Final Report:
Quantifying NPS Pollutant Discharges from an Urbanizing Headwater Basin

Investigators:
Mark Dougherty*
Randel L. Dymond
Adil N. Godrej
Thomas J. Grizzard, Jr.
John Randolph
Carl E. Zipper

PhD candidate, Civil and Environmental Engineering, Virginia Tech
Assoc. Professor, Civil and Environmental Engineering, Virginia Tech
Associate Director, Occoquan Monitoring Lab, Virginia Tech
Professor and Director, Occoquan Monitoring Lab, Virginia Tech
Dept. Head and Professor, Urban Affairs and Planning
Assoc. Professor, Crop and Soil Environmental Sciences, Virginia Tech

*Corresponding author:
mdougher@vt.edu

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Abstract

This research evaluates nonpoint source (NPS) sediment and nutrient fluxes from four headwater basins in the Piedmont physiographic province of the Chesapeake Bay drainage for up to 24 years. The basins are part of the 1530 km^2 Occoquan River watershed in northern Virginia. Three of the basins, ranging in size from 67 to 400 km^2, are predominantly forest and/or mixed agriculture. The fourth basin, the 127 km^2 Cub Run watershed, is rapidly urbanizing with approximately 50 percent of current land area classed as urban. Descriptions of the four Occoquan headwater basins, averaged over the study period, are presented below for reference throughout the document.

Watershed name	Station number	Land area, km^2	Average land use, forest/ag/urban, %	Ave. pop. density*	Ave. impervious area, %
Cedar Run	20/25**	398	47/48/5	0.45	1.6
Cub Run	50	127	47/16/37	4.95	13.1
Upper Bull Run	60	67	49/37/14	0.49	2.0
Upper Broad Run	70	131	48/48/4	0.19	1.6

*Average population density in persons/ha.
**Station 20 was replaced by station 25 on 8/20/91.

Basin outlets were monitored with discrete weekly or bi-weekly grab samples and automated daily discharge and flow-proportional, volume-integrating storm samplers, for characterization of storm and non-storm flows, respectively. Stream samples were analyzed for TSS concentrations and the composition of dissolved and particulate nutrients at known water discharge rates. Fifty-one years of consolidated precipitation data from eight rain gages are used to characterize rainfall during the study period. GIS-based measures of land use, population density, and landscape imperviousness are used to quantify urbanization. Nonparametric statistical methods are utilized to compare stream discharge and NPS fluxes between years, seasons, and basins. Results show that increased discharges and NPS fluxes are most responsive to increased rainfall and urbanization during winter and spring seasons, likely due to reduced natural ground cover and evapotranspiration. Cub Run basin was found to have the highest annual NPS sediment and nutrient flux of all headwater basins starting from 1983, when rapid population growth and massive land development began. Cub Run basin surpassed ten percent mean imperviousness at approximately the same time.

KEYWORDS: NPS pollution, urbanization, storm, precipitation

Introduction

In spite of several national nonpoint source (NPS) studies (U.S.EPA, 1983, Driver and Tasker, 1988), research in diffuse pollution that includes both urban and rural sources has been on the fringe of environmental engineering research (Novotny, 1999). A number of studies have measured pollutant fluxes from larger mixed land use watersheds, demonstrating the importance of land use and land use practices in controlling the magnitude of TSS-related fluxes, and that most TSS fluxes occur during large or intense storm events. However, few studies have the combined long-term precipitation and integrated pollutant discharge data necessary to analyze pollutant flux as a function of precipitation (Correll et al., 1999b). Although there is general agreement in literature that TSS and particulate nutrient concentrations increase with discharge, far less information is available on changes in the ratio of particulate to dissolved nutrients with discharge. Collecting long-term, continuous data from a watershed yields better estimates of pollutant loadings for assessing how individual land uses discharge pollutants to a waterbody (Richards and Holloway, 1987; EPA, 1990; Loftis et al., 1991; Dixon and Chiswell, 1996; Longabucco and Rafferty, 1998).

In recent years, mean watershed imperviousness has become an indicator for assessing water quality impacted by urban growth. According to Schueler (1994), adverse water quality effects above the 10 percent imperviousness threshold appear as increased pollutant loads from urban washoff, among other impacts. Long-term changes in a stream brought about by increased impervious areas can lead to reduced stream habitat and loss of biodiversity. In addition, pollutants transported downstream end up in the receiving water body. The Cub Run watershed and three adjacent rural watersheds which are the focus of this study are part of the larger Occoquan basin draining into the Occoquan Reservoir, an important water supply and recreational resource for more than one million people in northern Virginia.

Objectives of study

This research investigates fundamental watershed delivery relationships using a unique assembly of long-term spatial and water quality data. Total annual and seasonal loads of suspended solids, phosphorus, and nitrogen are partitioned into storm/non-storm and particulate/dissolved components for comparative unit-area analysis. Wilcoxon rank sum tests are used to compare stream discharge and NPS fluxes between years, seasons, and basins. Map-based measures of land use, US Census estimates of population density, and satellite-derived measures of imperviousness are used to measure urbanization.

A linkage is pre-assumed between basin hydrology (rainfall and basin discharge) and NPS pollutant delivery. Consequently, this study is divided into two main research divisions, hydrology and NPS pollution. Hydrologic objectives of the study include: 1) summarize mean annual and seasonal discharge for basins of different size and landscape, referenced to regional inter-annual precipitation variations; and 2) evaluate effects of landscape, including seasonal cover and watershed urbanization, on annual and seasonal unit stream discharge, partitioned into storm and non-storm components. NPS pollution objectives of the study include: 3) characterize TSS and nutrient fluxes from Occoquan headwaters as a function of precipitation (annual and seasonal), discharge (storm vs. non-storm), and constituent fractions (particulate vs. soluble); and 4) evaluate effects of landscape (seasonal cover and watershed urbanization) on annual NPS pollution flux. Methodologies and data developed as part of this research will serve as a basis for future NPS pollution studies in the Occoquan and other similar basins.

Methods

Site Description

The study area consists of four headwater catchments in the Piedmont physiographic province of the Chesapeake Bay drainage. The basins are part of the 1530 km^2 Occoquan River watershed in northern Virginia (figure 1). The three western basins, ranging in size from 67 to 400 km^2, are predominantly forest and/or mixed agriculture. The fourth basin, the 127 km^2 Cub Run watershed, is rapidly urbanizing, with 18 percent impervious surface and 50 percent of current land use classed as urban.

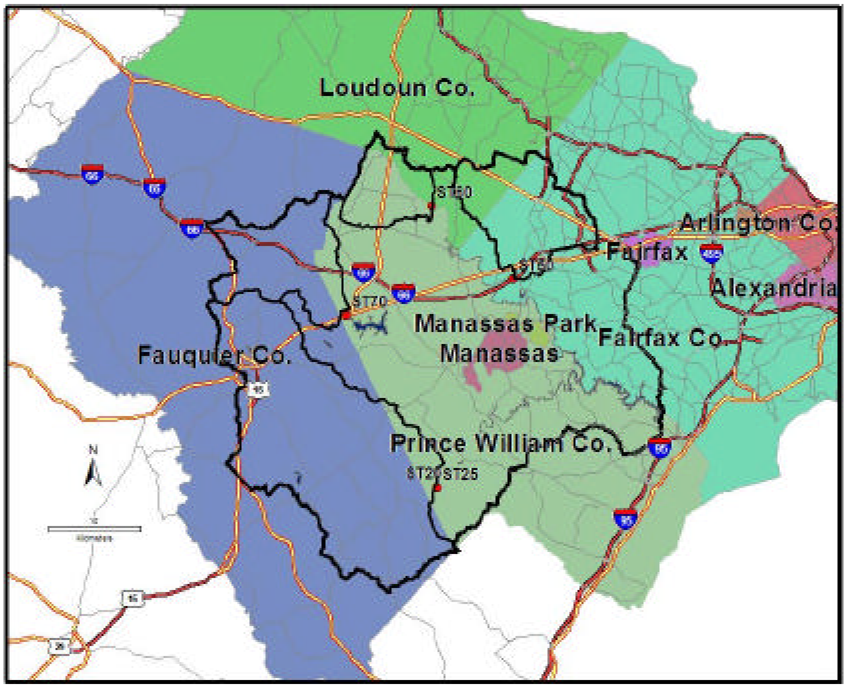


Figure 1. Location map: Occoquan River watershed study area, northern Virginia, USA.

Metcalf & Eddy (1970) determined that a major cause of water quality impairment in the Occoquan reservoir (figure 2) was nutrients from separate sewage treatment plants and from forested, agricultural, and urban lands, particularly phosphorus. Water supply protection began in 1971 through planned construction of an advanced wastewater treatment (AWT) plant and the establishment of the Occoquan Watershed Monitoring Program and Laboratory (OWML) (Randall and Grizzard, 1995). Continuing results from the monitoring program have established nonpoint nutrient pollution as a major cause of water quality impairment.

This study uses a unique combination of long-term data, including: over 30 years of integrated stream flow and water chemistry data from four OWML headwater monitoring stations (figure 2); over 50 years of daily precipitation data from eight local rain gages; over 30 years of independently-monitored continuous daily stream discharge; 20 years of land use mapping from the Northern Virginia Regional Commission (NVRC); and 14 years of remotely-sensed impervious surface estimates at 30 meter resolution from the Mid-Atlantic Regional Earth Science Applications Center (RESAC). The above data sets have been described previously by Dougherty et al. (2002).

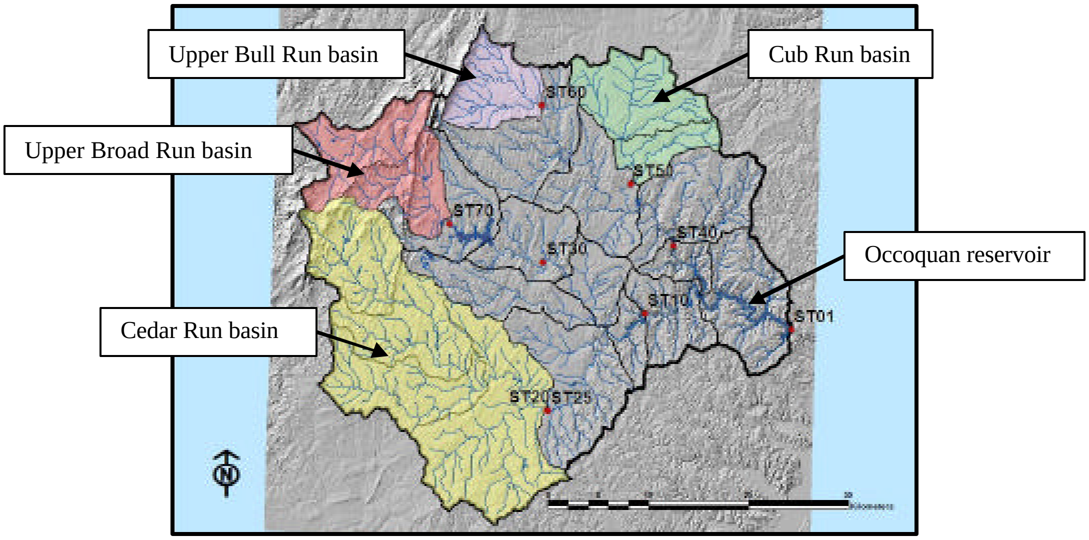


Figure 2. Occoquan basin (1530 sq. km): relief map showing four headwater basins, Occoquan reservoir, and major water monitoring stations.

Sampling

Study period

Point source contributions were effectively removed from the Cub Run basin when the AWT plant went on line in July of 1978. Consequently, the study period, which runs from 10/1/78 through 9/30/02 (water years 1979-2002) makes use of 24 years of integrated pollutant discharge data that is free from significant point source contributions. All four Occoquan headwater basin outlets were monitored with discrete weekly or bi-weekly grab samples and automated daily discharge and flow-proportional, volume-integrating storm samplers, for characterization of storm and non-storm flows, respectively. Stream samples were analyzed for TSS concentrations and the composition of dissolved and particulate nutrients at known water discharge rates. Resulting data sets, consisting of daily non-storm (grab) and automated storm (composite) sample analyses were assigned to sequential water years running from October 1 to September 30. Integrated sample constituent and flow values were identified by month, season, and water year, with data entries occurring in October, November, or December automatically incremented to the following calendar year for appropriate water year assignment and subsequent load summary.

Water years are excluded if there are more than 90 continuous days of missing samples. Seasonal data periods are excluded if there are more than 30 continuous days of missing samples (or greater than 45 continuous days during winter months December through February) in any monitoring station dataset. As a result, three water years (1979, 1980, and 1982), representing 13 percent of the annual data, are excluded. Likewise, eleven seasonal intervals, representing 11 percent of the seasonal data, are excluded (table 1). Missing water discharge and chemistry data falling below pre-assigned thresholds are infilled according to Johnston (1999), whose documented recommendations regarding OWML data analysis procedures are currently being used by that facility.

Table 1. Season periods excluded from analysis due to excessive missing data.

35 days	49 days	112 days*	468 days**
			7/18/1979-10/27/80 (Summer79) (Summer80) (Fall80) (Winter80) (Spring80)
		6/28/1982-10/17/82 (Summer82) (Fall82)	
	3/14/1983-5/2/83 (Spring83)		
10/22/1984-11/26/84 (Fall85)			
3/9/1987-4/13/87 (Spring87)			
3/8/1999-4/12/99 (Spring99)			

Data gap caused by relocation of Occoquan Watershed Monitoring Laboratory.
**Data gap caused by bridge construction near stream monitoring station 70.

After excluding periods of missing data, there are a total of 5,317 individual water samples remaining for analysis (3,680 taken as discrete weekly or bi-weekly grab samples and 1,636 taken using flow-proportional, volume-integrated storm samples). Consequently, there are an average 38 grab samples per year per monitoring station or approximately one grab sample every 10 days throughout the 24-year study period. Automated storm samples occur an average 17 times per year per monitoring station.

Stream discharge

Average daily flow data are tabulated from quarter-hour readings from stream-gaging equipment installed at all OWML monitoring stations. Average daily flow volumes (ft^3) are estimated during any given day by multiplying the average daily flow value against the number of seconds in a day (86,400 sec/day). These independent measurements are representative of the "true" flow since the average daily flow data are generated from continuous measurements (Richards and Holloway, 1987). Average daily discharge values are subsequently converted into mm for direct comparison with precipitation.

Missing stream discharge data was less than 5 percent of total data in this study. Johnston (1999) recommends the use of linear regression infilling between similar basins when missing data is less than 5 percent of the data. Subsequently, paired discharge regression equations are derived for infilling of missing discharge data. All derived equations below have a coefficient of determination, r^2, greater than 0.65. The coefficient of determination is a measure of the linearity of the regression relationship. The following regression equations are used for infilling of missing stream discharge data from 10/1/72 through 12/31/02, the period of longest common record.

Sta50 vs. Sta60:	Sta50 = 1.76(Sta60) + 7.67	r^2=0.68	N=10,869, p=0
Sta60 vs. Sta70:	Sta60 = 0.58(Sta70) – 4.89	r^2=0.71	N=10,478, p=0
Sta70 vs. Sta60:	Sta70 = 1.23(Sta60) + 21.14	r^2=0.71	N=10,478, p=0

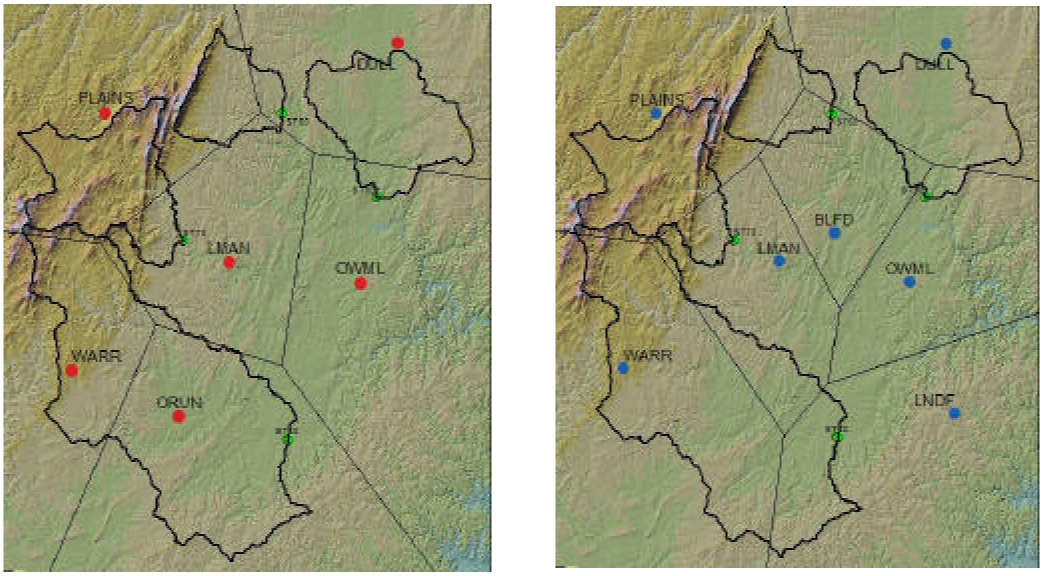
The drainage area ratio method is used as an alternate infilling method when matching data is unavailable in adjacent basins. Station 20/25 has no missing discharge data, and therefore has no need for regression or other infilling.

Rainfall volume

Daily precipitation data from eight rain gages (table 2) was synthesized into a modified Theissen rainfall estimate for the entire Occoquan basin. Replacement of missing rainfall data from inoperative rain gage stations was accomplished through hot-deck swapping (Johnston, 1999), which uses the most closely correlated adjacent rain gage for infilling. Five successive time periods, starting from 1951, were utilized to take advantage of rain gages that went in and out of service over the 51-year period of record. Manual modification of standard Theissen polygons to conform to mountainous terrain in the northwest section of the basin was found to moderately improve long-term precipitation estimates. Modified Theissen rainfall estimates were validated through linear correlation of annual and seasonal stream discharge with matching precipitation totals. All rainfall estimates, in inches, were subsequently converted to mm for further analysis.

Table 2. Dates during study period when Occoquan rain gages were active.

Station I.D.	Station name	Date
WARR	Warrenton (1951-2001)	2/24/51 - 6/30/01
PLAINS	The Plains (1954-2002)	4/1/54 - 9/30/02
DULL	Dulles International Airport (1963-2002)	1/1/63 - 9/30/02
OWML	Occoquan Watershed Monitoring Lab (1978-2002)	1/1/78 - 9/30/02
LMAN	Lake Manassas Water Treatment Plant (1984-2002)	11/11/84 - 9/30/02
ORUN	Owl Run (1986-1993)	6/16/86 - 6/30/93
LNDF	Prince William Landfill (1995-2002)	1/1/95 - 9/30/02
BLFD	Balls Ford Rd. Yard Waste Facility (1995-2002)	6/2/95 - 9/30/02



1986-1993 1995-2002

Figure 3. Standard Theissen polygons representing 14 years of the 51-year historic rainfall record.

Sample Analysis

Instantaneous and event-mean concentrations of total suspended solids (TSS), total phosphorus (TP), total soluble phosphorus (TSP), total Kjeldahl nitrogen (TKN), soluble Kjeldahl nitrogen (SKN), and oxidized nitrogen (OX_N) were measured and recorded at the Occoquan Watershed Monitoring Laboratory in Manassas, Virginia. Oxidized nitrogen represents the sum of nitrate-nitrogen and nitrite-nitrogen. Laboratory analysis methods were either U.S.EPA (1986) or Standard Methods (Greenberg et al., 1992) procedures, or as described in this section. Automated, composite sampling of storm flows was used throughout the study period to provide a single sample for analysis rather than the more costly method of analyzing many discrete samples.

Total suspended solids analyses were performed by filtering whole water samples through untreated glass fiber membrane filters, per EPA 160.2 until November 2000, then SM2540C. The difference in these two procedures is the way the sample is mixed and transferred to the filter. EPA 160.2 calls for thorough mixing and pouring into a graduated cylinder, while SM2540C requires mixing with a magnetic stirrer and transfer with wide-bore pipets from the middle of the sample. Whatman 934/AH filters with a nominal pore size of 1.5 µm were used for TSS analysis.

Phosphorus and nitrogen analyses were performed on both whole water samples and aliquots filtered though membrane filters per EPA 351.2 for TKN and SKN, EPA 365.4 for TP and TSP, and EPA 353.1 until November 2001 and EPA 353.2 from November 2001 for OX_N. Separate analyses were performed in order to determine particulate and dissolved phases, a distribution considered critical in assessing the water quality impact of nutrient loadings. In order for suspended nutrients to be directly related to TSS, the same size (1.5 µm) filter was used for nutrient analyses. This is a departure from EPA laboratory methods which call for use of a 0.45 µm membrane filter for nutrient analyses. The glass fiber filter used for nutrients was cleaned by rinsing with 0.5N HCl, rinsing with deionized water, heating to 475 degrees C, cooling at 103 degrees C, and then storage in a desiccator.

Samples for SKN, TSP, and OX_N were filtered through a Whatman 934/AH glass fiber filters as soon as samples were brought to the laboratory on the day of sample collection. OWML does not preserve samples for nutrients by acidification. Rather, the samples are collected, put on ice, and returned to the laboratory within a few hours for processing the same day. At the lab, all samples are received, logged-in, and analysis begun. Filtered SKN samples are added to prepared digestion tubes, while unfiltered TP and TKN samples are added directly to prepared digestion tubes (Daniels, 2003).

Preservation and analysis procedures remained consistent throughout the study period, although instruments were updated. Minimum detection limits (MDL) for all analyses remained constant throughout the period of study, as follows; TSS (1.0mg/L), TP (0.01mg/L), TSP (0.01mg/L), TKN (0.04mg/L), SKN (0.01mg/L), and OX_N (0.01mg/L). All constituents except nitrogen, which is ubiquitous in water, had a certain percentage of samples below the MDL. Analysis of the 5,317 individual water samples used in this study reveals that 7.5 percent of TSP, 6.3 percent of TSS, 5.0 percent of TP, and 5.0 percent of OX_N samples fell below MDL. A common technique, when the influence of detection limits is minor to insignificant, is to assign a proxy value to detection limited observations at one-half of the detection limit. Consequently, concentration values recorded in the database as below detection limit were converted to 1/2 minimum detection limit for use in this study.

Storm sampling

Before mid-1988, storm samples were collected by automatical triggering of samplers with a contact closure every 0.5 feet rise or fall in stage using magnets mounted on a float wheel which closed a reed switch mounted under the wheel. A mark on a stage chart corresponded to the time of sample collection. Storm start and end times were identified by visual interpretation of the stage chart. At the lab, stream discharge values for each discrete sample were determined and equal volume, flow-proportioned samples were made up using a computer program that calculated the amount of discrete sample to use for laboratory compositing (Grizzard et al., 1976).

Since mid-1988, storm identification at each monitoring station has been accomplished 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. If the stage has risen at least 0.01 foot over each of the last three intervals, then the storm sequence begins (Post and Grizzard, 1987). During a storm sequence, the computer tracks storm duration and flow volume at one-minute increments. Once a storm 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 to better identify the very beginning of the storm (Post, 2003).

The discontinuity in storm data collection method raises the possibility of human-induced bias in the pre-1988 storm data. Although graphical analysis suggests that pre-1988 storm duration values exhibit a wider range than post-1988 values, all storm and non-storm data are used without modification in this study, consistent with OWML procedures for chemical analysis and subsequent pollutant load calculation.

Data preparation

Population and impervious surface estimates

Land use analysis is completed using 1979 and 1989 rectified map images and 1995 and 2000 digital polygons from NVRC. Satellite-derived impervious surface (IS) estimates for 1986, 1990, 1996, and 2000 are derived from RESAC imagery. Planimetric reference data from Loudoun and Fairfax Counties (1997) is used to calibrate land class-based IS estimates (Dougherty et al., 2003).

The following four steps are used for IS estimation:

1. Calibrate land use IS estimates using Cub Run 1997 planimetric reference data (tables 3 and 4).
2. Determine IS means for all basins using 1997 calibrated land use IS assignments.

3. Estimate 1980 (no RESAC data available) IS basin means using 1980 land use mapping.
4. Interpolate 1986 (no NVRC mapping available) IS basin means using annual housing numbers from Loudoun and Fairfax Counties.

Table 3. IS calibration: land class IS estimates vs. 1997 planimetric reference data.

Land use category / Source data (date)	RESAC[1] (1996)	Planimetric data[2] (1997)
Institutional/commercial/industrial	46%	48%
Townhouse-garden apts.	34%	41%
Medium density residential	20%	23%
Low density residential	5%	5%
Agriculture/forest/idle land	4%	3%
Golf course	2%	3%
Disturbed lands (includes quarries)	55%	96%
Major roads	47%	60%
Airport and adjoining property	16%	10%

Note 1: Mean of 1990, 1996, and 2000 Mid-Atlantic RESAC 30m IS grids.
Note 2: From directly measured 1997 planimetric data for Cub Run supplied by Loudoun and Fairfax County GIS Depts., verified with circa 1997 Digital Ortho Quarter Quads (DOQQs) from Virginia Economic Development Partnership (VEDP).

Table 4. Occoquan headwater basin IS assignments, by land use class.

Combined land use category	IS estimate
Disturbed/construction, major roads/highways, minor roads	70%
Commercial/industrial	45%
Institutional/townhouse/med. density residential	35%
Low density residential/estate/golf	5%
Ag/forest/ idle land	0%
Dulles Airport w/ adjoining land (Cub Run basin only)	16%

Hydrologic data

Annual and seasonal precipitation observed for the 24-year study period is compared with the 51-year rainfall record in order to reference the data set to regional precipitation variations (table 5). Study period rainfall is comparable to the 51-year record, with the exception of a summer rainfall extreme in 1956 that has not since been repeated (table 6). Annual and seasonal precipitation sums exceeding two standard deviations above the 51-year mean are classified as extremely wet periods potentially triggering critical, maximum NPS pollution fluxes. Extreme, wet periods from 1952-2002 are tabulated below. Periods from 1952 to 2002 having rainfall amounts falling more than two standard deviations below the 51-year mean are defined as critical dry periods and are tabulated below (table 6).

Table 5. 24-year precipitation summary compared with 51-year summary, mm/period.

	Winter	Spring	Summer	Fall	Annual
Mean ± 1SD[1]	217 ± 69.5	268 ± 68.4	291 ± 96.4	248 ± 72.6	1024 ± 175
Range[1]	75.7 - 415	124 - 445	102 - 562	108 - 424	743 - 1405
Mean ± 1SD[2]	221 ± 80.1	276 ± 73.3	275 ± 85.4	263 ± 73.7	1023 ± 186
Range[2]	75.7 - 415	149 - 412	148 - 472	123 - 424	743 - 1405

All precipitation estimates derived from long-term, orographically-modified Theissen, basin-wide rainfall analysis, 1952-2002.

Note 1: From the 51-year precipitation record, 1952-2002 .

Note 2: From the 24-year study period, 1979-2002 (excluding 3 years and 11 seasons).

Table 6. Extreme, wet and dry periods, Occoquan headwater basins, 1952-2002.

	mean±2SD	1952-1979	1979-1984	1985-1990	1991-1996	1997-2002
Winter (1952-2002)	356 mm *78 mm*		415 mm (1979)			371 mm (1998) *76 mm (2002)*
Spring (1952-2002)	404 mm *131 mm*		445 mm (1983) *124 mm (1969)*	412 mm (1989)	406 mm (1993)	
Summer (1952-2002)	484 mm *98 mm*	562 mm (1956) 522 mm (1955)				
Fall (1952-2002)	393 mm *103 mm*				424 mm (1996)	
Annual (1952-2002)	1374 mm *674 mm*		1405 mm (1984) 1383 mm (1979)			

Extreme wet periods defined as those having rainfall sums above 2SD from the 51-year mean.

Extreme dry periods defined as those having rainfall sums below 2SD from the 51-year mean.

Graphical summaries of annual and seasonal rainfall (figures 4 and 5) are developed to visualize study period rainfall within the historic 51-year record. Annual precipitation trends in the latter part of the study period confirm the existence of a 4-year drought that officially began in summer/fall 1998 in Virginia (figure 4). Water year 2002 is the low rainfall year of record for the Occoquan basin. A similar low annual precipitation occurred in 1985; however, neither year exceeds two standard deviations below the 51-year mean. The maximum water year of record occurred in 1984, and exceeded two standard deviations of the 51-year annual precipitation mean (table 6). Graphical display of seasonal rainfall totals reveals widest ranges in summer precipitation (figure 5).

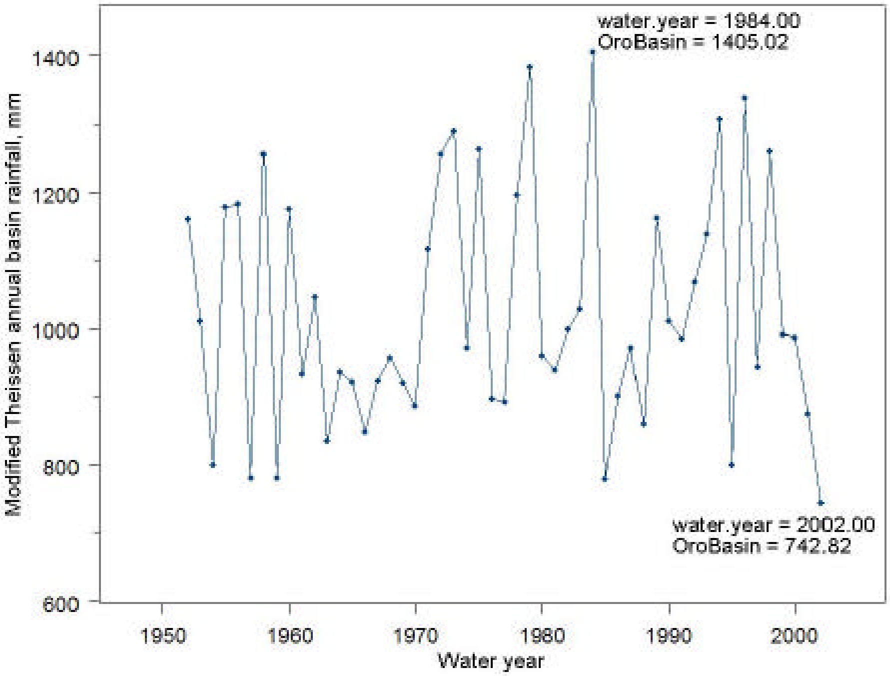


Figure 4. Occoquan basin, modified Thiessen annual rainfall means, 1951-2002.

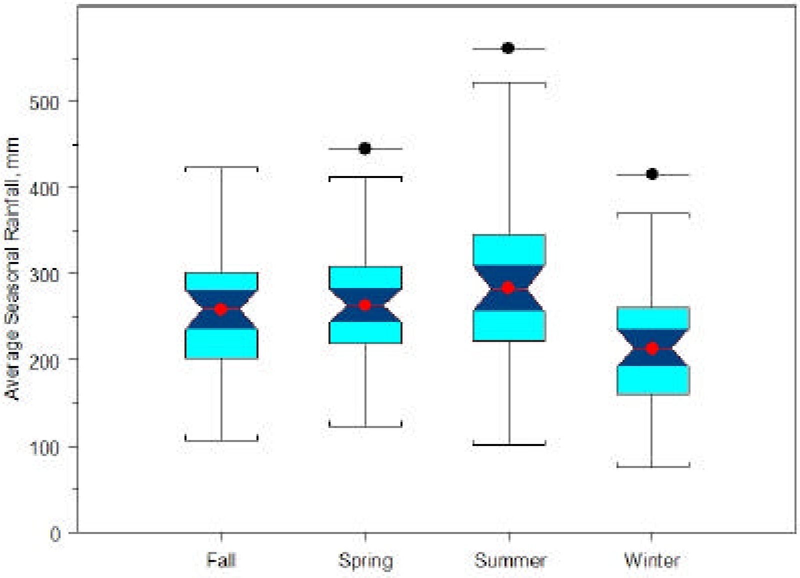


Figure 5. Seasonal basin-wide, modified Theissen rainfall, mm, 1951-2002.

Suspended solids and nutrient loads

A important part of this research is the determination of suspended solids and nutrient loads on an annual and seasonal basis. In order to summarize particulate and dissolved nutrient loads, the following constituent concentrations are calculated indirectly; particulate phosphorus (PartP = TP - TSP), total nitrogen (TN = TKN + OX_N), particulate nitrogen (PartN = TKN – SKN), and total soluble nitrogen (TSN = SKN + OX_N). All indirectly calculated nutrient values are adjusted to prevent negative concentrations, as follows:

- adjTSP: TSP values larger than TP are set equal to TP values.
- adjPartP: TP-adjTSP
- adjSKN: SKN values larger than TKN values are set equal to TKN values
- adjPartN: TKN-adjSKN
- adjTSN: adjSKN+OX_N (alternately, TN-adjPartN)

If continuous concentration and flow measurements could be made for the entire study period, the mass flux estimate for the period would be the integral of the product of concentration of a water quality parameter and flow, multiplied by the appropriate unit conversion (Yaksich and Verhoff, 1983). Even with automated stream-gaging monitoring equipment and periodic non-storm grab sampling, some estimate of load must be made for periods in which the measurements are not taken. The precision of the load estimate invariably depends on assumptions made about the period not sampled (Whitfield, 1988). In the present study, stormflow loads are tabulated as a time-ordered series at a constant step-loading rate extending from the beginning to the end of the storm (OWML, 1998). Non-storm loads, tabulated separately, are not counted in the individual basin's total load summation during periods of stormflow.

The methodology used for load calculation is a modified version of the Daily Flow-Data Integration (DFDI) method of Johnston (1999). This method uses average daily flow data collected from continuous stream-gaging equipment to estimate non-storm discharge. To estimate loads associated with non-storm flow, the DFDI Method assigns a chemical concentration value, in mg/L, based on simple linear interpolation of instantaneous grab samples.

Non-storm and storm intervals are identified within an Excel spreadsheet using the following unique labels (where DATE1/TIME1 represents sample time or beginning of storm event and DATE2/TIME2 represents the end of a storm event);

- **BASE**: a non-storm interval with no intervening storm interval, fixed (1 day)
- **STORM**: auto-sampled time interval representing storm flow condition, variable, (storm DATE2/TIME2 – storm DATE1/TIME1)
- **DELETE**: a non-storm interval included entirely within a storm interval, fixed (0 day)
- **ENDSTORM**: the time interval between the end of a storm and the following non-storm interval, variable (non-storm DATE1/TIME1 – storm DATE2/TIME2)
- **PRESTORM (following BASE or ENDSTORM)**: a regular non-storm interval occurring before a storm interval, variable (storm DATE1/TIME1 – non-storm DATE1/TIME1)

- **PRESTORM (following DELETE or STORM)**: a short non-storm interval occurring between two consecutive storms, variable, (stormB DATE1/TIME1 – stormA DATE2/TIME2)
- **PRE/POSTSTORM**: a non-storm interval remaining after abstracting a storm occurring entirely within the same day, variable (storm DATE1/TIME1 – non-storm DATE1/TIME1 + non-storm DATE1+1 – storm DATE2/TIME2)

The following procedures summarize the modified DFDI method of Johnston (1999) used in this study for calculating annual and seasonal loads.

1. Consolidate 24 water years of daily stream discharge and water chemistry data from 10/1/78 to 9/30/02 (water years 1979-2002) for monitoring stations 25, 50, 60 and 70.
2. Prepare nominal weekly non-storm (baseflow) discrete samples and auto-composited storm samples as separate databases called "B" (NON-STORM) and "R" (STORM), based on status of DATE2/TIME2 entries.
3. Infill missing chemistry data using a simplification of the method of Johnston (1999), as follows. If the missing constituent is strongly correlated with flow, then use regression with flow data to infill missing data. If the missing constituent is not strongly correlated with streamflow, then use the corresponding station-seasonal mean (non-storm or storm flow) for the study period.
4. Replace hydrologic "B" flow data with average daily flow values collected by continuous stream-gaging equipment, as described by Johnston (1999).
5. **Calculate STORM loads** by multiplying storm duration and average storm flow times storm EMC and applying the appropriate conversion factor.
6. Assign daily water constituent levels for "B" non-storm sample dates using linear interpolation between successive discrete "B" samples.
7. **Calculate NON-STORM loads** by multiplying assigned daily flows times linearly interpolated daily constituent levels and applying the appropriate conversion factor.
8. **Calculate STORM / NON-STORM intervals** by incorporating individual storm events into "B" dataset (step 7). Intervals defined by STORM begin / end dates.
9. Convert 186 high-flow, non-storm entries from "B" to "R" using a combination of daily rainfall and flow data, along with recorded field comments.
10. **Calculate TOTAL load** as the sum of calculated "B" and "R" loads sorted by date / time after applying appropriate conversion factor.
11. **Summarize TOTAL, STORM, and NON-STORM loads** as annual / seasonal and dissolved / particulate loads.

Results

Land use summaries

Land use classification for all four headwater basins were summarized from available 1980-2000 mapping, photo-digitized, and geo-referenced using standard GIS techniques. Analysis of resulting historic land use categories reveals a steady increase in Cub Run (station 50) urbanization between the years 1980 and 2000. Before 1990, there was more than twice as much rural land as urban land (table 7 and figure 6). By the year 2000, there was more urban than non-urban land (65 vs. 63 km^2). Corresponding mean basin impervious surface for Cub Run passed 10 percent sometime between 1980 and 1990.

Table 7. Cub Run land use, km^2, 1980-2000.

Land use category	1980	1985	1990	1995	2000
Forest/idle land	66.1	58.7	58.0	62.0	57.2
Mixed minimum till/pasture	27.9	22.1	16.2	4.0	2.3
Mixed conventional till/livestock	6.4	5.2	4.0	3.4	3.2
Disturbed land/roads	6.6	2.8	5.3	3.5	1.7
Industrial/commercial/institutional	9.2	14.5	15.6	20.4	23.2
Townhouse/medium density residential	7.5	19.5	23.5	26.9	31.5
Low density residential/golf course	3.4	4.4	4.6	7.0	8.1
Urban sub-total	26.8	41.2	49.0	57.8	64.5
Non-urban sub-total	100.4	85.9	78.2	69.4	62.7
Total area	127.2	127.2	127.2	127.2	127.2

Note: The 1980 area of disturbance is estimated as half of the 5-year urban increase, or 5 km^2 disturbed + 1.62 km^2 road (1.62 km^2 road area used throughout analysis). All 1985 urban land use areas are estimated using RESAC 1986 urban extents to back-classify NVRC 1990 land use (1985 agricultural land use interpolated between 1980 and 1990).

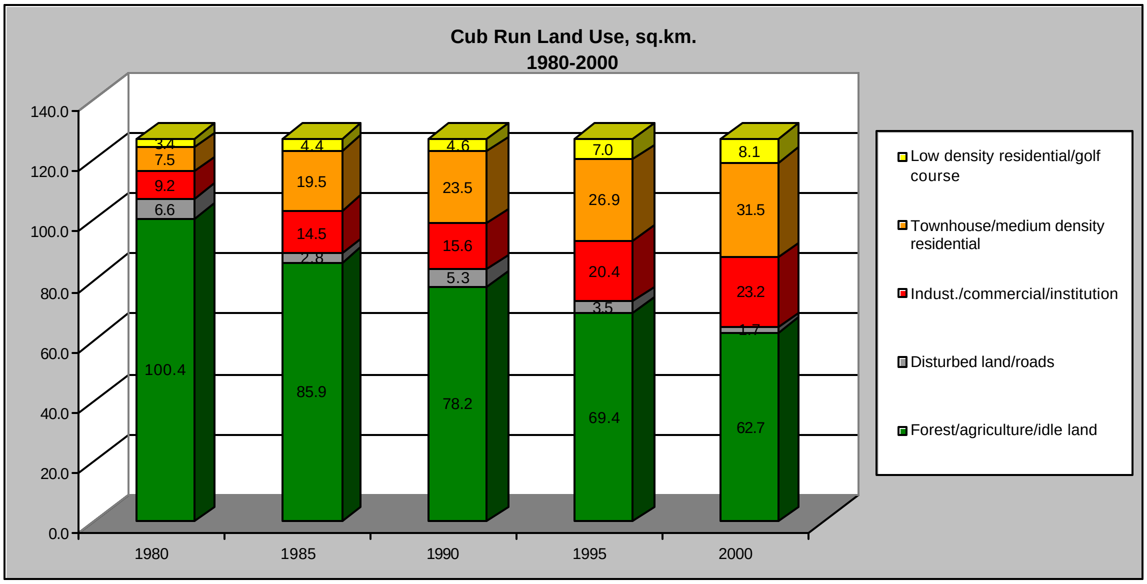


Figure 6. Cub Run land use, km^2, 1980-2000 (data from table 7).

Basin land use summaries for 1980 and 1990 were derived from hard copy maps (figure 7). Land use data for 1995 and 2000 was provided as pre-classified polygon shape files from NVRC. Land use data from 1985 was unavailable, so was synthesized using a combination of existing 1990 land use and 1986 satellite-derived impervious surface images of urban extent. The three non-urban headwater basins, Cedar Run, Upper Broad Run, and Upper Bull Run, exhibit a fundamentally different land use composition compared to Cub Run. Time series of land use mapping and bar graphs (figures 8 and 9) clearly illustrate that Cub Run land use change from 1980-2000 far outdistances the other three basins in both area and percent of basin being transformed into urban land.

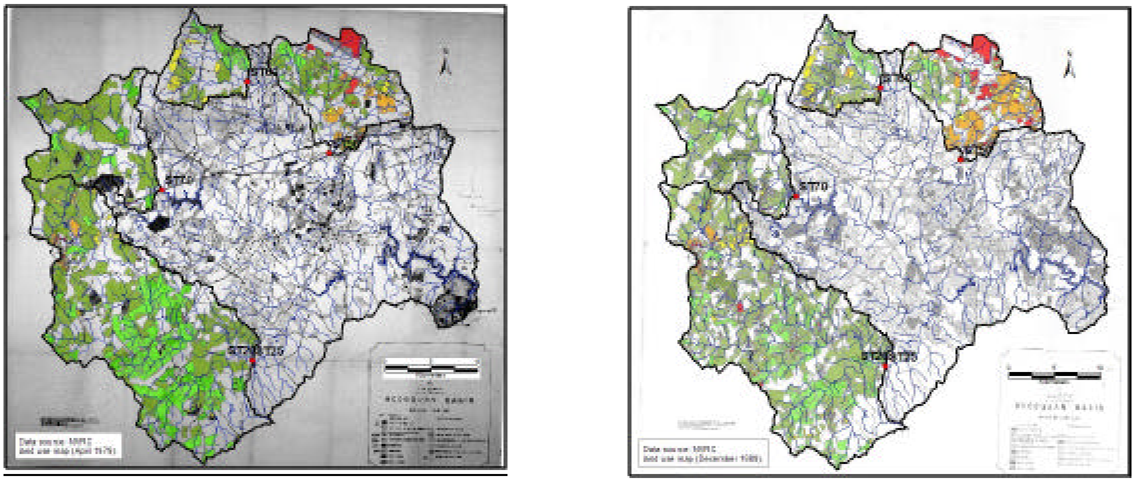


Figure 7. Four Occoquan headwater basins, circa 1980 and 1990 land use polygons (in color) digitized and georeferenced from hard copy mapping (B&W). Legend for figure 7 and 8: mixed minimum till agriculture/pasture (dark green), mixed conventional till agriculture/livestock (light green), low density residential/golf course (yellow), townhouse/medium density residential (orange), commercial/ industrial/disturbed land/roads (red), forest/idle land (no color).

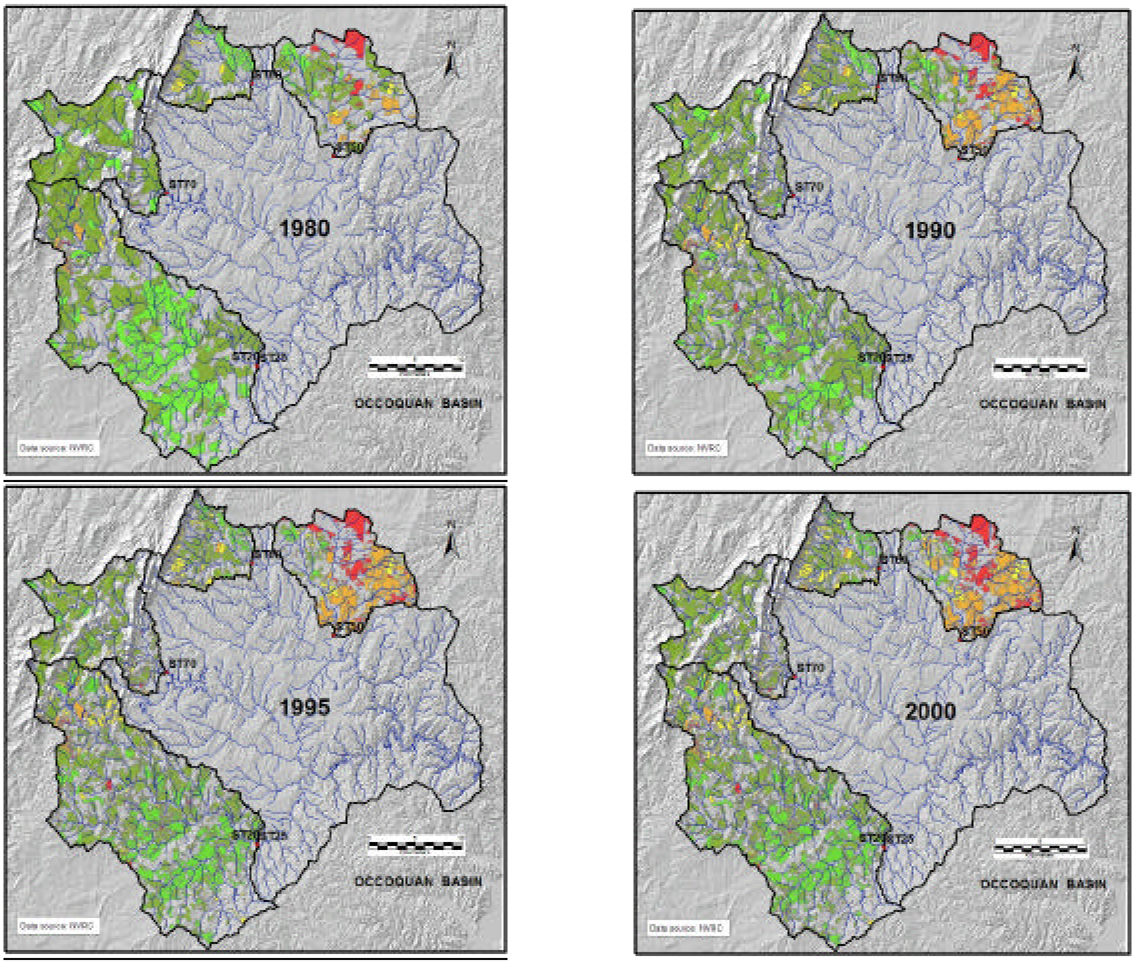


Figure 8. Land use relief maps, four Occoquan headwater basins, 1980-2000.

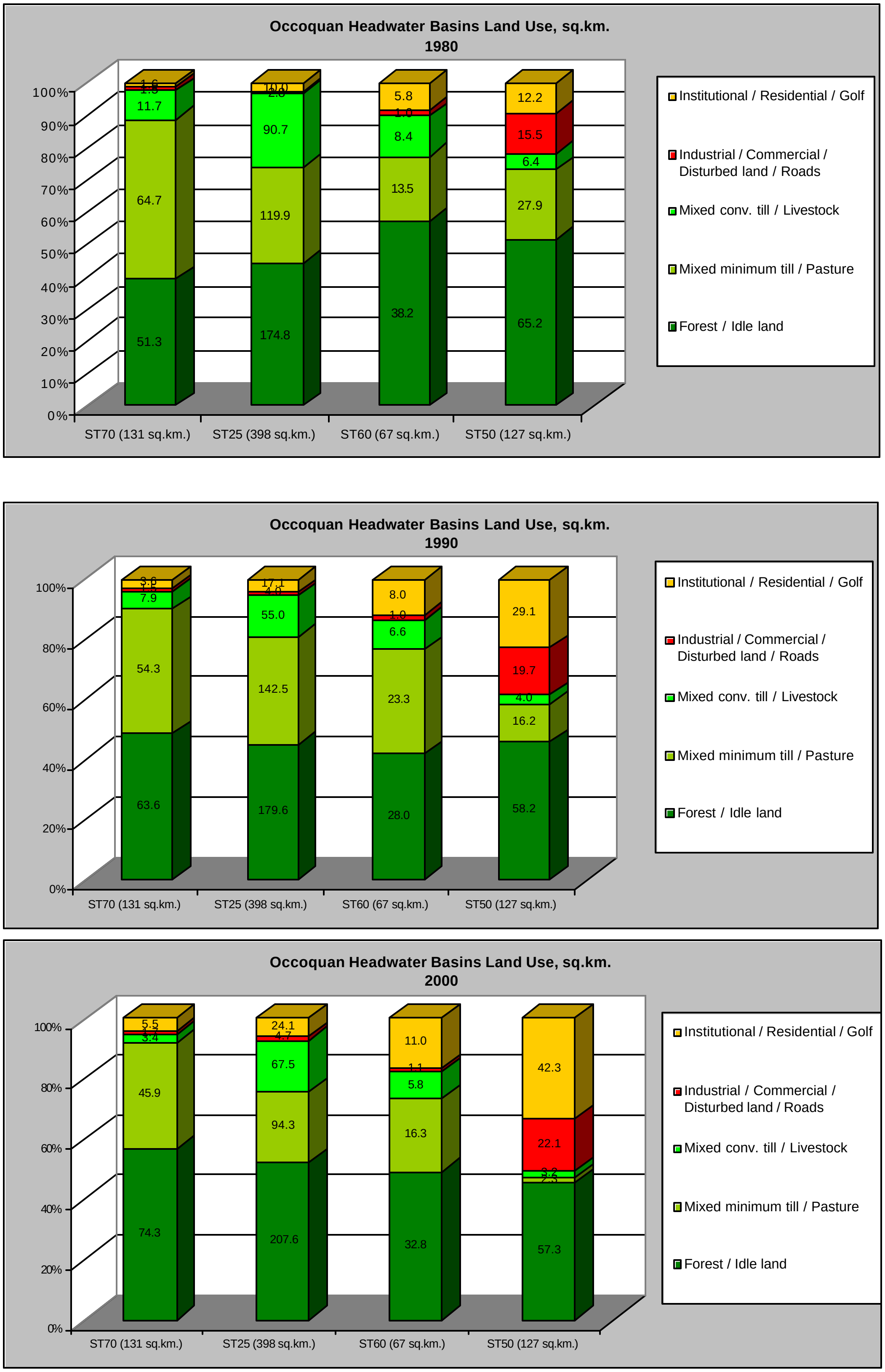
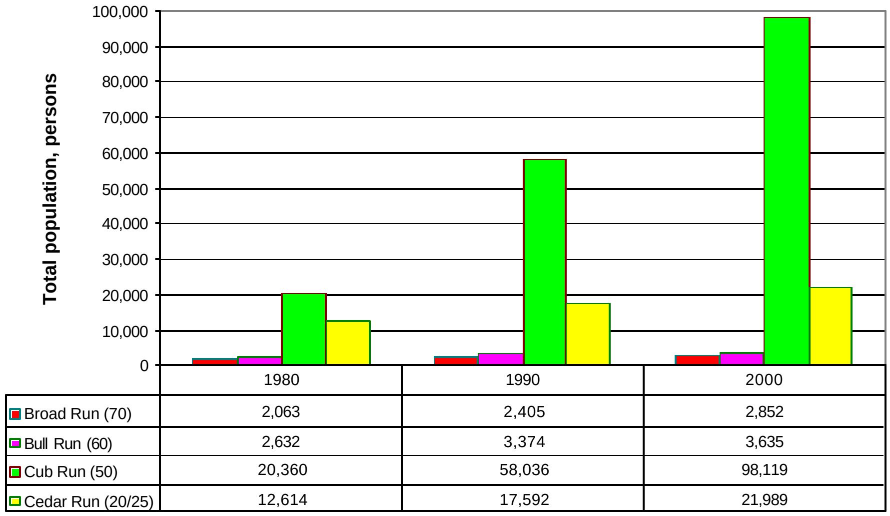


Figure 9. Occoquan headwater basin land use summaries, km^2, 1980-2000 (data derived from figure 8).

Population and impervious surface estimates

Population estimates from GIS analysis of US Census data shows increasing population in all Occoquan headwater basins (figure 10). Cub Run basin, located within rapidly growing Loudoun and Fairfax counties, far outdistances the other three basins with a total growth rate of 380 percent from 1980 to 2000. Nearly three times as much population growth occurred in the Cub Run basin from 1980 to1990 (185 percent increase) as did from 1990 to 2000 (69 percent increase). Independently derived estimates of impervious surface (IS) at five year intervals (table 8) reveal growth patterns nearly identical to population, with Cub Run basin again outdistancing all other headwater basins. Cub Run basin's mean IS percent increased 96 percent from 1980 to 1990, compared to a 36 percent increase from 1990 to 2000. Mean Cub Run basin IS percent exceeded 10 percent sometime around 1985.



	1980	1990	2000
🟥 Broad Run (70)	2,063	2,405	2,852
🟪 Bull Run (60)	2,632	3,374	3,635
🟩 Cub Run (50)	20,360	58,036	98,119
🟨 Cedar Run (20/25)	12,614	17,592	21,989

Figure 10. Occoquan headwater population, 1980-2000 (Source: ESRI 1990/2000 US Census data dot maps and GeoLytics, Inc. 1980/1990 US Census neighborhood change data).

Table 8. Mean impervious surface, %, Occoquan headwater basins, 1980-2000.

Basin	1980	1985	1990	1995	2000
Cedar Run	1.4	*1.5	1.7	1.8	1.8
Cub Run	6.7	**9.3	13.1	15.8	17.8
Upper Bull Run	1.7	*1.9	2.0	2.0	2.2
Upper Broad Run	1.5	*1.5	1.5	1.6	1.6

Derived from GIS analysis of NVRC land use data, except as noted.
*Linearly interpolated from 1980 and 1990 IS values.
**Interpolated proportionately from 1980 and 1990 IS values using annual residential housing numbers.

Above results demonstrate that Cub Run basin 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 housing start data (figures 11 and 12) reveal that the greatest 5-year growth in the Cub Run basin occurred between 1982 and 1987 (from 1.84 to 3.68 persons per hectare). The greatest one-year increase in population density occurred from 1985 to 1986 (from 2.78 to 3.30 persons per hectare). Impervious surface trends are similar to those for population (table 9, figure 12).

A lesser population surge occurred in the Cub Run basin in the years 1990 through 1994 with the maximum annual increase of 9.0 percent occurring between 1991 and 1992. The corresponding increase in impervious surface percent in 1992 was 4.4 percent. Between 1995 and 2002, annual population growth rates in Cub Run basin dropped off to an average 4.8 percent, with a corresponding average impervious surface growth rate of 2.4 percent.

Table 9. Maximum growth rates, Cub Run basin, 1980-2002.

	Maximum 1-year growth rate	Maximum 5-year growth rate
Population density, persons/ha	18.7% (1985-1986)	100% (1982-1987)
Impervious surface, percent	12.2% (1985-1986)	57.8% (1983-1988)

Source: Figures 11 and 12.

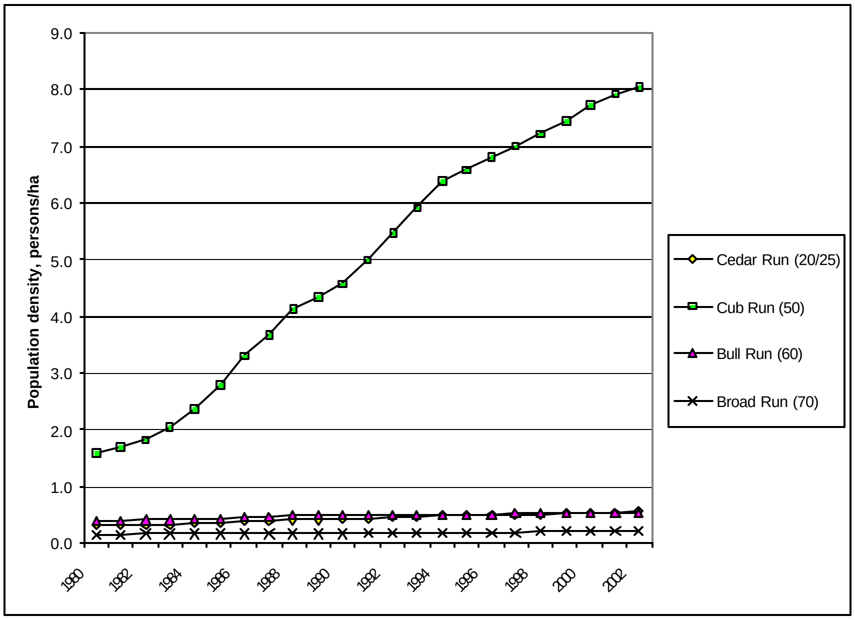


Figure 11. Annual population estimates, Occoquan headwater basins, 1980-2002 (Source: 1980, 1990, 2000 US Census and county housing data).

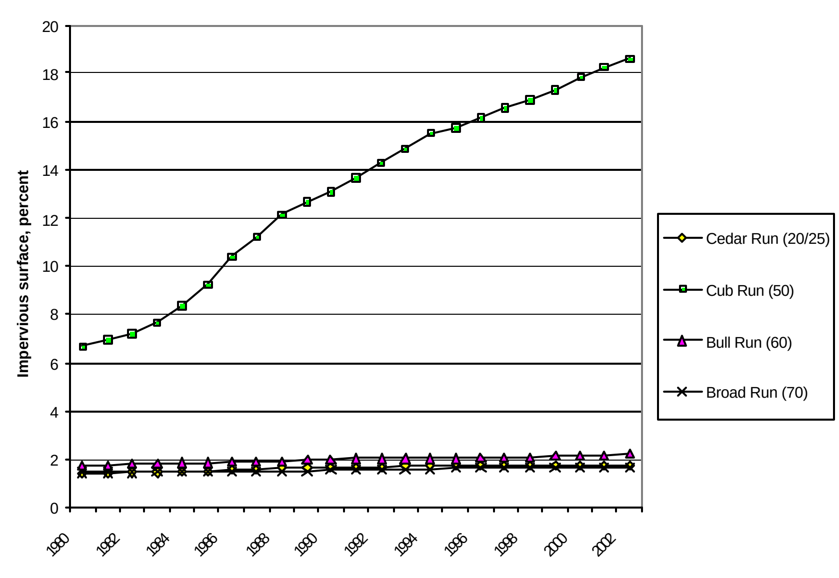


Figure 12. Annual impervious surface estimates, Occoquan headwater basins, 1980-2002 (Source: NVRC land use mapping and county housing data).

Stream discharge

Annual data

Previous studies have demonstrated the linkage between large storm events and NPS pollution flux (Haith and Shoemaker, 1987; Jordan et al., 1986; and Kronvang, 1992). Mean annual stream discharge for each of the Occoquan headwater basins reveal that Cub Run is the only basin with average annual storm discharge greater than non-storm discharge (table 10). In addition, the highly urbanizing Cub Run basin has a higher total average discharge than similarly-sized Upper Broad Run basin.

Table 10. Mean annual storm/non-storm discharge, m^3/yr, 1979-2002.

	Cedar Run basin (398km^2)	Cub Run basin (127km^2)	Upper Bull Run basin (67km^2)	Upper Broad Run basin (131km^2)
Non-storm flow	75,268,946 (189 mm)	24,113,359 (190 mm)	12,393,880 (185 mm)	30,013,602 (229 mm)
Storm flow*	60,521,239 (152 mm)^{a}	24,364,515 (192 mm)^{b}	10,637,271 (159 mm)^{a}	15,050,040 (115 mm)^{c}
Total flow	135,790,185 (341 mm)	48,477,874 (382 mm)	23,031,151 (344 mm)	45,063,642 (344 mm)

*A significant difference is found between at least two annual discharge means (a=0.05); superscripts a, b, c, d denote a significant difference between mean annual basin discharge.
Discharge means calculated using 21 years of data (1979, 1980, 1982 excluded).

Nonparametric Kruskal-Wallis rank sum tests, which require no distributional assumptions (Insightful, 2001), are used to discern statistical difference between annual discharge means. Comparison of unit-area annual discharge reveals significant difference between storm flows from at least two stations at the a=0.05 level (Kruskal-Wallis chi-square = 8.3589, df = 3, p-value = 0.0391). Subsequent analysis using the

Wilcoxon two-sample test, another nonparametric test that is not dependent upon the assumption of normality, shows that Cub Run basin (station 50) and Upper Broad Run basin (station 70) have significantly different storm runoff discharge means (Wilcoxon rank-sum statistic W = 564, n = 21, m = 21, p-value = 0.0041). The Wilcoxon test is used over the conventional t-test because it offers greater reliability and much less sensitivity to outliers than the well-known t-test (Noether, 1991).

Box plots illustrate the 30-year distribution of annual basin discharge for the four Occoquan headwater basins (figure 13). Cub Run (station 50) has the largest per unit area total discharge, but Cedar Run (station 25) and Upper Bull Run (station 60) have the widest range of total discharge. Graphical comparison of basin discharge vs. precipitation (figure 14) reveals a much steeper slope for Cub Run storm discharge (m=0.454) compared to the area-weighted slope of the non-urbanizing basins (m=0.166).

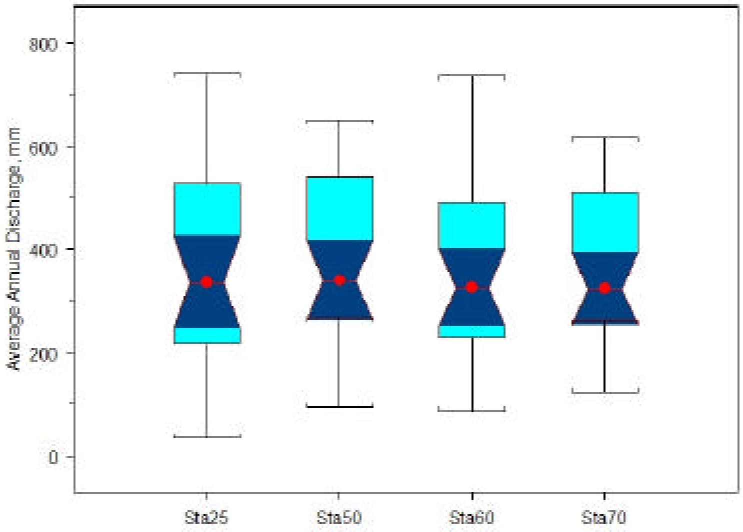


Figure 13. Box plots showing annual basin discharge, mm, for four Occoquan headwater basins, 1972-2002.

Robust MM regression (Insightful, 2001) is a nonparametric technique used for fitting linear relationships when the random variation in the data is not normal and the data contains significant outliers. Although least squares regression is more firmly established, least squares often carries with it the assumption that observations are normally distributed. If this is not the case, standard least squares regression may return inaccurate estimates. Also, least squares regression is considerably more sensitive to erratic observations than the nonparametric approach (Noether, 1991). The robust MM regression used in this study is convenient for comparative analysis as it returns a model that is almost identical in structure to a standard linear regression model. Graphical results (figure 14) suggest that there is a higher storm runoff response in Cub Run basin than in other basins during wetter years when a larger portion of runoff bypasses natural soil infiltration.

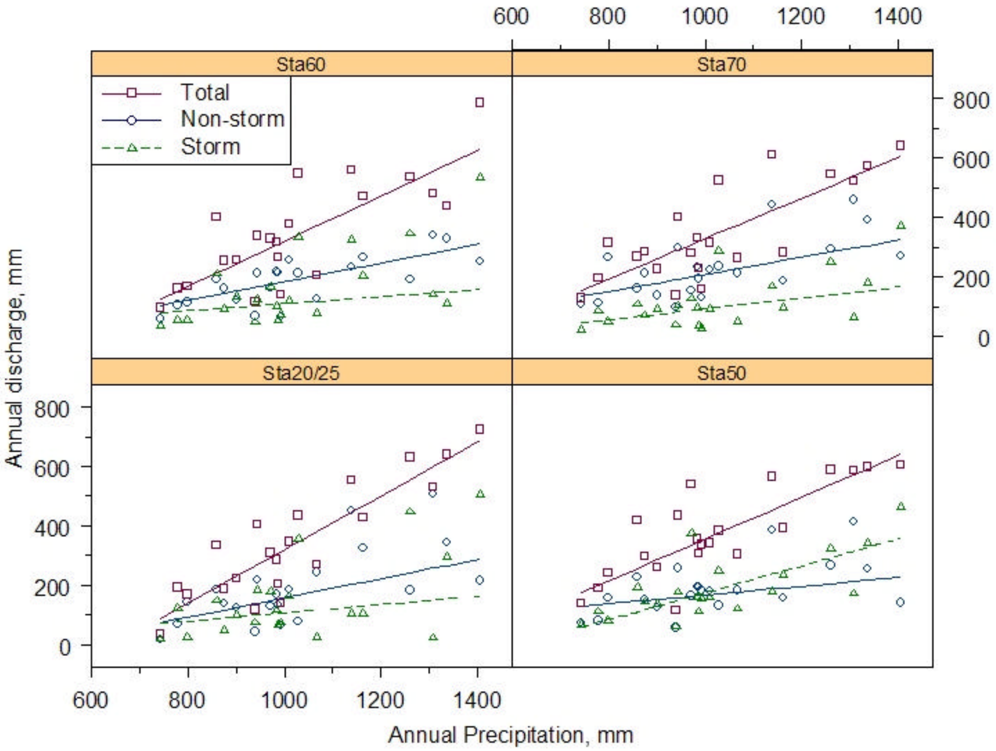


Figure 14. Annual storm and non-storm discharge as a function of precipitation, four Occoquan headwater basins, 1979-2002 (robust MM regression).

Mean runoff ratios calculated for Occoquan headwater basins (table 11) reveal higher storm and total runoff ratios for the Cub Run basin. The similarly-sized upper Broad Run basin has a greater non-storm runoff ratio than Cub Run. Statistical comparison of the three runoff ratios (storm, non-storm, and total) reveals significant difference between at least two basin storm ratios at a p-value of 0.05 (Kruskal-Wallis chi-square = 9.8559, df = 3, p-value = 0.0198). Further two-sample testing between basins shows a significant difference between the storm runoff ratios of Cub Run and Upper Broad Run at a p-value of 0.05 (Wilcoxon rank-sum test rank-sum statistic W = 584, n = 21, m = 21, p-value = 0.0006). Hewlett (1967) ultimately selected the ratio of annual mean storm runoff to mean precipitation as the most useful hydrologic response characteristic.

Table 11. Annual runoff ratios, Occoquan headwater basins, 1979-2002.

	Cedar Run ($398km^2$)	Cub Run ($127km^2$)	Upper Bull Run ($67km^2$)	Upper Broad Run ($131km^2$)
Non-storm discharge / precipitation	0.185	0.186	0.181	0.224
Storm discharge / precipitation*	0.149^a	0.188^b	0.155^a	0.112^c
Total discharge / precipitation	0.333	0.373	0.336	0.336

**A significant difference is found between at least two annual discharge means (a=0.05); superscripts a, b, c, d denote a significant difference between mean annual runoff ratio.
Runoff ratio means calculated using 21 years of data (1979, 1980, 1982 excluded).

Graphical representation of annual runoff ratios as a function of basin and water year illustrates hydrologic response over time (figure 15). Local (Loess) regression, a nonparametric generalization of multivariate polynomial regression, is used to fit a general smooth surface. Comparison of figure 15 with figure 16 reveals a general similarity between annual runoff ratio and annual rainfall over time, especially for station 70 (Upper Broad Run). Results from this section suggest that annual precipitation can be a good predictor of watershed discharge in these Piedmont watersheds.

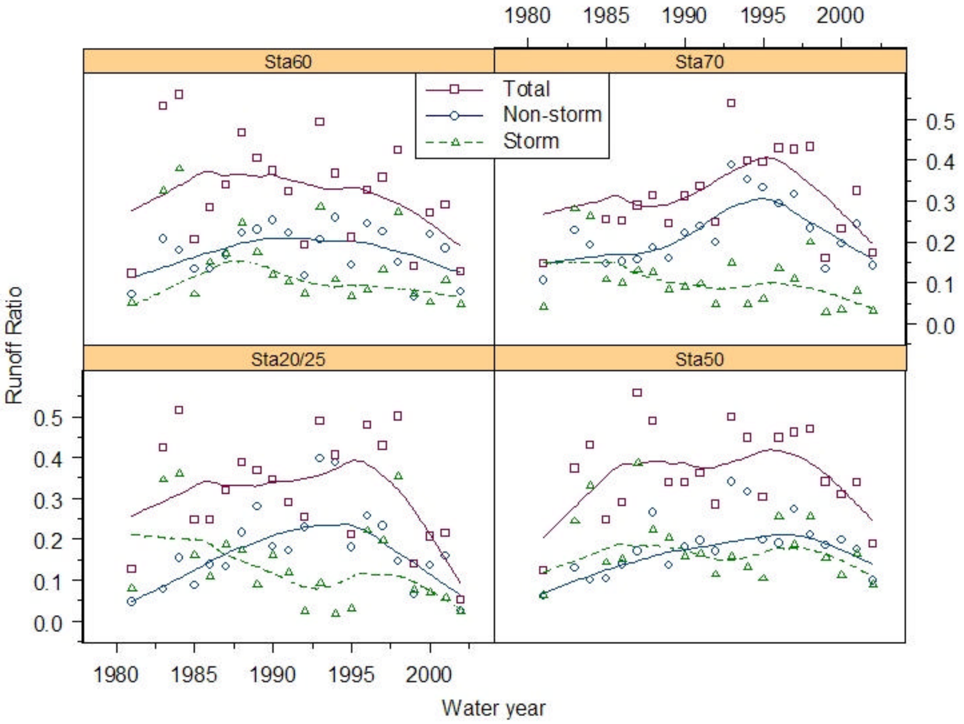
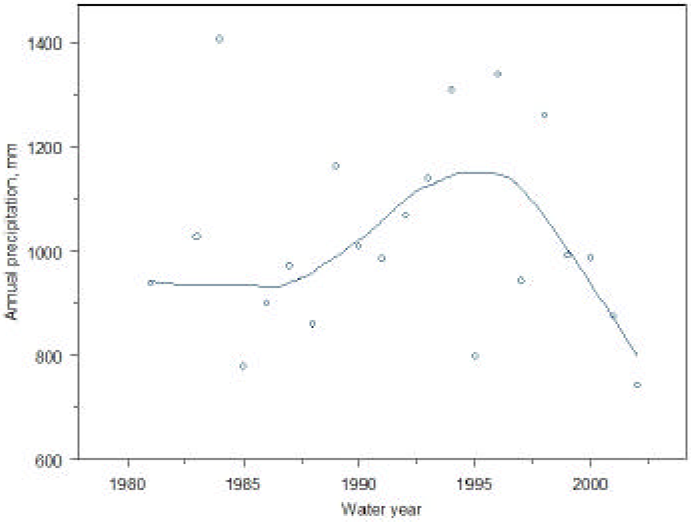


Figure 15. Runoff ratios as a function of water year, four Occoquan headwater basins, 1981-2002 (local Loess regression).

Figure 16. Annual precipitation as a function of water year, 1981-2002 (local Loess regression).



Seasonal data

Seasonal storm discharge-precipitation relationships from 1981 through 2002 show a generally lower runoff response in summer and fall (June through November) across all Occoquan headwater basins. A higher discharge response is observed during winter and spring (December through May), a trend that is most pronounced in the urbanizing Cub Run basin (station 50). Graphical results show that Cub Run basin has the highest discharge response of all basins and seasons (figure 17).

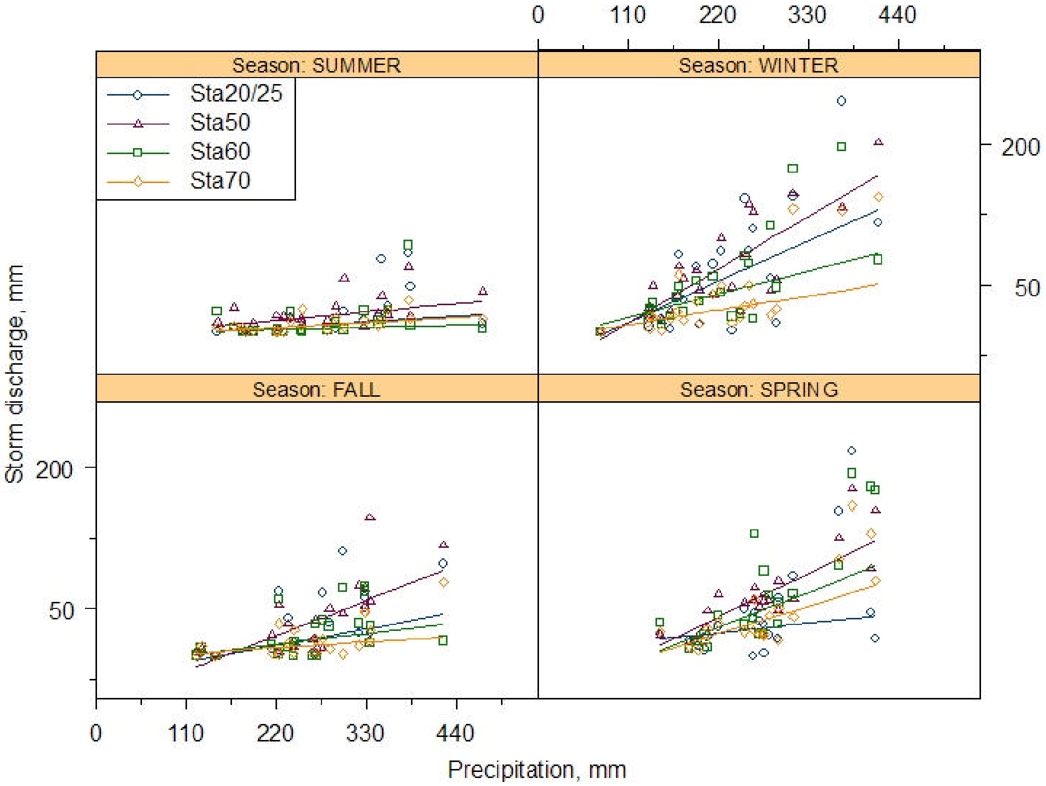


Figure 17. Seasonal storm discharge as a function of precipitation, 1981-2002 (Robust MM regression).

Further analysis of a monthly water balance for all basins over the 30-year period of common record (1972-2002) reveals several unifying patterns. Linear correlation of area-weighted annual stream discharge with annual precipitation is significantly lower during the peak growing season from June through August, thereafter increasing, peaking, and declining naturally during the ensuing dormant season (upper section, figure 18). Higher discharge vs. precipitation correlations occur during the periods of increased stream discharge in winter and spring. Average annual precipitation minus area-weighted discharge estimates of evapotranspiration (lower section, figure 18) suggest that lower monthly discharge correlations are due to increased vegetative ground cover and evapotranspiration during the growing season. Average annual water balance results for the urbanizing Cub Run basin over the same 30-year period are similar to area-weighted results. These results highlight the significant hydrologic impact of vegetated landscape cover on all Occoquan headwater basins, including the highly urbanizing Cub Run basin.

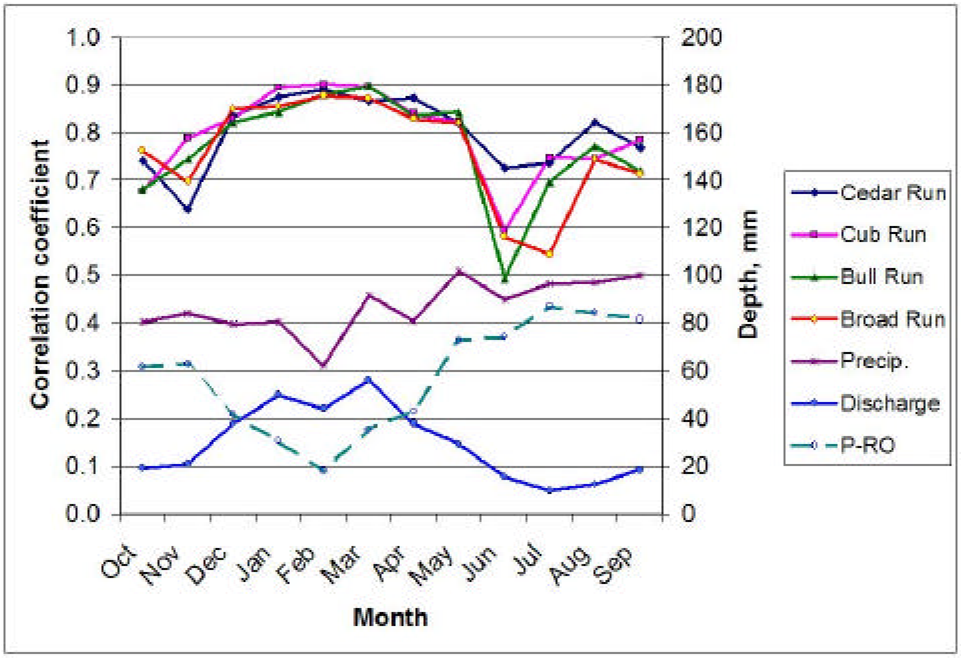


Figure 18. Correlation of average stream discharge to precipitation (upper family of curves), and average area-weighted hydrologic balance (lower family of curves), Occoquan headwater basins, 1972-2002.

Total suspended solids and nutrient fluxes

Annual data

Selected NPS pollutant concentrations, loads, and fluxes are summarized and displayed as a function of precipitation in this section. The highest mean annual storm TSS concentration (195 mg/L) is found in Cub Run; and the highest mean annual non-storm concentration (8.13 mg/L) is found in Upper Broad Run (table 12). Mean annual NPS pollutant loads from each of the four Occoquan headwater basins (table 13) are generally proportional to drainage area, with the notable exception of Cub Run, where mean annual TSS loads over the 24-year study period are approximately twice those delivered from similarly-sized Upper Broad Run. The reverse is true for non-storm TSS loads (not shown), with Upper Broad Run more than doubling the mean annual non-storm TSS loads of Cub Run. Mean annual particulate P, dissolved P, particulate N, and dissolved N storm loads from Cub Run are, respectively, 1.2, 1.6, 1.4, and 1.5 times those from Upper Broad Run. Summaries of TSS flux in the four Occoquan headwater basins reveals that from 88 to 98 percent of mean annual TSS flux is delivered by storm flow.

Table 12. Mean annual NPS pollutant concentrations, mg/L, 1979-2002.

	Cedar Run ($398km^2$)	Cub Run ($127km^2$)	Upper Bull Run ($67km^2$)	Upper Broad Run ($131km^2$)
Non-storm flow				
TSS, mg/L	4.27	5.48	4.05	8.13
Particulate P	0.012	0.013	0.010	0.020
Dissolved P*	0.043	0.032	0.019	0.021
Particulate N	0.077	0.076	0.074	0.091
Dissolved N**	1.02	0.982	0.616	0.811
Storm flow				
TSS, mg/L	108	195	163	113
Particulate P	0.167	0.197	0.203	0.205
Dissolved P*	0.102	0.057	0.061	0.051
Particulate N	0.629	0.727	0.822	0.623
Dissolved N**	1.58	1.16	1.16	1.22

Calculated using 21 years of data (1979, 1980, 1982 excluded).
*Directly measured as total soluble phosphorus, mg/L.
**Indirectly measured as the sum of soluble Kjeldahl nitrogen and oxidized nitrogen.

Table 13. Mean annual particulate/dissolved NPS pollutant loads (fluxes), kg (kg/ha), 1979-2002.

	Cedar Run ($398km^2$)	Cub Run ($127km^2$)	Upper Bull Run ($67km^2$)	Upper Broad Run ($131km^2$)
Total flow				
TSS	9,154,087 (230)	6,391,677 (503)	2,746,840 (411)	3,076,016 (235)
Particulate P	12,444 (0.32)	5,689 (0.45)	3,211 (0.48)	5,374 (0.42)
Dissolved P*	10,040 (0.26)	2,278 (0.18)	942 (0.15)	1,618 (0.13)
Particulate N	43,584 (1.09)	19,602 (1.55)	12,563 (1.88)	15,455 (1.18)
Dissolved N**	180,617 (4.53)	56,392 (4.43)	22,116 (3.31)	46,630 (3.57)

Calculated using 21 years of data (1979, 1980, 1982 excluded).
*Directly measured as total soluble phosphorus, mg/L.
**Indirectly calculated as the sum of soluble Kjeldahl nitrogen and oxidized nitrogen, mg/L.

Mean annual TSS concentration as a function of annual precipitation (figure 19) illustrates the relative distribution of storm and non-storm TSS concentrations. Upper Bull Run (station 60) and Cub Run (station 50) have mean annual storm TSS concentrations approximately 40 times the non-storm concentrations. Upper Broad Run (station 70) and Cedar Run (station 20/25) have mean annual storm TSS concentrations, respectively, 14 and 25 times non-storm concentrations. The negative slope on Cub Run's storm regression line suggests that TSS concentrations during wet years are impacted by higher sustained runoff volumes. Studies by Zhang (2000) describe how pollutant concentrations during a certain "critical" stream flow reach a peak, then decline due to exponential "first flush" decay and wet weather stream dilution. In spite of the potential effects of event-based flushing and dilution, higher annual precipitation is shown in the present study to produce generally increasing mean annual TSS fluxes (figure 20), with the apparent exception of Upper Bull Run (station 60).

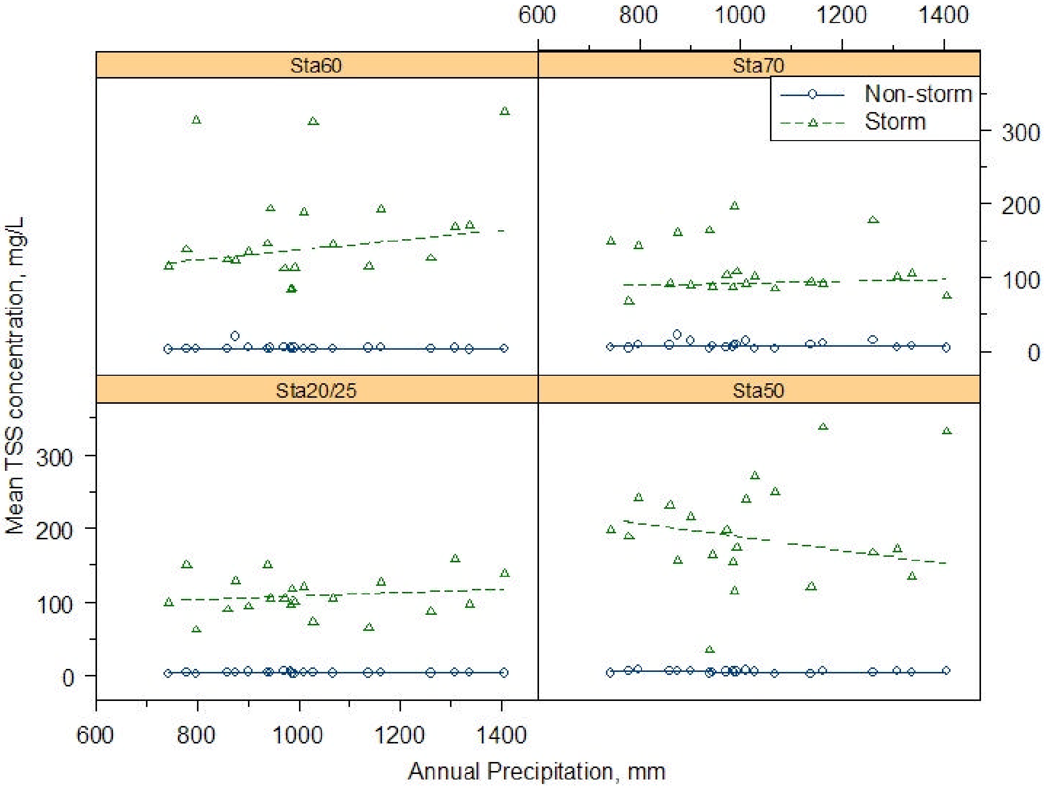


Figure 19. Annual TSS concentration (storm and non-storm) as a function of precipitation, 1981-2002 (Robust MM regression).

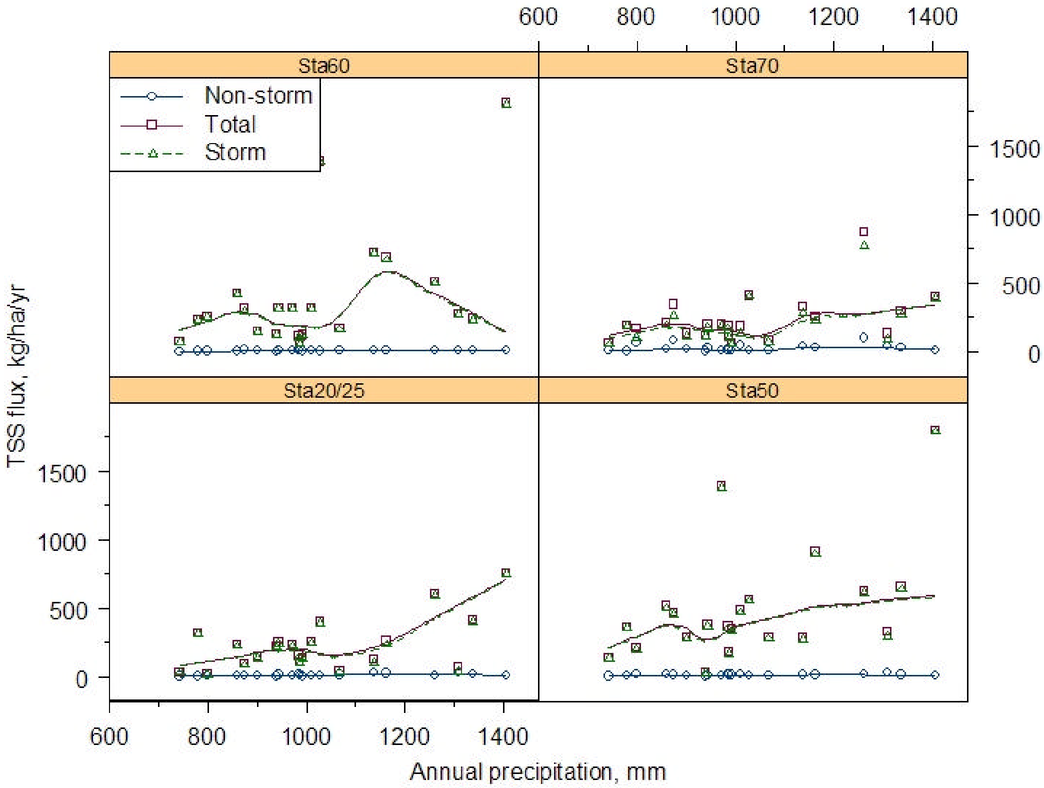


Figure 20. Annual TSS flux (storm, non-storm, and total) as a function of precipitation, 1981-2002 (local Loess regression).

Seasonal data

Seasonal summaries reveal that the majority of TSS flux occurs during winter and spring, seasons which have higher average discharge. The highest variability in annual TSS flux occurs during the summer months June through August (table 14). Upper Broad Run yields 82 percent of annual suspended solids during winter and spring (November through May). All other basins yield between 57 to 68 percent of their annual suspended solids during winter and spring. Cub Run and Upper Bull Run basins have the highest annual TSS flux. Significantly, Cub Run TSS fluxes during the growing season (summer and fall) are approximately double those from Upper Bull Run (figure 21).

Table 14. Mean 21-year total TSS flux (±1SD) from Occoquan headwater basins, kg/ha/time period.

Time period (no. periods)	Cedar Run ($398km^2$)	Cub Run ($127km^2$)	Upper Bull Run ($67km^2$)	Upper Broad Run ($131km^2$)
Annual (21)	230 ± 187	503 ± 416	411 ± 439	235 ± 178
Winter (23)	87.3 ± 93.7	130 ± 128	109 ± 126	89.9 ± 174
Spring (20)	64.2 ± 69.1	161 ± 157	171 ± 191	105 ± 87.5
Summer (21)	37.1 ± 61.7	96.4 ± 123	56.3 ± 121	22.5 ± 25.5
Fall (21)	40.3 ± 43.2	110 ± 176	40.1 ± 43.5	32.2 ± 35.1

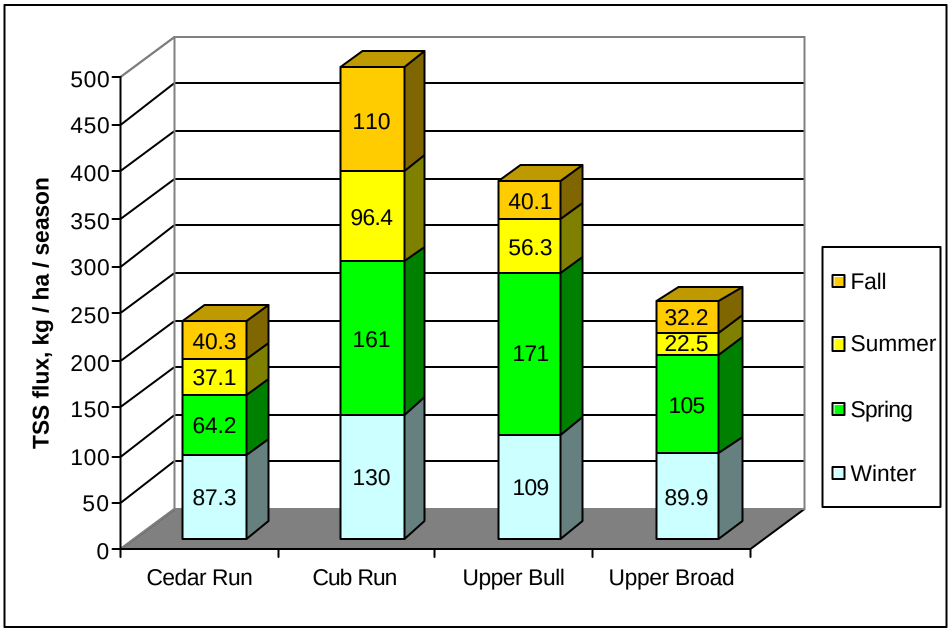


Figure 21. Mean 21-year seasonal TSS flux, kg/ha, Occoquan headwater basins, 1981-2002.

Changes in proportion of dissolved and particulate nutrients with discharge

Annual data

In Cub Run basin, the mean annual particulate/dissolved phosphorus and nitrogen ratios during storm flow are approximately 8.5 times greater than the non-storm flow ratios (table 15). In non-urbanizing basins, corresponding phosphorus and nitrogen storm ratios are on average 5.5 times higher than non-storm ratios. The ratio of annual particulate/dissolved phosphorus concentration during storm flow as a function of precipitation increases in both Upper Bull Run and Cub Run; while Upper Broad and Cedar Run basins have relatively stable annual particulate/dissolved phosphorus concentration ratios (figure 22). Annual nitrogen concentration ratios behave similarly to phosphorus in all basins. Particulate/dissolved ratios for nutrient flux are relatively stable across all basins and precipitation ranges, with the exception of Upper Bull Run, which exhibits increasing annual particulate/dissolved nutrient flux ratios with increasing annual rainfall (figure 23). Annual nitrogen flux ratios as a function of annual precipitation behave similar to phosphorus in all basins.

Table 15. Mean annual particulate/dissolved nutrient concentration ratios, 1979-2002.

	Cedar Run ($398km^2$)	Cub Run ($127km^2$)	Upper Bull Run ($67km^2$)	Upper Broad Run ($131km^2$)
Non-storm flow				
Phosphorus particulate/dissolved ratio	0.279	0.406	0.526	0.952
Nitrogen particulate/dissolved ratio	0.076	0.077	0.120	0.112
Storm flow				
Phosphorus particulate/dissolved ratio	1.64	3.46	3.33	4.02
Nitrogen particulate/dissolved ratio	0.398	0.627	0.709	0.511

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

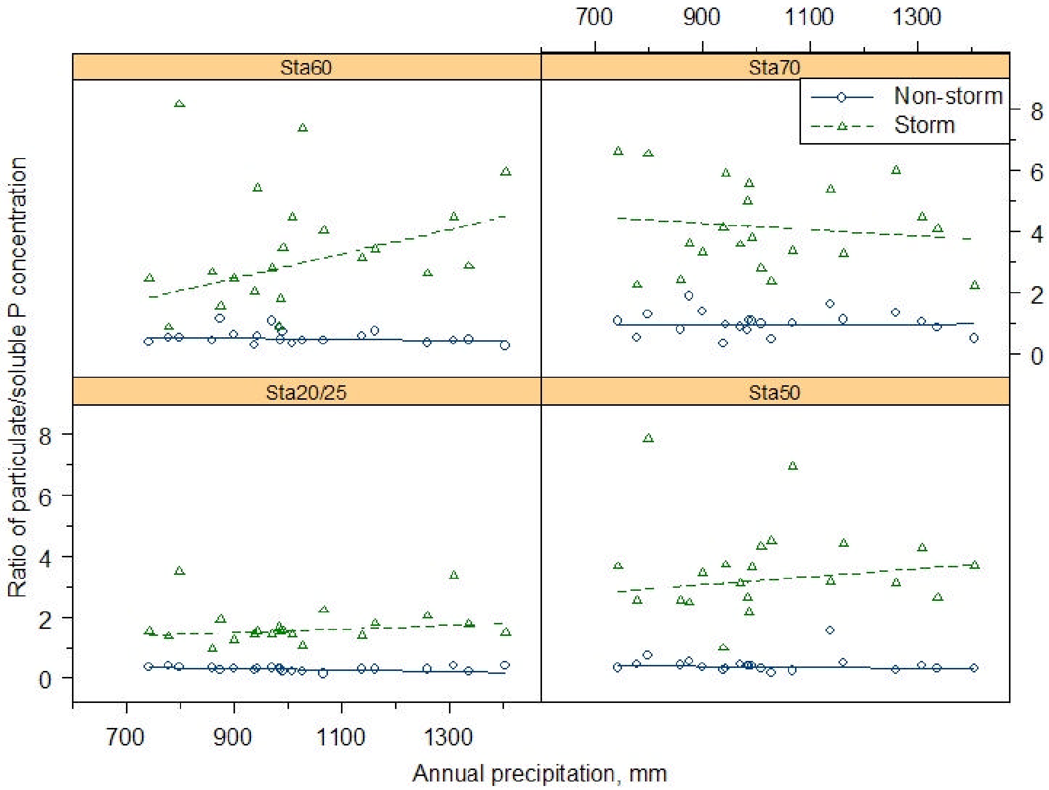


Figure 22. Ratio of mean annual particulate/soluble-P concentration (storm and non-storm) as a function of precipitation, 1981-2002 (robust MM regression).

Annual phosphorus and nitrogen concentrations are summarized as the percent of total storm and non-storm nutrients in the dissolved phase (table 16). In all basins, the percentage of mean annual storm-dissolved phosphorus in the water column is approximately half that of non-storm flows, which means the inverse is true for particulate phosphorus. Mean annual dissolved concentrations of nitrogen make up approximately 64 percent of total nitrogen in storm flows, and approximately 91 percent of total nitrogen in non-storm flows. Cedar Run has the highest overall dissolved nutrient percentages, but also the lowest TSS flux (table 14), suggesting non-erosive losses of nutrients from agricultural drainage and/or leaking septic systems. More detailed seasonal analysis is available in the following section.

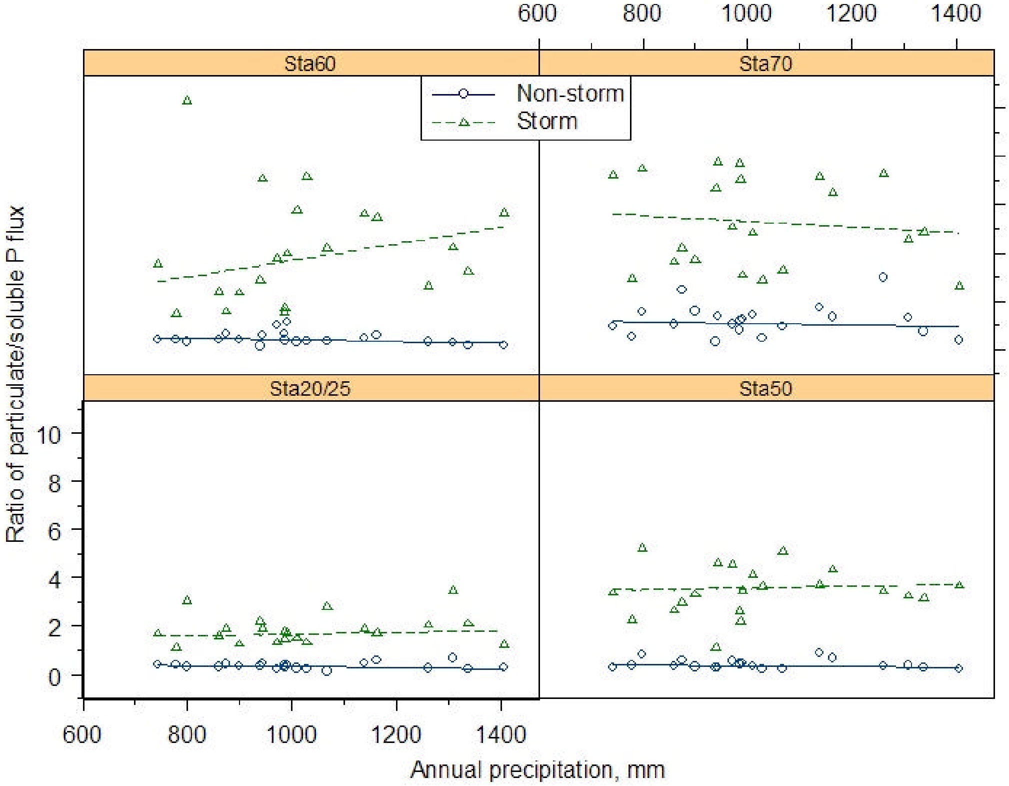


Figure 23. Ratio of mean annual particulate/soluble-P flux, kg/ha (storm and non-storm) as a function of precipitation, 1981-2002 (robust MM regression).

Table 16. Percent of mean annual total phosphorus and nitrogen concentration in dissolved phase during storm and non-storm discharge, Occoquan headwater basins.

Watershed	Phosphorus Storm “R”	Phosphorus Non-storm “B”	Nitrogen Storm “R”	Nitrogen Non-storm “B”
Annual:				
Cedar Run (25)	37.9	77.6	71.5	92.9
Cub Run (50)	22.4	70.8	61.4	92.8
U. Bull Run (60)	23.2	65.5	58.4	89.3
U. Broad Run (70)	19.9	50.6	66.1	89.9

Seasonal data

Seasonal phosphorus and nitrogen concentrations are summarized as percent of total storm and non-storm nutrients in the dissolved phase (table 17). In most basins and seasons, the percentage of seasonal dissolved phosphorus in storm flows is approximately half that of non-storm flows. Mean seasonal dissolved concentrations of nitrogen range from 45 to 78 percent of total nitrogen in storm flows to approximately 82 to 96 percent of total nitrogen in non-storm flows.

Cedar Run has the highest overall dissolved nutrient percentages, except for Cub Run non-storm phosphorus (fall) and Cub Run and Upper Bull Run non-storm nitrogen (spring). Upper Broad Run has the lowest percentage of dissolved phosphorus concentration (storm and non-storm) for most seasons. Therefore, except for Cub Run and Bull Run in the summer, Upper Broad Run has the highest percentage of particulate (storm and non-storm) phosphorus. Cub Run and Upper Bull Run have the lowest percentages of dissolved storm nitrogen concentration for most seasons, which means they have the highest percent of particulate storm nitrogen.

Table 17. Percent of mean seasonal total phosphorus and nitrogen concentration in dissolved phase during storm and non-storm discharge, Occoquan headwater basins.

Watershed	Phosphorus	Phosphorus	Nitrogen	Nitrogen
	Storm “R”	Non-storm “B”	Storm “R”	Non-storm “B”
Winter:				
Cedar Run (25)	45.4	78.9	79.0	95.5
Cub Run (50)	27.0	76.0	70.9	95.0
U. Bull Run (60)	30.4	67.2	71.4	94.1
U. Broad Run (70)	25.9	53.0	77.7	93.2
Spring:				
Cedar Run (25)	36.7	75.9	72.5	91.5
Cub Run (50)	24.0	65.2	64.9	94.2
U. Bull Run (60)	25.6	78.0	62.6	92.5
U. Broad Run (70)	20.1	49.4	64.6	90.6
Summer:				
Cedar Run (25)	39.7	79.9	66.9	92.4
Cub Run (50)	18.0	69.6	53.1	91.7
U. Bull Run (60)	13.0	61.6	49.2	82.7
U. Broad Run (70)	18.4	56.0	61.4	88.7
Fall:				
Cedar Run (25)	39.8	75.6	70.0	90.9
Cub Run (50)	26.6	76.6	60.3	89.3
U. Bull Run (60)	22.8	65.9	45.1	85.7
U. Broad Run (70)	18.5	48.0	62.5	85.9

Discussion

Hydrologic and environmental impacts of urbanization

Results of this study show that the Cub Run basin, unlike its three adjacent headwater neighbors, is being rapidly urbanized. Strong growth trends are documented for the Cub Run basin (station 50), which far outdistances the other three Occoquan headwater basins in both population density and impervious surface growth (figure 24). NPS pollutant fluxes in Cub Run basin began to surpass other headwater basins around 1983, at about the same time that the basin reached a mean imperviousness of 10 percent.

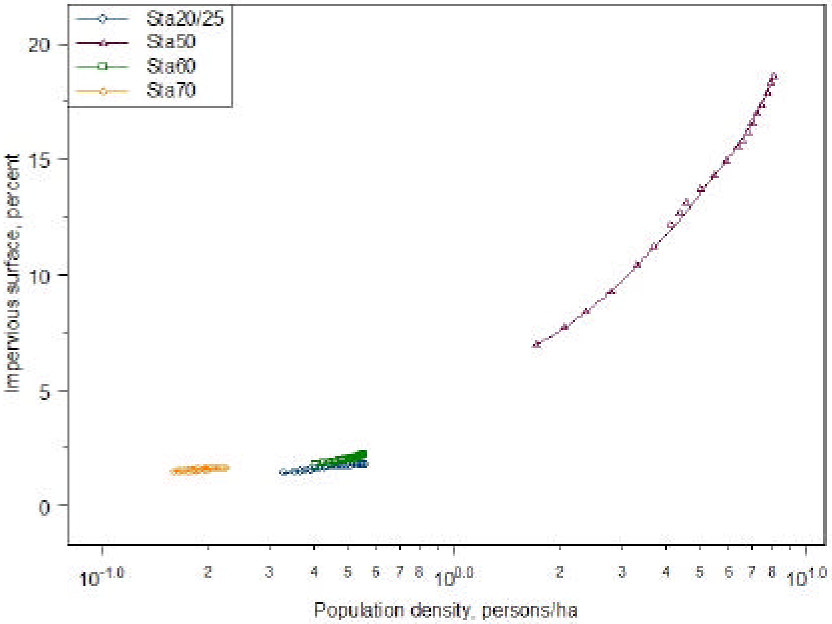


Figure 24. Impervious surface as a function of population density, 1981-2002, Occoquan headwater basins (local Loess regression).

Use of a water balance approach, including the use of three runoff ratios (storm, non-storm, and total), is adopted to quantify the hydrologic impacts of urbanization. Annual mass balance theory supports the assumption that precipitation minus basin discharge (P-RO) is equal to evapotranspiration plus groundwater loss, conveniently called total non-discharge loss in this study. The average area-weighted non-discharge loss for the three non-urbanizing Occoquan headwater basins is 681mm, while average annual non-discharge loss for Cub Run is 641mm (table 18). The water balance approach highlights the fundamental hydrologic impact of urbanization reported in this research, increased discharge volumes. Comparative results show that increased discharges from urbanizing basins such as Cub Run result mainly from storm runoff. In addition, discharges in the study basins were most responsive to increased rainfall and urbanization during winter and spring seasons, likely due to reduced natural ground cover and evapotranspiration.

Table 18. Comparison of average annual hydrologic balance for Occoquan headwater basins and other small watershed sites, mm/yr.

	Cedar Run Sta25	Cub Run Sta50	Upper Bull Run Sta60	Upper Broad Run Sta70	Rhode River, MD	Fernow, WV (WS4)	Little River, GA	Coweeta, NC (WS2)
Data period, years	21	21	21	21	25	40	11	37
Non-storm discharge	189	190	185	229	na	na	na	na
Storm discharge	152	192	159	115	na	na	na	na
Total discharge	341	382	344	344	332	640	379	854
Precipitation	1023	1023	1023	1023	1139	1458	1258	1772
Total runoff ratio	0.33	0.37	0.34	0.34	0.29	0.44	0.30	0.48
P-RO*	682	641	679	679	807	818	879	918

Table adapted from Correll et al. (1999b).

Discharge and precipitation means for Occoquan stations calculated using 21 years of data (1979, 1980, 1982 excluded).

*P-RO, precipitation minus total discharge (runoff), is equal to total non-discharge losses (evapotranspiration plus deep percolation).

Basin estimates of non-discharge loss (P-RO) are somewhat lower than those reported for other watersheds in the eastern United States having long-term records (table 18). Coweeta and Fernow watersheds are primarily forested, with higher rainfall, which helps explain differences between them and the Occoquan headwater basins. Lower P-RO losses are the result of reduced evapotranspiration and/or lower groundwater losses, both of which may be occurring in the urbanizing Cub Run basin. However, below-average P-RO values in the four Occoquan headwater basins are likely the result of lower-than-average rainfall totals in the study area, rather than high groundwater losses, since average annual runoff ratios are comparable to other reported eastern watersheds. Therefore, P-RO is considered a reasonable estimate of basin evapotranspiration in the four Occoquan study basins; and groundwater losses are assumed to be insignificant.

Twenty-one year annual average fluxes (kg/ha) of total suspended solids, phosphorus, and nitrogen were partitioned into storm/non-storm and particulate/dissolve fractions. Annual nonpoint source pollution flux in the headwater basins of the Occoquan were found to generally track precipitation, which was expected. Of more direct interest to this research, Cub Run basin was found to have the highest annual TSS flux of all headwater basins starting from about 1983, when rapid population growth and land development began (figure 25). Total phosphorus flux for Cub Run and the other headwater basins over the 21-year study period mirrored TSS flux to a large degree. Cub Run basin subsequently became the largest unit-area phosphorus contributor around 1986, and the largest unit-area nitrogen contributor in 1990 (figure 26), about the time of the second documented growth surge in the Fairfax and Loudoun County portions of Cub Run basin.

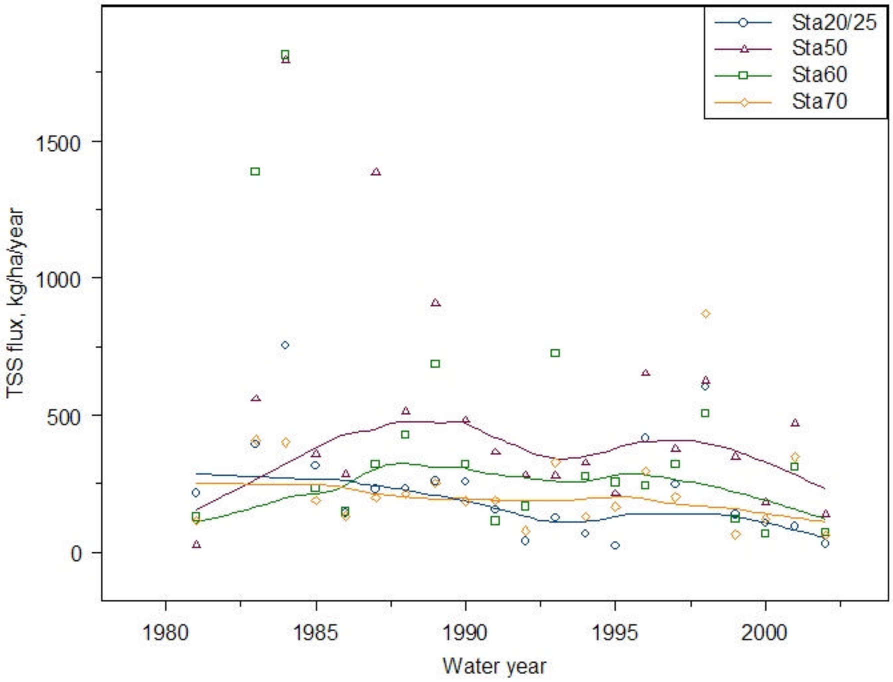


Figure 25. Mean annual TSS flux, Occoquan study basins (local Loess regression).

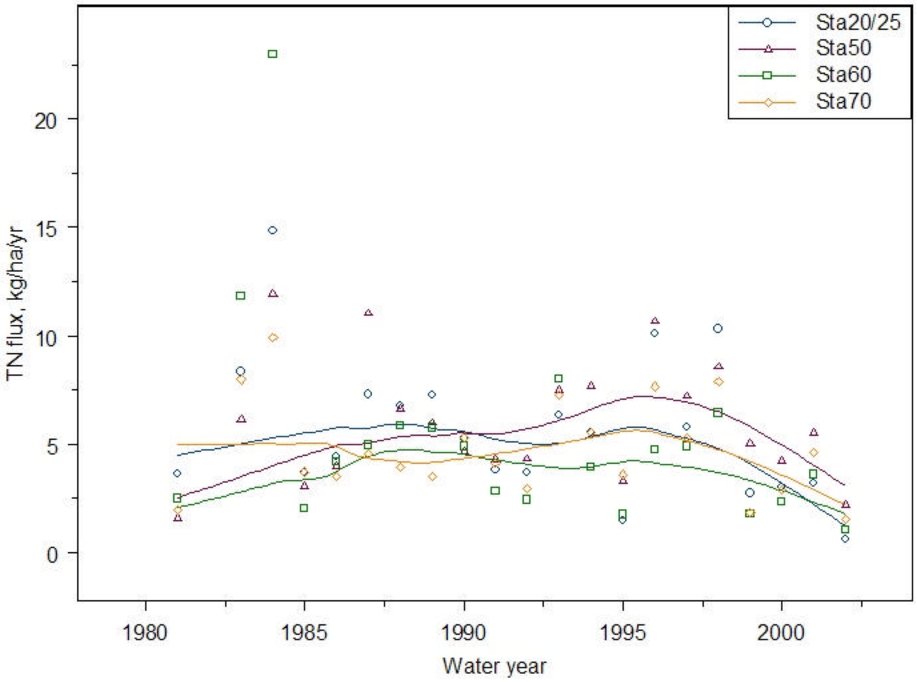


Figure 26. Mean annual TN flux, Occoquan study basins (local Loess regression).

Recommendations for further research

Hydrologic studies

- Seasonal analysis of Cub Run storm discharge volumes and runoff ratios across the entire 30-year period of common record (1972-2002) is recommended. The objective is to quantify the hydrologic impacts of urbanization as a function of seasonal precipitation and landscape in order to identify thresholds for hydrologic change within an urbanizing basin.
- Long-term (30-year) trend analysis of annual Cub Run water balance components, especially storm runoff ratio and non-storm loss (P-RO) is recommended. The objective is to quantify hydrologic impacts of urbanization across time.

NPS pollution studies

- Regression analysis of Cub Run data is recommended to quantify fundamental relationships between NPS pollutant flux and precipitation, represented by ±2SD of the 51-year annual and seasonal means. Two standard deviations from the 51-year annual precipitation mean are used in this report to identify extremely dry and wet years. The objective is to identify thresholds for change in NPS pollutant flux within an urbanizing basin.
- Trend analysis of Cub Run NPS (storm) pollutant fluxes, excluding the 5-year period of excessive land disturbance between 1985 and 1990, is recommended. Seasonal Kendall trend analysis, a nonparametric technique that is robust regarding missing data, is well-suited for this type of analysis. The objective is to quantify long-term impacts of urbanization on NPS pollutant flux.

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