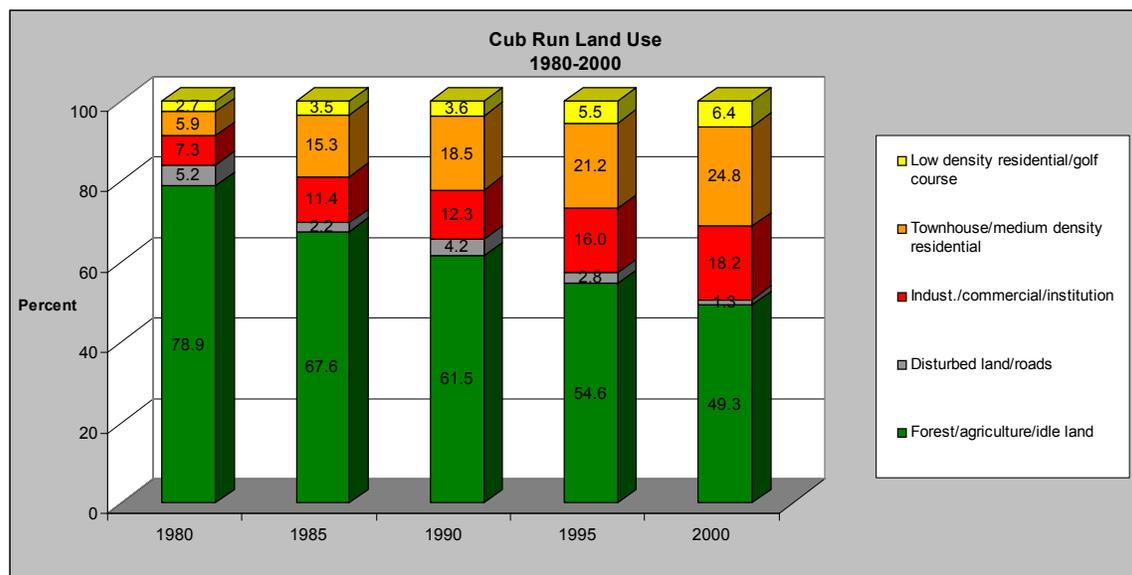


Figure 3-2. Cub Run land use, as a percent of total, 1980-2000.

Source: NVRC land use mapping, 1980, 1990, 1995, 2000 (1985 land use estimated using modified NVRC 1990 land use mapping and 1986 Mid-Atlantic RESAC 1986 urban extents).

Mean IS percent as derived from GIS analysis of NVRC land use data increased 96 percent from 1980 to 1990 in Cub Run basin, compared to a 36 percent increase from 1990 to 2000. Impervious surface estimates at five year intervals (Table 3-3) reveal IS growth that matches population, with Cub Run basin widely outdistancing the other three headwater basins. Cub Run basin surpassed 10 percent mean imperviousness sometime around 1985.

Table 3-3. Mean impervious surface, %, Occoquan headwater basins, 1980-2000.

Basin	1980	1985	1990	1995	2000	20-year average
Cedar Run	1.4	1.5 ¹	1.7	1.8	1.8	1.6
Cub Run	6.7	9.3 ²	13.1	15.8	17.8	12.5
Upper Bull Run	1.7	1.9 ¹	2.0	2.0	2.2	2.0
Upper Broad Run	1.5	1.5 ¹	1.5	1.6	1.6	1.5

Source: NVRC land use mapping and Mid-Atlantic RESAC impervious surface estimates.

¹Linearly interpolated from 1980 and 1990 IS values.

²Interpolated proportionately from 1980 and 1990 IS values using annual building numbers.

Results of this study demonstrate that the Cub Run basin, unlike its three adjacent headwater neighbors, is undergoing quantifiable transformation into an urban landscape. Randall and Grizzard (1995) reported that most of the increase in new development in the Occoquan basin occurred after 1984, when a moratorium on building in Fairfax County was lifted. Annual estimates of population density interpolated from actual building numbers suggest that the greatest 5-year growth in Cub Run basin occurred in the mid-1980s between 1982 and 1987 (from 1.8 to 3.7 persons per hectare); and the greatest one-year increase in population density occurred from 1985 to 1986 (from 2.8 to 3.3 persons per hectare). Impervious surface trends are similar to those for population (Table A-2). A smaller population surge occurred in the Cub Run basin in the years 1990 through 1994 with a maximum annual increase (9.0 percent) occurring between 1991 and 1992 (Figure A-1). The corresponding increase in impervious surface percent was 4.4 percent (Figure A-2). After 1995, annual population growth rates in Cub Run basin slowed to an average 4.8 percent, with a corresponding average impervious surface growth rate of 2.4 percent. Results indicate roughly a 2:1 relationship between population and IS growth rates.

Hydrologic Summaries

Annual and seasonal precipitation for the 24-year period from 1979 to 2002 is representative of the 51-year period of record (Table 3-4) and includes both high and low record rainfall years (2002 and 1979, respectively). The record high annual rainfall (1352 mm) is nearly twice the lowest rainfall (697 mm), indicating not only a large annual variation, but a discernable 20-year pattern (Figure E-1). Summer rainfall sums exhibit the highest long-term variability of any season (Figure E-2 and E-3), due to high-intensity convectonal storms and occasional tropical hurricanes.

Table 3-4. Precipitation during 24-year study, Occoquan basin, mm/period. Compared with long-term (51-year) precipitation.

	Winter	Spring	Summer	Fall	Annual
51-yr mean \pm 1SD (range)	210 \pm 69.2 (78 – 421)	261 \pm 64.1 (121 – 410)	288 \pm 98.3 (107 – 586)	244 \pm 73.0 (109 – 417)	1004 \pm 176 (697 – 1352)
24-yr mean \pm 1SD (range)	203 \pm 79.0 (78 – 421)	264 \pm 71.2 (123 – 410)	267 \pm 83.0 (146 – 476)	250 \pm 73.8 (112 – 417)	983 \pm 185 (697 – 1352)

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.
Annual averages above based on water years beginning Oct. 1 through Sept. 30.
Winter=Dec, Jan, Feb; Spring=Mar, Apr, May; Summer=Jun, Jul, Aug; Fall=Sept, Oct, Nov.

Annual Discharge

Long-term annual basin discharge summaries from OWML (Table 3-5) reveal that Cub Run basin has the highest ratio of storm to nonstorm discharge, the lowest precipitation minus runoff (P-RO) value, and is the only basin with mean annual storm flow greater than nonstorm flow. More importantly, urbanizing Cub Run basin has a significantly higher storm discharge per area (192 mm) than the three neighboring headwater basins. Upper Broad Run basin, the steepest and most elevated basin (Table 3-1), has *lower* storm discharge per area and the highest mean and median *nonstorm* unit discharge. Swift et al. (1988) referenced a number of studies at Coweeta Experimental Forest in North Carolina that verified the importance of unsaturated flow through soils on steep slopes as a source of baseflow. Blomquist et al. (1996) reported that Piedmont areas underlain with Triassic and Jurassic sedimentary rocks such as the Occoquan basin have approximately 35 percent of total streamflow comprised of baseflow. Mean annual

nonstorm discharge volumes from this study range from 50 to 67 percent of total stream flow, highlighting the distinction between nonstorm discharge, reported in this study, and baseflow.

Table 3-5. Mean and median annual unit discharge, 1979-2002, mm.

Basin	Cedar Run basin	Cub Run basin	Upper Bull Run basin	Upper Broad Run basin
Storm discharge	152	192	159	115
(median)	(104) ^b	(162) ^a	(121) ^b	(91) ^b
Nonstorm discharge	189	190	185	229
(median)	(169) ^a	(182) ^a	(190) ^a	(212) ^a
Total discharge	341	382	344	344
(median)	(309) ^a	(356) ^a	(329) ^a	(283) ^a
Storm/nonstorm discharge ratio	0.80	1.00	0.85	0.50
P - RO ¹	721	639	712	710

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

Annual averages above based on water years beginning Oct. 1 through Sept. 30.

Discharge means calculated using 21 years of data (1979, 1980, 1982 excluded).

Similar superscripts indicate no significant difference between groups ($\alpha = 0.05$).

¹ P - RO = precipitation minus total discharge (or runoff) is equal to total non-discharge losses (which include interception, surface storage, evapotranspiration, deep percolation).

Annual storm and nonstorm discharge graphed as a function of annual precipitation for each basin (Figure 3-3) reveals a significantly higher storm discharge response in Cub Run compared to the three rural basins. Hewlett (1967) ultimately selected the ratio of annual mean storm runoff to mean annual precipitation as the most useful hydrologic response characteristic; and Woodruff and Hewlett (1971) used this metric to develop a response map for the entire eastern United States.

Unit storm discharge is summarized by era (Table 3-6) in order to assess changing hydrologic response over time, an important goal of this study. In spite of excluded data for the first era (see Appendix L), results reveal that Cub Run mean and median storm discharge exceeded other basins in all post-1983 eras. For example, during the 1979 high rainfall year of record, unit storm discharge for Cedar Run, Cub Run, Upper Bull Run, and Upper Broad Run was 353, 302, 251, and 169 mm, respectively. These results suggest a reduced hydrologic response in Cub Run basin before the mid-1980s.

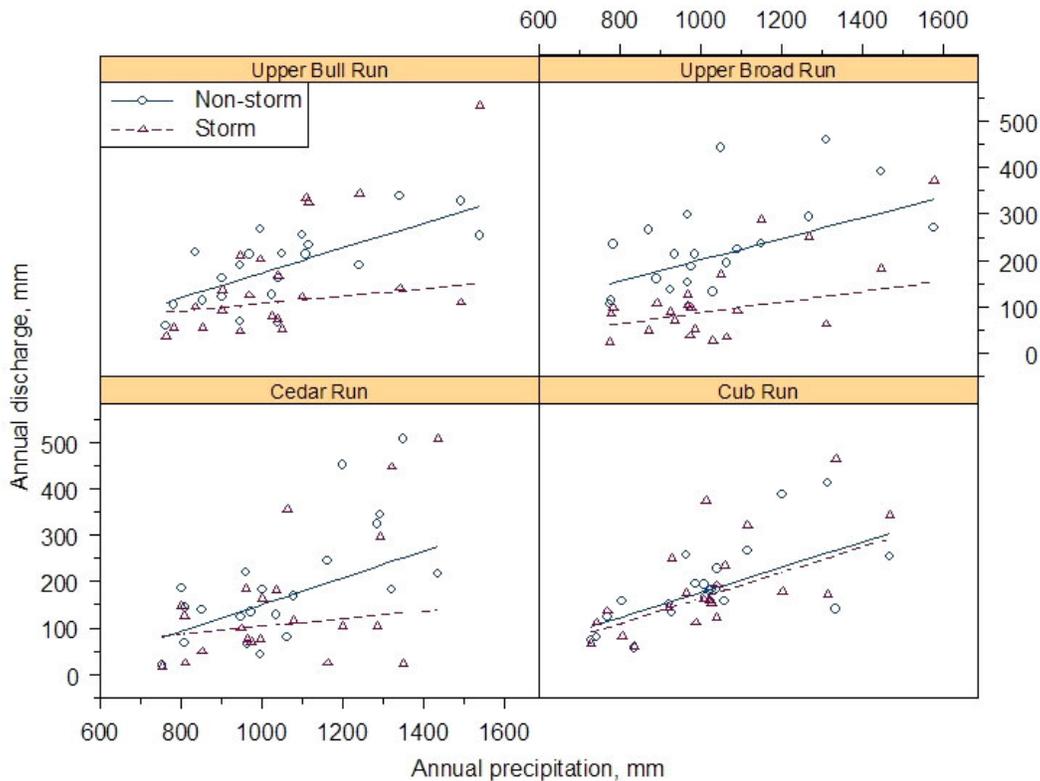


Figure 3-3. Annual storm and nonstorm discharge as a function of annual precipitation, four Occoquan headwater basins, 1979-2002.

Slope of the Cub Run storm discharge response is significantly higher than three rural basins ($p < 0.05$) (Robust MM regression, Insightful Corp., 2001).

Table 3-6. Mean and median annual unit storm discharge, by era, (Occoquan headwater basins, 1979-2002, mm).

Era	N years	Cedar Run basin	Cub Run basin	Upper Bull Run basin	Upper Broad Run basin
1979-1983 (median)	2	215 (215) ^a	155 (155) ^a	191 (191) ^a	164 (164) ^a
1984-1988 (median)	5	212 (148) ^a	256 (192) ^a	220 (166) ^a	156 (108) ^a
1989-1995 (median)	7	80.0 (103) ^b	159 (162) ^a	146 (121) ^a	88.1 (91.0) ^b
1996-2002 (median)	7	163 (75.1) ^a	188 (155) ^a	119 (92.6) ^a	98.6 (70.8) ^a

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.
 Discharge means calculated using 21 years of data (1979, 1980, 1982 excluded).
 Similar superscripts indicate no significant difference between groups ($\alpha = 0.10$).

Seasonal Discharge

Seasonal discharge summaries from OWML (Table 3-7) reveal that the majority of discharge in all basins occurs during winter and spring (December through May), and that summer discharges have the largest variability. Increased basin discharge in winter and spring is not matched by proportional increases in rainfall during these seasons (Table 3-4), so must be caused by other components of the hydrologic cycle, likely dormant season reductions in vegetated cover. Seasonal discharge summaries also reveal that Cub Run has the largest mean and median discharge only during the growing season (summer and fall). Further comparison of summer and fall storm discharge means by era (Table G-5) reveals that Cub Run exceeded other basins, again only in post-1983 eras.

Table 3-7. Mean seasonal stream discharge means \pm 1 SD and medians, 1979-2002, Occoquan headwater basins, mm.

Season (p-value) ¹	Cedar Run basin	Cub Run basin	Upper Bull Run basin	Upper Broad Run basin
Winter (0.955)	138 \pm 91.9 122 ^a	131 \pm 68.9 105 ^a	125 \pm 71.8 113 ^a	119 \pm 65.3 106 ^a
Spring (0.788)	124 \pm 84.2 91.5 ^a	130 \pm 66.1 117 ^a	137 \pm 83.5 112 ^a	136 \pm 72.2 121 ^a
Summer (0.132)	36.7 \pm 38.2 24.5 ^a	49.2 \pm 30.3 43.5 ^a	32.2 \pm 30.3 16.6 ^a	37.7 \pm 24.6 34.8 ^a
Fall (0.233)	51.9 \pm 44.0 39.0 ^a	73.9 \pm 44.4 82.1 ^a	50.9 \pm 29.1 46.6 ^a	54.2 \pm 34.2 45.1 ^a

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.
 Winter=Dec, Jan, Feb; Spring=Mar, Apr, May; Summer=Jun, Jul, Aug; Fall=Sept, Oct, Nov.
 Seasonal means calculated using 85 seasons of data (11 seasons excluded due to missing data).
¹Significant p-value indicates that at least two basins have different central measures of location.
 Similar superscripts indicate no significant difference between groups ($\alpha = 0.10$).

Seasonal storm discharge versus precipitation for each basin (Figure 3-4) reveals a generally lower storm runoff response (smaller slope) in the summer and fall for all basins, but especially in rural basins. A generally higher storm response (greater slope) is observed across all basins during the winter and spring, as expected. Cub Run's seasonal storm discharge response is most similar to rural basins during the dormant season. However, during the summer and fall, Cub Run has a noticeably greater storm response than the other basins.

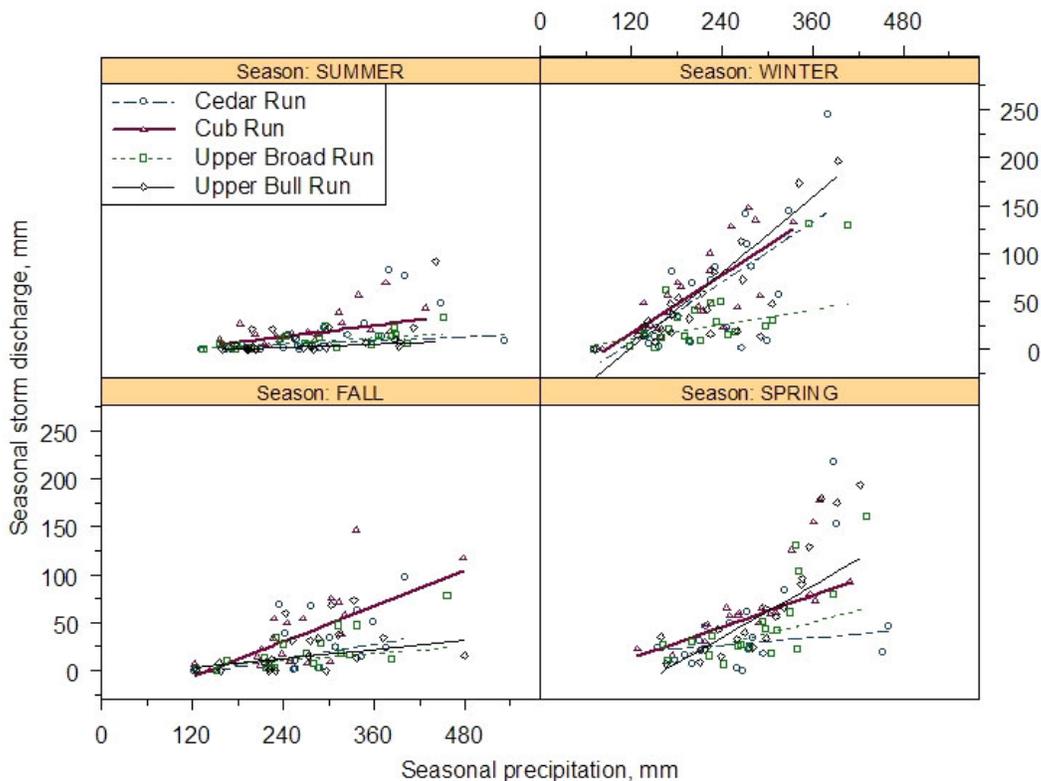


Figure 3-4. Seasonal storm discharge as a function of precipitation, 1979-2002.

Slope of Cub Run storm discharge response is significantly higher than three rural basins in summer ($p < 0.05$) and fall ($p < 0.20$) (MM Robust regression, Insightful Corp., 2001).

3.4. Discussion

This section focuses on the relationship between catchment-scale urbanization and basin hydrology, reviewing differences between the urbanizing Cub Run basin and the three rural basins, as well as differences over time. The four headwater basins of the Occoquan River provide an excellent opportunity to observe the long-term impact of changing precipitation and impervious surface on basin discharge from contrasting land forms and land covers. Cedar Run basin is six times larger than the smallest basin, Upper Bull Run, but has similar average slope, elevation, and stream density. Cub Run and Upper Broad Run basins have similar size and stream density, but widely contrasting average slope and elevation. The urbanizing Cub Run basin is characterized as having the highest mean annual impervious surface area, but the lowest mean elevation and slope

of any basin. In spite of its slight topographic relief, Cub Run basin has the highest mean annual storm drainage per surface area. Differences in storm discharge are attributed to permanent changes in land cover due to urbanization since Cub Run has the highest annual and growing season storm discharge only after the mid-1980s, about the time that documented rapid population growth and land development began. Time series of annual storm discharge per area fitted with nonparametric smoothed curves (Figure 3-5) provide graphical support for the hypothesis that annual Cub Run storm discharge per area surpassed other Occoquan headwater basins sometime around 1985, when Cub Run reached an estimated impervious surface area of approximately nine percent (Table 3-3).

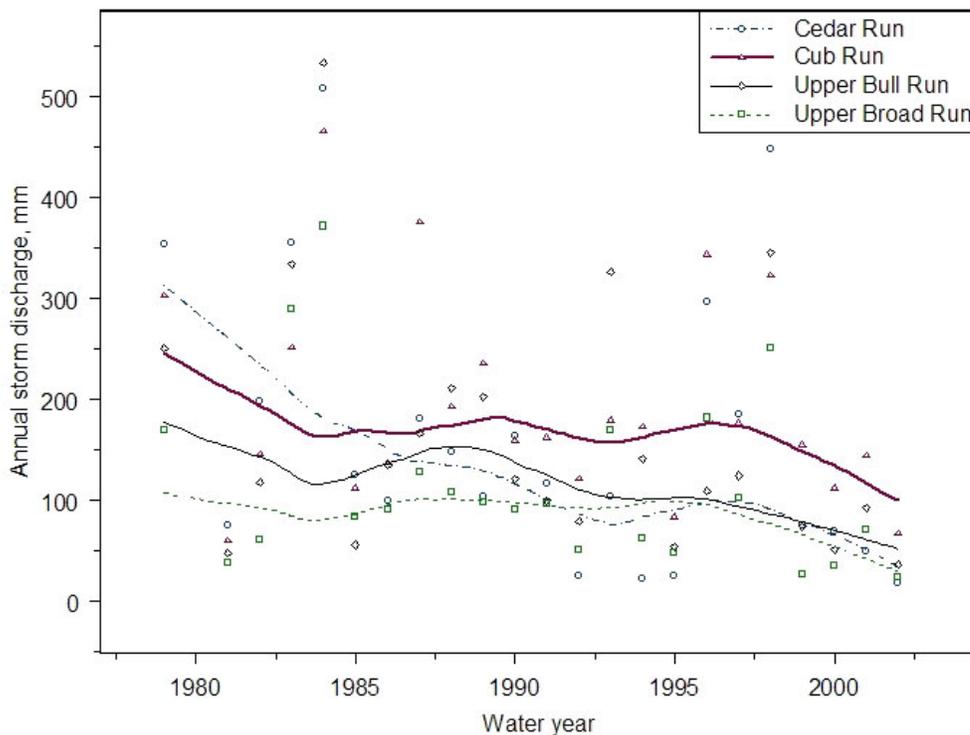


Figure 3-5. Annual time series of unit storm discharge, 1979-2002, mm. (local Loess regression, Insightful Corp., 2001).

Use of a water balance approach quantifies the hydrologic impact of urbanization observed in Figure 3-5. Mass balance theory states that P-RO is equal to interception, surface storage, evapotranspiration, and groundwater loss, collectively referred to as non-

discharge loss in this section. Significantly, average area-weighted non-discharge loss for the three rural basins during the study period is 718 mm, while average annual non-discharge loss for Cub Run basin is 639 mm (Table 3-5). Lower non-discharge losses between adjacent watersheds with similar rainfall indicate higher runoff due to reduced interception, infiltration, and/or evapotranspiration. All of these are likely occurring in the urbanizing Cub Run basin. Therefore, the water balance approach highlights the fundamental hydrologic impact observed in this study, increased annual and growing season discharge response due to urbanization. Results demonstrate that increased total discharge from the urbanizing Cub Run basin is due to increased storm runoff response, providing indirect evidence of lower interception, infiltration (including deep percolation), and/or evapotranspiration. Reduced interception and evapotranspiration are an expected biophysical response to reduced vegetated cover; and reduced infiltration and deep percolation are also likely as vegetated surface are replaced with paved surface in the Cub Run basin (Table 3-2).

Unit storm discharge is more responsive to rainfall during winter and spring in all Occoquan headwater basins as a consequence of generally denuded land surfaces during the dormant season (Figure 3-4). Seasonal discharge totals in all basins are most variable during the summer (Table 3-7) due to high intensity thunderstorms that primarily generate overland flows (Correll et al., 1987). The finding that Cub Run storm runoff response continues to be high throughout the summer and fall supports expected reductions in growing season interception, infiltration, and evapotranspiration in catchments with higher IS area. The mean 20-year impervious surface area of Cub Run basin during this study is 12.5 percent (Table 3-3), supporting literature regarding significantly increased storm volumes in catchments above ten percent imperviousness (Schueler, 1994a). Further supporting evidence of anthropogenic impact is found in comparison of summer and fall discharge response by era (Table G-4), with results revealing that Cub Run mean and median unit storm discharge surpasses other basins in all post-1983 eras. Increased unit storm discharge in Cub Run basin during the growing season has important implications for seasonal NPS pollutant flux (see Chapter 4).

3.5. Conclusions

This paper investigates the relationship between catchment-scale urbanization and basin hydrology. Results indicate that hydrologic characteristics of the urbanizing Cub Run watershed are significantly different from three adjacent basins, and have changed over time with increasing urbanization. Observed differences correspond with what would be expected, based on previous studies and/or hydrologic principles. Increased storm flow volumes in the urbanizing Cub Run basin are well documented by the long-term observations in this study. The finding that Cub Run storm runoff means and medians are higher than three adjacent rural basins only during the summer and fall provides evidence for expected theoretical reductions in growing season interception, infiltration, and evapotranspiration in catchments over 10 percent impervious surface area. It is hoped that methodologies and data developed as part of this study will serve as a base for continuing long-term hydrologic and NPS pollution studies in the Occoquan basin.

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4. Quantifying Long-term NPS Pollutant Flux in an Urbanizing Basin*

Summary: This paper describes long-term NPS pollutant flux within a rapidly developing watershed in the western suburbs of Washington, DC, within the Chesapeake Bay drainage. Data consist of up to 24 years of observed rainfall, integrated pollutant discharge, and land use/land cover (LULC) from four headwater basins of the Occoquan River in northern Virginia. Basin outlets are monitored for storm and nonstorm flows, respectively, using flow-proportional, volume-integrating storm samplers and continuous stream gaging. Streams are sampled weekly or biweekly and analyzed for concentrations of total suspended solids (TSS) and soluble and particulate forms of nitrogen and phosphorus at known discharge rates. Three of the four study basins, ranging in size from 67 to 400 km², are predominantly forest and/or mixed agriculture. The fourth basin, the 127 km² Cub Run watershed, has urbanized rapidly over the past 20 years with approximately 50 percent of current land area classed as urban. Significantly, none of the four study basins contain major point source contributions during the study period. Results indicate that several long-term hydrologic and NPS pollutant flux characteristics in Cub Run basin are significantly different from adjacent non-urban basins. Higher annual NPS sediment and nutrient fluxes in Cub Run are linked to increased soil disturbance from documented urban construction and increased post-1984 storm volumes resulting from increased mean impervious cover. Storm fluxes of NPS particulate P, soluble P, particulate N, and soluble N make up 92, 67, 89, and 50 percent, respectively, of total NPS nutrient fluxes from all headwater basins, with between 88 and 98 percent of mean annual TSS fluxes delivered by storm flow. Comparatively higher TSS and nutrient fluxes in Cub Run basin, specifically during the summer and fall growing season after 1984, demonstrate a catchment-scale, seasonal impact of replacing vegetated cover with urban impervious surface.

KEYWORDS: NPS pollutant flux, runoff, urbanization, LULC, impervious surface

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4.1. Introduction

Land use changes associated with urbanization typically include increased numbers of roads, buildings, and other paved surfaces, with a proportional reduction in vegetated surfaces. A number of authors (Wheater et al., 1982; Laenen, 1983; Booth and Reinelt, 1993; Schueler, 1994a; Arnold and Gibbons, 1996) have discussed the hydrologic impacts of urbanization, which include shorter times of concentration, higher peak flows, larger storm volumes, and potentially lower baseflow volumes. Related studies have documented the impact of intense storm events and land use practices on the magnitude of total suspended solids (TSS) and related nutrient fluxes (Omernik, 1976; Jordan et al., 1986; Haith and Shoemaker, 1987; Osborne and Wiley, 1988; Kronvang, 1992; and Correll et al., 1999b). Several national studies have modeled nonpoint source (NPS) pollution from exclusively urban (U.S.EPA, 1983; Driver and Tasker, 1988; Driscoll et al., 1989) or exclusively rural (Clark et al., 2000) sources. However, NPS pollution research that includes both urban and rural sources has been on the fringe of environmental engineering research (Novotny, 1999). Although many authors have cited the benefits of collecting long-term, continuous watershed data (Richards and Holloway, 1987; U.S.EPA, 1990; Loftis et al., 1991; Dixon and Chiswell, 1996; and Longabucco and Rafferty, 1998), few studies have the combined long-term precipitation, integrated pollutant discharge, and land use/land cover (LULC) data necessary to analyze basin discharge and pollutant flux as a function of precipitation and LULC.

In recent years, mean watershed imperviousness has become an indicator for assessing water quality impacted by urban growth. Many analysts have argued that impervious surface (IS) coverage in a watershed is a good indicator of potential impact on stream health (Booth and Reinelt, 1993; Schueler, 1994a; Arnold and Gibbons, 1996; and Randolph, 2004). According to Schueler (1994a), adverse water quality effects above the 10 percent mean imperviousness threshold appear as reduced stream habitat, loss of biodiversity, and increased downstream pollutant loading. The four headwater basins of the Occoquan River watershed which are the focus of this study drain into the environmentally-sensitive Occoquan reservoir, an important water supply and recreational resource for over one million people in northern Virginia. The Occoquan

watershed lies within one of the most rapidly growing areas of the country west of Washington, DC.

As a consequence of increased urbanization within the Occoquan watershed throughout the 1960s, the waters of the Occoquan reservoir became increasingly eutrophic. Water supply protection began in 1971 through the mandated replacement of the watershed's 11 publicly-owned wastewater treatment plants with a regional wastewater facility and the establishment of the Occoquan Watershed Monitoring Program (Randall and Grizzard, 1995). Since then, extensive monitoring of precipitation, stream flow, water quality, and to a lesser extent, land use, has continued within the Occoquan basin. The result of state-mandated wastewater export from Cub Run basin starting in 1978 is that none of the study basins contain significant point source contributions during the analysis period (water years 1979 to 2002), making them excellent sites for summary and comparison of long-term, NPS pollutant flux.

Objectives of Study

The purpose of this study is to investigate the relationship between precipitation and basin characteristics to selected NPS pollutant responses, with specific focus on the effects of urbanization. The objective is to quantify long-term NPS pollutant flux within the four headwater basins of the Occoquan River using long-term records of basin precipitation, integrated pollutant discharge, and regional LULC.

Study Area

The study area includes four headwater basins in the Piedmont physiographic province of the Chesapeake Bay drainage. The basins are part of the 1530 km² Occoquan River watershed in northern Virginia (Figure 4-1). The three western basins, ranging in size from 67 to 400 km², are predominantly forest and mixed agriculture. The fourth basin, the 127 km² Cub Run watershed, is rapidly urbanizing, with 18 percent IS and 50 percent of current land use classed as urban.

A summary of the physical characteristics for each basin (Table 4-1) reveals that Cub Run basin has the lowest average slope and elevation of all Occoquan headwater basins, and is most similar in area and stream density to Upper Broad Run basin. The

three rural basins in this study extend into the upland western section of the Occoquan basin and include areas of significant relief (Figure 4-1).

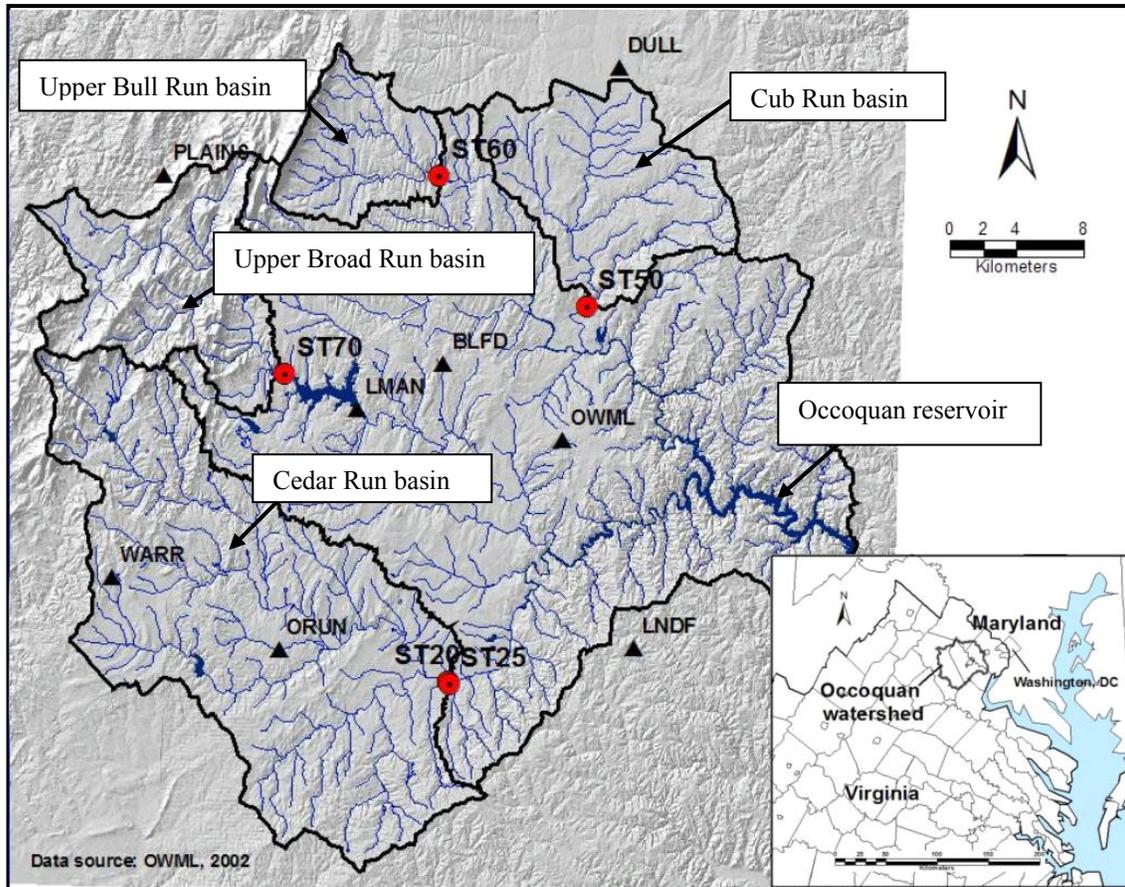


Figure 4-1. Occoquan River watershed study area, northern Virginia, USA.

Occoquan watershed (1530 sq. km) showing headwater basin water monitoring stations (red circles), rain gages (black triangles), and Occoquan reservoir. Insert: location map.

Table 4-1. Physical attributes of Occoquan headwater basins.

Basin	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
OWML monitoring station ¹	ST20/25 ²	ST50	ST60	ST70
Area, km ²	398	127	66.9	131
Ave. slope, %	5.3	3.4	6.9	10.3
Average elevation, m (range)	114 (53-416)	94 (48-154)	132 (75-387)	194 (87-417)
Stream length, km	389	112	66.4	107
Inverse drainage density, km [‡]	1.02	1.14	1.01	1.22

¹Occoquan Watershed Monitoring Laboratory, Manassas, Virginia.

²Station 20 was replaced by station 25 on 8/20/91.

[‡]1/DD = basin area/stream length (Reckhow et al., 1985).

4.2. Methods

The following section describes methods of collecting and summarizing NPS pollutant, LULC, and hydrologic data, as well as statistical procedures used to compare resulting summaries.

Basin Characteristics

Spatial data products available from Environmental Systems Research Institute, Inc. (ESRI®) and GeoLytics, Inc. (GeoLytics®), derived from U.S. Census data, are used to assemble decennial estimates of population density from 1980 to 2000 for each of the four Occoquan headwater basins (Appendix A). Land use analysis is completed within a geographic information system (GIS) using pre-classified 1979, 1989, 1995, and 2000 land use mapping (Figure Q-2) from the Northern Virginia Regional Commission (NVRC). Landsat-derived IS estimates for 1986, 1990, 1996, and 2000 (Figure A-5) are used as an indicator of urban land cover. Impervious surface estimates for 1980 are synthesized using calibrated land use and IS relationships (Table A-1) derived from a previous study evaluating IS estimation methods in Cub Run basin (Dougherty et al., in press).

Hydrologic Data

Daily precipitation data from eight rain gages (Figure 4-1), provided by the Occoquan Watershed Monitoring Laboratory (OWML), are used to synthesize Thiessen polygon-weighted rainfall estimates for the four headwater basins (Figure D-1). Missing rainfall data are replaced through hot-deck infilling, which involves substitution of individual values from similarly responding units (Appendix B). Average daily discharge data are tabulated from quarter-hour readings taken from stream-gaging equipment installed at all OWML monitoring stations (Figure 4-1). Average daily discharge volume is estimated using the daily (15-min) average flow. Missing discharge data are infilled using regression flow relationships between adjacent basins (Appendix F).

NPS Constituent Data

Occoquan headwater basin outlets are monitored throughout the study period for characterization of storm and nonstorm flows. Stream samples are analyzed for concentrations of total suspended solids (TSS) and both soluble and particulate forms of

nitrogen and phosphorus at known water discharge rates (Appendix I). During nonstorm flow, basin outlets are monitored using discrete weekly or bi-weekly grab samples and continuous daily discharge records. During storm discharge events, stream volume and composite samples are taken automatically using flow-proportional, volume-integrating storm samplers.

Concentrations of TSS, total phosphorus (TP), total soluble phosphorus (TSP), total Kjeldahl nitrogen (TKN), soluble Kjeldahl nitrogen (SKN), and oxidized nitrogen (OX_N) are measured and recorded at OWML in Manassas, Virginia. Minimum detection limits (MDL) for all analyses remain constant throughout the period of study, as follows; TSS (1.0 mg/L), TP (0.01 mg/L), TSP (0.01 mg/L), TKN (0.04 mg/L), SKN (0.01 mg/L), and OX_N (0.01 mg/L). The following constituent concentrations are determined indirectly; particulate phosphorus (TP–TSP), total nitrogen (TKN+OX_N), particulate nitrogen (TKN–SKN), and total soluble nitrogen (SKN+OX_N). Under certain conditions, TSP fractions are set less than or equal to TP and SKN fractions are set less than or equal to TKN to prevent negative concentration values.

Storm Sampling

Before mid-1988, storm samples were automatically collected by triggering of samplers with a contact closure every 0.5 feet rise or fall in stream stage using magnets mounted on a float wheel which closed a reed switch mounted under the wheel (Grizzard et al., 1976). Since mid-1988, storm flows at each monitoring station are initiated through station-based micro-processors that test for the start of a storm every five minutes by comparing the stage of the past three five-minute intervals with the previous stage (Post and Grizzard, 1987). During a storm sequence, the computer tracks storm duration and flow volume at one-minute increments. Once storm flow starts, the program begins to test for the end of the storm using a modified version of the baseflow separation equation developed by Hewlett and Hibbert (1967) for small watersheds. In 1998, data intervals for storm flows were switched from a five- to a two-minute interval.

A distinction is made in this study between nonstorm discharge and baseflow. Pollutant fluxes not categorized as storm fluxes are reported as nonstorm fluxes, and are therefore likely to contain flows in excess of baseflow.

Excluded Data

Raw data partitioned as storm and nonstorm samples are assigned to sequential water years running from October 1, 1978 to September 30, 2002. Water years are excluded if there are more than 90 consecutive calendar days without an analytical sample (storm or nonstorm) in any basin. Similarly, seasonal data periods are excluded if there are more than 30 consecutive calendar days (more than 45 days in the winter) without a sample in any basin. As a result, three water years (1979, 1980, and 1982) are excluded from annual analysis, except where noted otherwise, and eleven seasonal intervals are excluded from seasonal analysis (Table L-1).

Calculation of NPS Pollutant Loads

Calculation of NPS pollutant load follows a modified version of the Daily Flow-Data Integration (DFDI) method of Johnston (1999), which uses average daily flow (15-min) data to estimate daily nonstorm flow. To estimate daily loads associated with nonstorm flow, daily constituent concentrations, in mg/L, are assigned using simple linear interpolation of weekly and biweekly grab samples. Stormflow loads are tabulated individually as a time-ordered series at a constant step-loading rate extending from the beginning to the end of each storm (OWML, 1998). Daily nonstorm loads are tabulated separately, and are not included as part of a basin's total load during stormflow. Complete procedures are described in Appendix K.

Statistical Approach

The study reported in this paper is observational, utilizing a combination of long-term data to contrast NPS pollutant flux responses from four headwater basins under a variety of precipitation and LULC conditions. NPS pollutant flux summaries generated by these data have non-normal distributions and contain significant outliers. Consequently, nonparametric methods, which require no distributional assumptions, are used to discern statistical difference between central measures of group location. Because of the possibility of data bias due to the change in storm sampling method in 1988 (Appendix H), statistical comparisons are limited to between-basin tests. Robust MM regression routines from S-Plus™ (Insightful Corp., 2001) are used to fit linear relationships (Appendix O). Resulting regressions are not intended to be predictive, rather are used to identify and explore linkages between annual/seasonal precipitation,

discharge, and NPS pollutant flux in the four mixed-land use basins. Local (Loess) regression, a nonparametric generalization of multivariate polynomial regression (Insightful Corp., 2001), is used to fit a general smooth surface to reveal the underlying structure of the data and encourage further exploration. Automatic (variable) span selection for the Loess smooth surface is done by means of cross validation, with a reasonable span value between 0.3 and 0.5 (Insightful Corp., 2001).

4.3. Results

This section describes LULC and NPS constituent summaries developed for this study, as well as important relationships identified by descriptive and comparative statistics, regression relationships, and graphical analysis.

Population Density and LULC Summaries

Results of this study demonstrate that the Cub Run basin, unlike its three adjacent neighbors, is rapidly urbanizing (Figure Q-4). The population growth rate of Cub Run basin far exceeds the other three basins, with nearly three times as much growth occurring in the 1980s compared to the 1990s (Figure A-1). Randall and Grizzard (1995) reported that most of the increase in new development in the Occoquan basin occurred after 1984, when a moratorium on building in Fairfax County was lifted. Annual estimates of population density confirm that the greatest 5-year growth in Cub Run basin occurred between 1982 and 1987 (Table A-2). A smaller population surge occurred in the Cub Run basin in the years 1990 through 1994, followed by slower growth rates. Observed trends in annual imperviousness (Figure A-2) are similar to those for population, indicating roughly a 2:1 relationship between population and IS growth rates.

Average land use summaries (Table 4-2, Figure Q-1) from NVRC from 1980 through 2000 document differences in land use between the four basins. In Cub Run basin before 1990, there was more than twice as much rural land as urban land; however, by 2000 there was more urban than non-urban land. Based on IS estimates derived from GIS analysis of NVRC data, Cub Run basin surpassed 10 percent mean imperviousness sometime after 1985. By 2000, the three rural basins had not yet exceeded three percent mean imperviousness (Table 4-3).

Table 4-2. Land use percentages, Occoquan headwater basins, 1980, 1990, and 2000.

Land use category	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
Forest/idle land	44, 45, 52	51, 46, 45	57, 42, 49	39, 47, 57
Agricultural	53, 50, 41	27, 16, 4	33, 45, 33	58, 48, 38
Urban	3, 5, 7	22, 38, 51	10, 14, 18	2, 4, 6
Total	100, 100, 100	100, 100, 100	100, 100, 100	100, 100, 100

Source: Northern Virginia Regional Commission (NVRC) land use mapping, circa 1980, 1990, 2000.

Table 4-3. Mean impervious surface percent, Occoquan headwater basins, 1980-2000.

Basin	1980	1985	1990	1995	2000	20-year average
Cedar Run	1.4	1.5 ¹	1.7	1.8	1.8	1.6
Cub Run	6.7	9.3 ²	13.1	15.8	17.8	12.5
Upper Bull Run	1.7	1.9 ¹	2.0	2.0	2.2	2.0
Upper Broad Run	1.5	1.5 ¹	1.5	1.6	1.6	1.5

Source: NVRC land use mapping and Mid-Atlantic RESAC impervious surface estimates.

¹Linearly interpolated from 1980 and 1990 IS values.

²Interpolated proportionately from 1980 and 1990 IS values using annual building numbers.

Hydrologic Summaries

Rainfall during the 24-year period from 1979 to 2002 is characterized by large annual and seasonal variation (Table 4-4, Figure E-1). Summer rainfall exhibits the highest long-term high variability (Table 3-4 and Figures E-2 and E-3) due to high-intensity convectonal storms and occasional tropical hurricanes. Annual discharge summaries (Table 3-5) confirm that Cub Run basin has significantly higher storm discharge per area than the three rural basins. Seasonal discharge means, normalized by area (Table 4-5), reveal that the majority of discharge in all basins occurs during winter and spring (December through May), and that summer discharges have the largest variability. Increased runoff during winter and spring is attributed to dormant-season reductions in vegetated cover. Seasonal storm discharge summaries reveal that Cub Run has the largest mean and median discharge per area only during the summer and fall growing season, a finding that has direct implications for seasonal NPS pollutant delivery.

Table 4-4. Precipitation during study period, 1979-2002, Occoquan basin, mm/period.

	Winter	Spring	Summer	Fall	Annual
Mean ± 1SD	203 ± 79.0	264 ± 71.2	267 ± 83.0	250 ± 73.8	983 ± 185
Range	78 - 421	123 - 410	146 - 476	112 - 417	697 - 1352

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

Annual averages above based on water years beginning Oct. 1 through Sept. 30.

Winter=Dec, Jan, Feb; Spring=Mar, Apr, May; Summer=Jun, Jul, Aug; Fall=Sept, Oct, Nov.

Table 4-5. Mean seasonal stream discharge ±1SD and medians, 1979-2002, Occoquan headwater basins, mm.

Season (P-value) ¹	Cedar Run basin	Cub Run basin	Upper Bull Run basin	Upper Broad Run basin
Winter (0.955)	138±91.9 122 ^a	131±68.9 105 ^a	125±71.8 113 ^a	119±65.3 106 ^a
Spring (0.788)	124±84.2 91.5 ^a	130±66.1 117 ^a	137±83.5 112 ^a	136±72.2 121 ^a
Summer (0.132)	36.7±38.2 24.5 ^a	49.2±30.3 43.5 ^a	32.2±30.3 16.6 ^a	37.7±24.6 34.8 ^a
Fall (0.233)	51.9±44.0 39.0 ^a	73.9±44.4 82.1 ^a	50.9±29.1 46.6 ^a	54.2±34.2 45.1 ^a

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

Winter=Dec, Jan, Feb; Spring=Mar, Apr, May; Summer=Jun, Jul, Aug; Fall=Sept, Oct, Nov.

Seasonal means calculated using 85 seasons of data (11 seasons excluded due to missing data).

¹Significant p-value indicates that at least two basins have different central measures of location. Similar superscripts indicate no significant difference between groups ($\alpha = 0.10$).

NPS Pollutant Summaries

This section summarizes and compares NPS pollutant deliveries between years, seasons, and basins. Stream flow is divided into storm and nonstorm components; and nutrients are partitioned into particulate and soluble fractions.

Annual Data

Mean annual NPS pollutant concentrations and fluxes for the 24-year period from 1979 to 2002 are summarized in Table 4-6 and Table 4-7, respectively. Cub Run has the highest mean *storm* TSS concentration (195 mg/L) and Upper Broad Run has the highest mean *nonstorm* TSS concentration (8.13 mg/L). Cedar Run has the highest mean soluble nutrient concentrations (storm and nonstorm). Resulting NPS pollutant *loads* from each of the four headwater basins are generally proportional to drainage area (Figure M-1 and M-2), with the notable exception of Cub Run, which has long-term total and storm TSS loads approximately twice those delivered from similarly-sized Upper Broad Run basin (Table M-1). Long-term summaries of storm and nonstorm TSS *flux* in the four headwater basins (Table M-2) reveal that from 88 to 98 percent of mean annual TSS

fluxes across all basins are delivered by storm flow. Corresponding storm fluxes for NPS particulate P, soluble P, particulate N, and soluble N make up 92, 67, 89, and 50 percent, respectively, of total NPS nutrient fluxes (Table M-2). Cub Run, the most urbanized basin, and Upper Bull Run, the smallest basin, have the highest annual TSS and particulate nutrient fluxes, respectively (Table 4-7). Total particulate and soluble nutrient fluxes graphed for each basin (Figure M-3 and M-4) reveal certain differences between basins, and some constituent-flow relationships that are common to all basins.

Table 4-6. Mean annual NPS pollutant concentrations, nonstorm and storm flow, 1979-2002, mg/L.

	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
Nonstorm / storm flow				
TSS, mg/L	4.27 / 108	5.48 / 195	4.05 / 163	8.13 / 113
Particulate P [*]	0.01 / 0.17	0.01 / 0.20	0.01 / 0.20	0.02 / 0.21
Soluble P ^{**}	0.04 / 0.10	0.03 / 0.06	0.02 / 0.06	0.02 / 0.05
Particulate N [†]	0.08 / 0.63	0.08 / 0.73	0.07 / 0.82	0.09 / 0.62
Soluble N [‡]	1.02 / 1.58	0.98 / 1.16	0.62 / 1.16	0.81 / 1.22

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

Calculated using 21 years of data (1979, 1980, 1982 excluded).

^{*}Indirectly measured as total phosphorus minus total soluble phosphorus, mg/L.

^{**}Directly measured as total soluble phosphorus, mg/L.

[†]Indirectly measured as the difference between total Kjeldahl nitrogen and soluble Kjeldahl nitrogen, mg/L.

[‡]Indirectly measured as the sum of soluble Kjeldahl nitrogen and oxidized nitrogen, mg/L.

Table 4-7. Mean annual total NPS pollutant fluxes, 1979-2002, kg/ha.

Basin (area)	Cedar Run (398 km ²)	Cub Run (127 km ²)	Upper Bull Run (67 km ²)	Upper Broad Run (131 km ²)
TSS	230	503	411	235
Particulate P [*]	0.32	0.45	0.48	0.42
Soluble P ^{**}	0.26	0.18	0.15	0.13
Particulate N [†]	1.09	1.55	1.88	1.18
Soluble N [‡]	4.53	4.43	3.31	3.57

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

Calculated using 21 years of data (1979, 1980, 1982 excluded).

^{*}Indirectly measured as total phosphorus minus total soluble phosphorus, mg/L.

^{**}Directly measured as total soluble phosphorus, mg/L.

[†]Indirectly measured as the difference between total Kjeldahl nitrogen and soluble Kjeldahl nitrogen, mg/L.

[‡]Indirectly measured as the sum of soluble Kjeldahl nitrogen and oxidized nitrogen, mg/L.

Event-mean concentrations (EMCs) of NPS suspended solids for 1,636 individual storms across the entire study period are summarized by era (Table 4-8). During the period of rapid urbanization from 1984 to 1988, Cub Run median TSS EMC (167 mg/L) is significantly higher than Cedar Run (104 mg/L) and Upper Broad Run (82 mg/L), but not significantly different from Upper Bull Run (133 mg/L). Median TSS EMC in Cub

Run from 1989 to 1995 (176 mg/L), immediately following the period of rapid land development in Cub Run basin, is significantly higher than all other basins of that era. In the four years preceding rapid development in Cub Run, when mean basin IS was less than 10 percent, Cub Run has the lowest median TSS EMC. Corresponding results for *particulate* phosphorus and nitrogen are similar to TSS, except for significantly higher particulate nutrient EMCs in Upper Broad Run basin after 1996 and, more relevant to this study, significantly lower particulate phosphorus and nitrogen EMCs in Cub Run before 1984 (Table M-6). In addition, during the years of rapid urbanization in the mid-1980s and the era immediately following, Cub Run has significantly higher particulate phosphorus and nitrogen EMCs than all basins but Upper Bull Run (Table M-6). Cedar Run basin has the highest median *soluble* nutrient EMCs across all eras (Table M-7).

Table 4-8. Mean \pm 1SD and median storm TSS concentration by era, 1979-2002, Occoquan headwater basins, mg/L.

Era (no. storms)	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
1979-1983 (384)	98.6 \pm 119 53.0 ^a	123 \pm 265 41.0 ^a	151 \pm 259 61.0 ^a	150 \pm 223 62.5 ^a
1984-1988 (349)	126 \pm 117 104 ^b	270 \pm 327 167 ^a	234 \pm 261 133 ^a	103 \pm 100 82 ^b
1989-1995 (440)	114 \pm 107 80.0 ^b	225 \pm 168 176 ^a	168 \pm 234 105 ^b	119 \pm 113 85.0 ^b
1996-2002 (463)	106 \pm 87 85.5 ^b	163 \pm 119 133 ^a	150 \pm 129 106 ^a	187 \pm 157 156 ^a

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.
Event-mean concentration (EMC) means calculated using 1,636 individual storms.
Similar superscripts indicate no significant difference between groups ($\alpha = 0.05$).

Mean annual phosphorus and nitrogen concentrations, partitioned into storm and nonstorm flows, are summarized as a percentage of nutrient in the soluble phase (Table 4-9). Long-term summaries reveal a higher percent of soluble nutrients in nonstorm discharge, with a higher percent of nonstorm nitrogen (average 91%) in the soluble phase than phosphorus (average 66%). Across all basins, there is approximately twice the particulate phosphorus in storm flows as in nonstorm flows. Results are consistent with the literature that TSS and particulate nutrient concentrations increase with discharge (Haan et al., 1994; Reid and Frostick, 1994). Cedar Run, the largest and most agriculturally-based basin, is observed to have the highest soluble nutrient percentages of any basin. Cedar Run also has the lowest mean annual TSS storm concentrations (Table

4-6) and lowest total mean annual TSS flux (Table 4-7), suggesting non-erosive losses of nutrients, possibly from agricultural drainage and/or leaking septic systems.

Table 4-9. Percent of total phosphorus and nitrogen in soluble phase during storm and nonstorm discharge, 1979-2002, Occoquan headwater basins.

	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
Phosphorus (storm)	37.9	22.4	23.2	19.9
Phosphorus (nonstorm)	77.6	70.8	65.5	50.6
Nitrogen (storm)	71.5	61.4	58.4	66.1
Nitrogen (nonstorm)	92.9	92.8	89.3	89.9

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

Calculated using 21 years of data (1979, 1980, 1982 excluded).

Soluble phosphorus directly measured as total soluble phosphorus, mg/L.

Soluble nitrogen measured indirectly as the sum of soluble Kjeldahl nitrogen and oxidized nitrogen, mg/L.

While there is general agreement in the literature that TSS and particulate nutrient concentrations increase with discharge, far less information is available on changes in the ratio of particulate to soluble nutrients with discharge (Correll et al., 1999b). The particulate to soluble nutrient ratio is useful for comparison since it provides a single metric that accentuates differences in water column partition of nutrients between basins. Mean annual particulate to soluble phosphorus concentration ratios (Table 4-10) are graphed as a function of precipitation (Figure 4-2). Robust regressions show that long-term annual particulate to soluble phosphorus concentration ratios are generally stable across the range of precipitation in all basins except Upper Bull Run, the smallest basin. Cedar Run, the largest basin, has the most reliable central measure (i.e., lowest variability and flattest slope) of annual particulate to soluble nutrient concentration ratio across the range of annual precipitation. Long-term particulate to soluble nitrogen ratios are generally more stable than phosphorus (Figure M-5). Upper Broad Run and Upper Bull Run have the highest long-term particulate to soluble phosphorus and nitrogen ratios, respectively, of any basin (Table 4-10).

Table 4-10. Mean annual particulate/soluble nutrient concentration ratios. (Occoquan headwater basins, 1979-2002).

	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
Nonstorm flow:				
Particulate/soluble P	0.30	0.44	0.54	0.98
Particulate/soluble N	0.08	0.08	0.13	0.12
Storm flow:				
Particulate/soluble P	1.7	3.6	3.5	4.1
Particulate/soluble N	0.42	0.65	0.75	0.54

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia. Calculated using 21 years of data (1979, 1980, 1982 excluded).

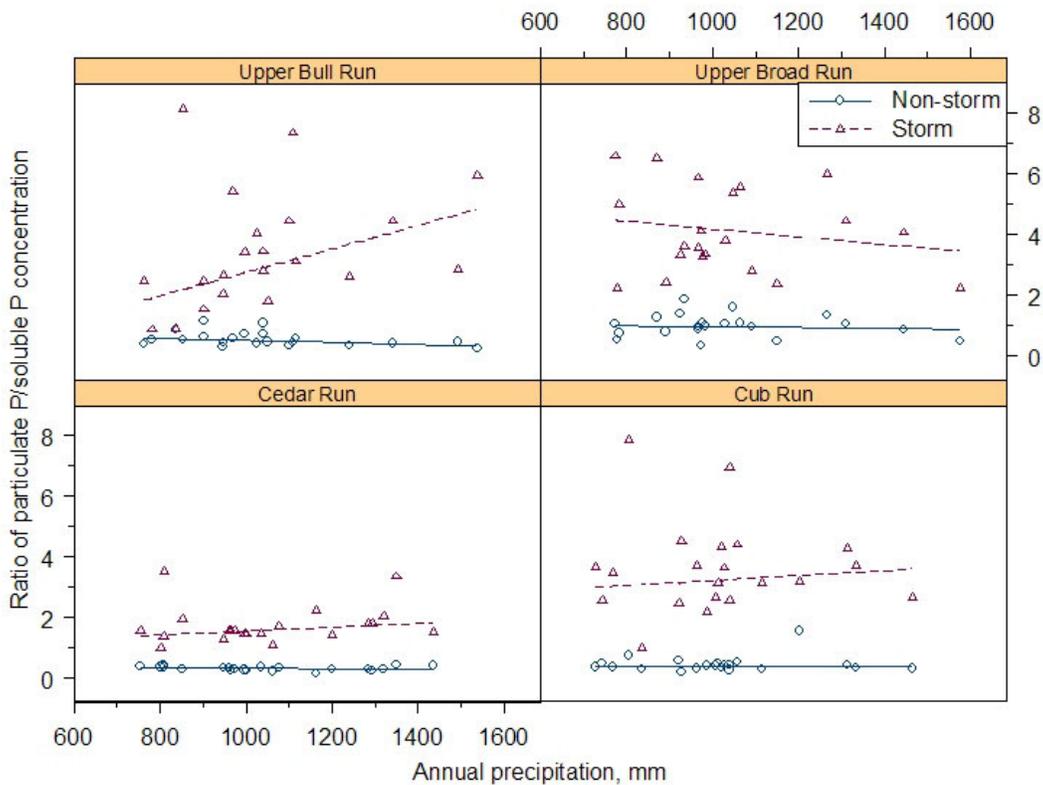


Figure 4-2. Ratio of mean annual particulate P/soluble P concentration (storm and nonstorm) as a function of precipitation, 1979-2002.

(Source: Occoquan Watershed Monitoring Laboratory, Manassas, Virginia).

Analysis of mean annual particulate to soluble nutrient concentrations by era, similar to Table 4-8, reveals differences in water column partition of nutrients between basins. Particulate to soluble nitrogen ratios during storm flow generally increase across the 24-year study period (from 0.26 to 0.99), except for a post-1995 drop in Cub Run and Upper Bull Run (Figure M-12). *Nonstorm* nitrogen ratios also generally increase across

the study period (from 0.05 to 0.18), except for equivalent post-1995 drops in Cub Run and Cedar Run, while Upper Broad Run nitrogen ratios continue to climb (Figure M-13).

Mean nonstorm particulate to soluble *phosphorus* ratios in three of the study basins are relatively stable over time (range 0.22 to 0.59) compared to Upper Broad Run, which has increasing mean phosphorus ratios (Figure M-11). Cub Run is the only basin with reduced mean *nonstorm* phosphorus ratios (from 4.79 to 3.05), which occur after 1995. Corresponding *storm* phosphorus ratios (Figure M-10) reveal that Cedar Run has lower and more stable particulate to soluble storm phosphorus ratios (range 1.27 to 2.20) than the other three basins (range 2.74 to 5.07). Both Cub Run and Upper Bull Run have decreased particulate to soluble storm phosphorus ratios after 1995 (from 4.79 to 2.88).

Seasonal Data

Seasonal TSS flux summaries (Table 4-11) reveal that the majority (between 58 to 83 percent) of TSS flux from all basins occurs during winter and spring, seasons which also have the highest basin discharge (Table 4-5). The highest variability in annual TSS flux is observed during the summer, which also has high variability in seasonal discharge. Cub Run and Upper Bull Run basins have significantly higher mean annual TSS fluxes over the study period (Table 4-11). However, during the growing season (summer and fall) Cub Run TSS fluxes are approximately double those of Upper Bull Run and three times those of the other two basins (Figure 4-3). Long-term TSS fluxes in Cub Run, during the summer in particular, are significantly higher than those from any other basin. In addition, median summer TSS flux in Cub Run is higher than fall TSS flux, which is a reversal of the other basins.

Partitioning of seasonal TSS flux data into four eras reveals similar trends in all post-1984 eras. However, during the period 1979 through 1983 (Figure M-6), Upper Bull Run, not Cub Run, has the highest total annual TSS flux (337 kg/ha), with a mean summer TSS flux (126 kg/ha) nearly twice that of Cub Run basin (66 kg/ha).

Table 4-11. Mean \pm 1SD and median total TSS flux from Occoquan headwater basins, kg/ha/time period, 1979-2002.

Time period (no. periods)	P-value ¹	Cedar Run (398 km ²)	Cub Run (127 km ²)	Upper Bull Run (67 km ²)	Upper Broad Run (131 km ²)
Winter (23)	0.107	87.3 \pm 93.7 47.8 ^a	130 \pm 128 83.1 ^a	109 \pm 126 59.8 ^a	89.9 \pm 174 28.2 ^a
Spring (20)	0.030	64.2 \pm 69.1 40.4 ^b	161 \pm 157 119 ^a	171 \pm 191 95.9 ^a	105 \pm 87.5 73.0 ^a
Summer (21)	0.008	37.1 \pm 61.7 9.4 ^b	96.4 \pm 123 71.4 ^a	56.3 \pm 121 11.2 ^b	22.5 \pm 25.5 13.8 ^b
Fall (21)	0.060	40.3 \pm 43.2 14.9 ^b	110 \pm 176 62.8 ^a	40.1 \pm 43.5 34.8 ^b	32.2 \pm 35.1 28.3 ^b
Annual (21)	0.004	230 \pm 187 215 ^b	503 \pm 416 365 ^a	411 \pm 439 277 ^a	235 \pm 178 189 ^b

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

Annual means calculated using 21 years of data (1979, 1980, 1982 excluded).

Seasonal means calculated using 85 seasons of data (11 seasons excluded).

Winter=Dec, Jan, Feb; Spring=Mar, Apr, May; Summer=Jun, Jul, Aug; Fall=Sept, Oct, Nov.

¹ Significant p-value denotes at least two basins have different central measures of location (Kruskal-Wallis rank sum test).

Similar superscripts indicate no significant difference between groups ($\alpha=0.10$).

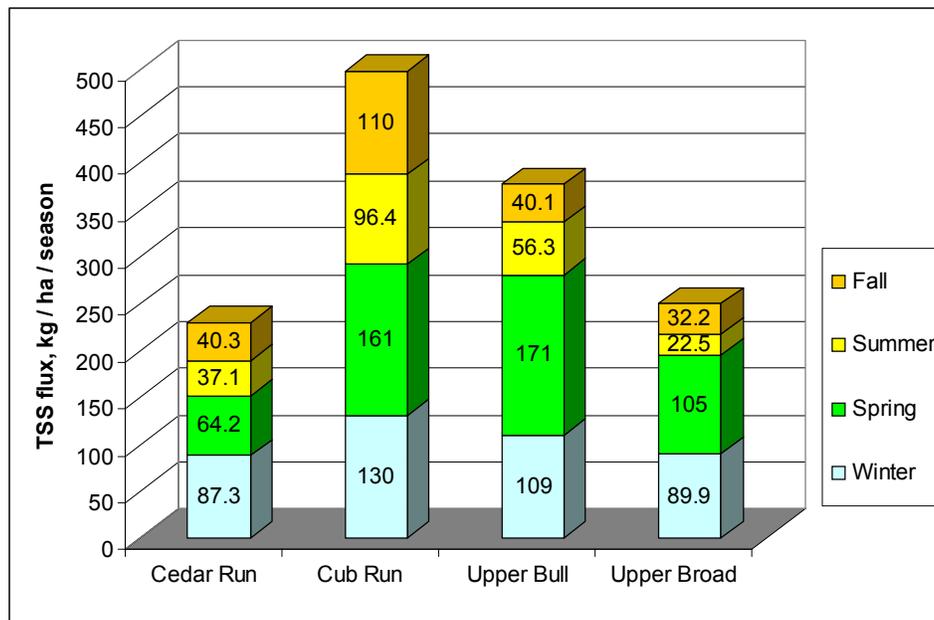


Figure 4-3. Mean seasonal TSS flux, Occoquan headwater basins, 1979-2002, kg/ha.

(Source: Occoquan Watershed Monitoring Laboratory, Manassas, Virginia).

Seasonal analysis of total phosphorus and nitrogen flux produces results similar to those shown for seasonal TSS flux (Table M-12 and M-13), with median TP and TN fluxes in Cub Run during the fall (0.12 and 1.10 kg/ha, respectively) higher than those for summer (0.08 and 0.55 kg/ha, respectively). Median fall and summer nutrient fluxes in Cub Run are generally twice those of all basins except Upper Broad Run, which has a

relatively high median summer TN flux (0.52 kg/ha) compared to the other rural basins. Further analysis of seasonal nutrient fluxes by era (Table M-14 and M-15) reveals that prior to 1984 Cub Run has summer and fall nutrient fluxes similar or lower than other basins. After 1984, Cub Run has the highest mean summer and fall nutrient fluxes of any basin except Cedar Run TN flux during the summers of 1989 to 1995 (0.83 kg/ha in Cedar Run versus 0.79 kg/ha in Cub Run).

Event-mean concentrations (EMCs) of NPS suspended solids from 1,636 individual storms from the period 1979 to 2002 are summarized by season (Table 4-12). In the winter and fall, Cub Run basin has significantly higher TSS EMCs than the other three basins. In the summer, both Cub Run and Upper Bull Run basins have significantly higher TSS EMCs. In the spring, Cedar Run basin has significantly lower TSS EMCs than the other three basins. Similar comparison of seasonal particulate nitrogen and phosphorus EMCs (Table M-4) reveals few significant differences. Corresponding analysis of storm soluble nutrient summaries (Table M-5) confirms that Cedar Run basin has consistently higher soluble nitrogen and phosphorus EMCs in all seasons, likely due to the sustained agricultural presence in that basin (Table 4-2, Figure Q-3).

Table 4-12. Mean and median storm TSS concentration by season, 1979-2002, Occoquan headwater basins, mg/L.

Season (no. storms)	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
Winter (384)	103±102 75.0 ^b	140±138 106 ^a	124±165 69.0 ^b	134±206 56.5 ^b
Spring (349)	98.5±91.9 73.5 ^b	167±170 128 ^a	168±151 130 ^a	140±126 104 ^a
Summer (440)	169±146 136 ^c	342±381 231 ^a	358±446 204 ^a	195±142 165 ^b
Fall (463)	84.0 ± 67.9 66.5 ^b	170±141 137 ^a	109±108 85.0 ^b	92.6±103 42.5 ^b

Source: Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.
 Event-mean concentration (EMC) means calculated using all 24 years of data (1,636 individual storms).
 Similar superscripts indicate no significant difference between groups ($\alpha = 0.05$).

Seasonal phosphorus and nitrogen concentrations are summarized as a percent of total storm and nonstorm nutrients in the soluble phase (Table M-16). Cedar Run has the highest overall soluble nutrient percentages in all seasons, except for Cub Run nonstorm phosphorus (fall), Cub Run and Upper Bull Run nonstorm nitrogen (spring), and Upper Bull Run nonstorm phosphorus (spring). Upper Broad Run has the lowest percentage of

soluble storm phosphorus concentration in most seasons. Consequently, except for Cub Run and Bull Run in the summer, rural Upper Broad Run, the steepest basin, has the highest percentage of water column particulate *phosphorus*, both storm and nonstorm. For most seasons, Cub Run and Upper Bull Run have the highest percent of particulate *nitrogen* in their storm water. Generally higher percentages of particulate storm nitrogen concentration are observed in all basins during the summer and fall.

Graphical analysis of mean particulate to soluble nutrient *ratios* by season (Figure 4-4) reveals that mean *nonstorm* particulate to soluble *nitrogen* ratios are much lower than corresponding storm ratios, as expected, and are generally lowest in the winter and spring. Corresponding *storm* nitrogen ratios are also lowest in the dormant season, with higher summer and fall storm particulate to soluble nitrogen ratios for all basins.

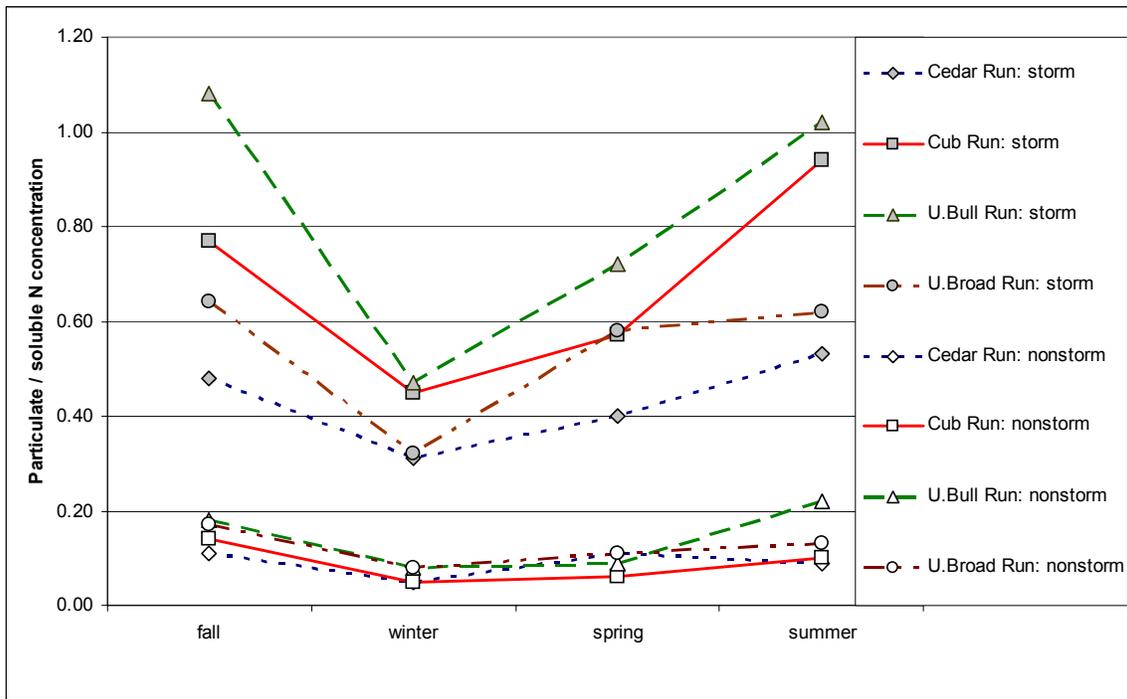


Figure 4-4. Particulate to soluble nitrogen ratios, by season, Occoquan headwater basins, 1979-2002 (storm and nonstorm partitions).

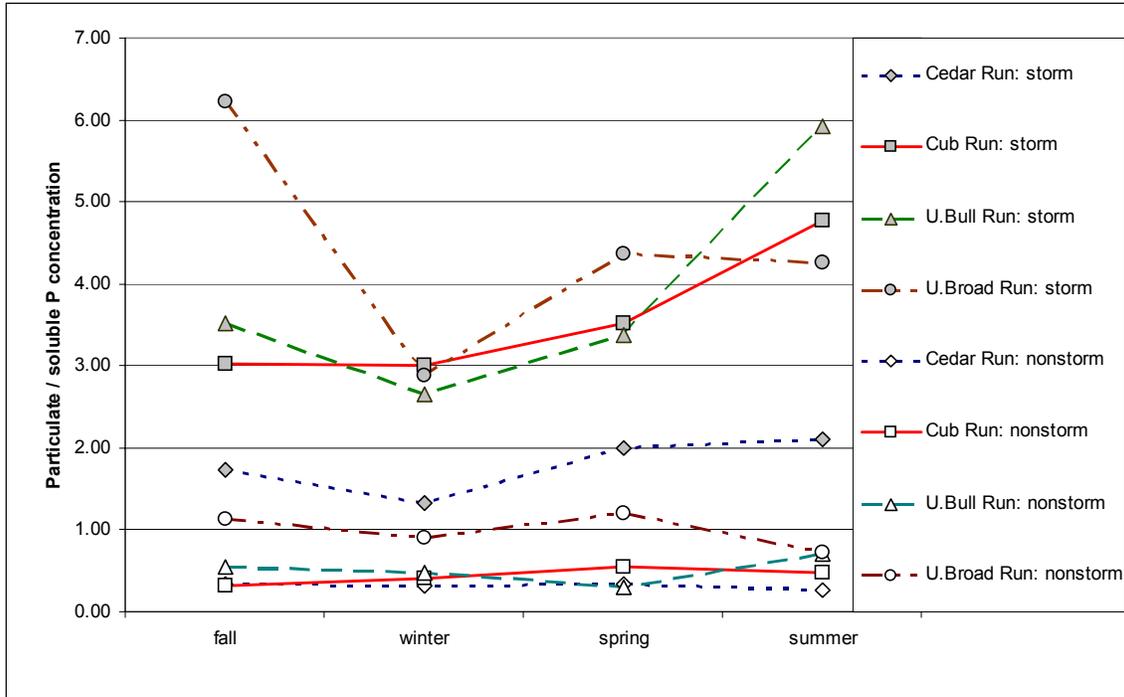


Figure 4-5. Particulate to soluble phosphorus ratios, by season, Occoquan headwater basins, 1979-2002 (storm and nonstorm partitions).

Seasonal patterns in particulate to soluble *phosphorus* ratios (storm and nonstorm) are observed to have more inter-basin variability than corresponding nitrogen ratios (Figure 4-5). Seasonal *nonstorm* particulate to soluble phosphorus ratios in Upper Broad Run, which is the steepest basin, are high compared to the other basins. Corresponding *storm* phosphorus ratios exhibit generally lower winter values, with Cedar Run, the largest basin, having consistently lower and less varied seasonal storm values than the other basins.

4.4. Discussion

The four headwater basins of the Occoquan provide an excellent opportunity to study the long-term delivery of NPS pollutants from mixed-land use catchments, only one of which is rapidly urbanizing. Findings can be categorized as two types; general effects observed across all basins, and effects due to urbanization. The majority of all NPS suspended solids and nutrient fluxes observed by OWML and reported in this study are associated with storm flows, supporting what is known about the precipitation-driven nature of NPS pollution (Novotny and Chesters, 1981). Our previous findings (Chapter

3) that Cub Run annual storm runoff is significantly higher than non-urban basins (Table 3-5) and that mean and median seasonal discharge in Cub Run is greatest only during the summer and fall (Table 4-5) provides evidence of reduced interception, infiltration, and evapotranspiration in catchments with higher imperviousness. Higher mean and median storm discharges observed in Cub Run basin during post-1983 growing seasons have important implications for seasonal NPS pollutant flux in the urbanizing Cub Run basin.

Annual time series of NPS total suspended solids flux fitted with nonparametric smoothed curves (Figure 4-6) suggest that annual Cub Run TSS flux surpassed other Occoquan headwater basins sometime in the mid-1980s, about the time that documented rapid population growth and land development began. Before 1984, Cub Run had significantly lower particulate phosphorus and nitrogen EMCs (Table M-6). Higher mean and median storm discharge (Table 3-6) and TSS concentrations (Table 4-8) after 1983 combine for sustained TSS fluxes. Continued high TSS fluxes in Cub Run may be caused by factors other than urban soil disturbance from land development, which appears to slow somewhat after the mid-1990s (Figure A-2). Other sediment-producing processes such as scour of suspended solids may be occurring in Cub Run. Regardless of the source of high post-1983 TSS concentrations in Cub Run, the impact of significantly increased storm flow volumes as a fundamental NPS pollution conduit is well demonstrated.

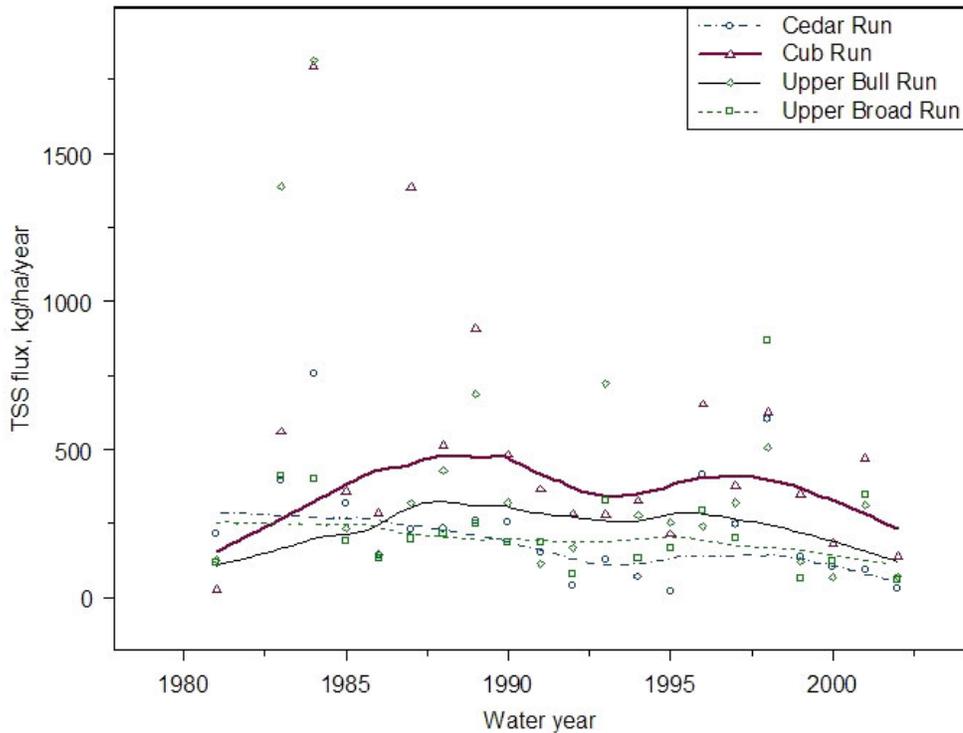


Figure 4-6. Annual time series of TSS flux, 1981-2002, kg/ha/yr. (local Loess regression, Insightful Corp., 2001).

Significantly, smooth curves of annual total phosphorus and nitrogen flux (Figure M-14 and M-15) are similar to those for TSS, suggesting that Cub Run began to surpass other basins in sustained high total phosphorus flux at about the same time as TSS. Total nitrogen fluxes in Cub Run exceeded other basins somewhat later, about the time of the second documented growth surge in Cub Run basin, as mean IS approached 15 percent (Table 4-3, Figure A-2). Significantly lower pre-1984 annual phosphorus and nitrogen EMCs (Table M-6) and lower median TSS concentrations (Table 4-8), demonstrate that Cub Run has undergone rapid changes in NPS pollutant flux over time relative to non-urban basins.

Seasonal analysis of NPS sediment and nutrient flux demonstrates the impact of reduced vegetated cover on Cub Run summer and fall TSS fluxes, which are two and three times, respectively, corresponding fluxes from rural basins (Figure 4-3, Table 4-11).

This finding indicates that the loss of vegetated cover in urban catchments such as Cub Run, accompanied by documented increases in mean IS, can result in lower NPS pollutant retention during the growing season. As a result of urbanization, high-intensity tropical storms and occasional hurricanes during the summer and early fall may have a more pronounced seasonal effect on Cub Run TSS and total nutrient flux than on adjacent headwater basins (Figure 4-3). Follow-up analysis of NPS total phosphorus and total nitrogen fluxes by era and season confirms that mean summer and fall nutrient fluxes are greater in Cub Run only after 1983 (Table M-14 and M-15); and long-term summer and fall TSS flux in Cub Run is significantly higher than those from any other basin (Table 4-11). Since mean growing season discharge in Cub Run exceeded other basins only after 1983 (Table G-5), a linkage is observed between increased summer and fall discharge response and increased NPS sediment and nutrient flux, which appears more prominent in the summer.

Annual TSS fluxes from this study, ranging from 230 to 503 kg ha⁻¹yr⁻¹, are within the range of values reported in other long-term watershed studies (Table 1-3), with the longest comparable study (Correll et al., 1999b) lasting 18 years. The proportion of total phosphorus discharged in the soluble phase from basins in this study, 24 to 45 percent, also compares favorably with the range of values from literature, 3 to 66 percent (Table 1-4). The tendency of smaller watersheds to produce higher TSS fluxes is well known, and has been documented by numerous studies. Naiman (1982) cited decreased channel and floodplain storage as a cause for larger TSS flux in smaller watersheds. Therefore, it is noteworthy that Cub Run basin, almost twice as large as Upper Bull Run, has comparable annual TSS fluxes and higher nutrient fluxes (Figure M-3 and M-4). Previous literature values suggest that annual Cub Run TSS fluxes are similar to basins having active tillage and/or livestock agriculture (Table 1-3).

Under equal LULC conditions, Upper Broad and Bull Run would be expected to have the highest particulate nutrient deliveries, due to high slope in the case of Upper Broad Run, and due to lower total channel storage in Upper Bull Run, the smallest basin. Upper Broad Run and Upper Bull Run do in fact have the highest long-term particulate to soluble phosphorus and nitrogen ratios, respectively, of any basin (Table 4-10), in spite of the fact that median Cub Run particulate nutrient concentrations are the highest of any

basin during and immediately following the years of rapid urbanization (Table M-6). Even after an unexplained post-1995 drop in particulate nutrient flux in Cub Run, particulate to soluble nutrient ratios from this urbanizing basin are comparable to those from the steepest and smallest basins in this study.

Across most basins and flow conditions, long-term partitions of water column phosphorus and nitrogen indicate particulate to soluble *phosphorus* ratios at least five times higher than corresponding *nitrogen* ratios (Table 4-10). Further analysis, by era, reveals that most basins, including Cub Run, have higher mean particulate to soluble nutrient ratios in the years 1989 to 1995 (Figures M-10 to M-13), years characterized by generally higher annual rainfall (7-year mean = 1017 mm). Cub Run is the only basin with reduced particulate to soluble nutrient ratios for both storm and nonstorm flows in the post-1995 era (Figure M-10 through M-13), an era characterized by the existence of a four-year drought in Virginia beginning in the summer and fall of 1998. After 1995, Cub Run median particulate nutrient concentrations decrease, while other basins remain the same or increase (Table M-6). These results indicate reduced NPS particulate nutrient fractions in Cub Run some ten years after the most active period of urbanization. Possible reason for the drop, aside from drought, are stricter urban stormwater and NPS management in Loudoun and Fairfax Counties, reduced rates of urbanization, and/or an equilibrating stream and riparian ecosystem. Additional monitoring will be required to determine if the observed drop in post-1995 nutrient flux in Cub Run is caused by improved land use management or by reduced rainfall.

Across all basins, water column partitions of phosphorus and nitrogen, as measured by the particulate to soluble nutrient ratio, demonstrate the influence of seasonal vegetation (Figure 4-4), basin area, and slope (Figure 4-5). In general, higher phosphorus and nitrogen ratios are observed in the summer and fall, lower storm phosphorus ratios are observed in larger basins, and larger nonstorm phosphorus ratios are observed in steeper basins. Storm phosphorus load is twice that of the nonstorm P load, and is made up mostly of particulate phosphorus. Storm nitrogen load makes up about 60 percent of total NPS nitrogen load, and the soluble fraction dominates. Total phosphorus load is dominated by particulate P, but total nitrogen load is dominated by soluble N, with the magnitude of both nutrient loads a function of basin size (Figure M-1,

M-2). Cub Run and Upper Bull Run have the highest total phosphorus *flux*, and in all basins phosphorus flux is dominated by particulate forms (Figure M-3). Cub Run has the highest total nitrogen flux, and Cub Run and Upper Bull Run have the highest percentages of particulate N (Figure M-4). Most TSS and nutrient flux occurs during winter and spring seasons (Figure 4-3) as a result of higher discharge response (Table 4-5). However, Cub Run growing season TSS and nutrient fluxes are at least twice those of other basins. Cub Run also has twice the storm TSS loads as similarly-sized Upper Broad Run. One of the most striking changes due to urbanization in Cub Run appears to be the growing season linkage of discharge and NPS pollutant flux, which occurs most prominently in the summer due to replacement of natural, vegetated surfaces with impervious cover.

4.5. Conclusions

This research investigates the relationship between basin characteristics and selected NPS pollutant responses to precipitation, with specific focus on the effects of urbanization. Results indicate that several long-term hydrologic and NPS pollutant flux characteristics in the urbanizing Cub Run basin are significantly different from three adjacent non-urban basins. Higher annual NPS sediment and nutrient fluxes in Cub Run are linked to increased soil disturbance from documented urban construction and significantly increased post-1983 unit storm volumes resulting from higher mean impervious cover. Higher TSS and nutrient fluxes from Cub Run basin during the summer and fall growing season, linked to higher unit storm discharge only after 1983, demonstrate the catchment-scale impact of replacing vegetated cover with impervious surface. The effect of impervious surface appears some time in the mid-1980s, when the basin was reaching a mean IS of 10 percent.

Long-term summaries of nutrient flux, partitioned into particulate and soluble phases, are consistent with literature documenting increased ratios of particulate to soluble nutrients with increased discharge. Storm flows provide the majority of all NPS pollutant fluxes in this study, providing evidence of the important link between storm discharge and long-term annual TSS and nutrient flux. In most basins and seasons, the percentage of soluble phosphorus in storm flows is approximately half that of nonstorm

flows. Mean seasonal concentrations of soluble nitrogen range from 45 to 78 percent of total nitrogen in storm flows to approximately 82 to 96 percent of total nitrogen in nonstorm flows. In spite of the inter-basin seasonal variability observed in particulate to soluble phosphorus ratios, results confirm generally higher percentages of storm particulate nutrients during summer and fall in all basins.

It is hoped that methodologies and data sets developed as part of this study will serve as a base for continuing long-term hydrologic and NPS pollution studies in the Occoquan basin. For example, ongoing LULC and stream monitoring within the four Occoquan headwater basins can provide data necessary to determine whether post-1995 reductions in Cub Run NPS suspended solids and particulate nutrient concentrations are due principally to improved land management, ecosystem equilibrium, or drought conditions. Regardless of the source of continued high TSS and nutrient fluxes in Cub Run, the impact of increased storm flow volumes as a fundamental conduit of NPS pollutant flux is well demonstrated by the long-term observations in this study.

4.6. References

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