# 5. Empirical Modeling of Hydrologic and NPS Pollutant Flux in an Urbanizing Basin*

Summary: This paper models the long-term effects of precipitation and land use/land cover (LULC) on basin discharge and nonpoint source (NPS) pollutant flux from a rapidly developing watershed on the urban fringe of Washington, DC. Data consist of 24 years of observed rainfall, discharge, water chemistry, and LULC from four headwater basins of the Occoquan River in northern Virginia. Basin outlets are monitored for storm and nonstorm flows and concentrations of total suspended solids (TSS) and soluble and particulate nitrogen and phosphorus.

Empirical models quantify the annual and seasonal response of basin discharge and NPS pollutant flux to precipitation, mean impervious surface (IS), and land use. Annual change in mean impervious surface (delta IS) is used as a temporal indicator of urban soil disturbance. Hydrologic models indicate that total annual surface discharge is significantly associated with precipitation and mean IS ($r^2$=0.65), which supports literature associating higher surface discharge with mean IS above 10 percent. Seasonal hydrologic models reveal that basin discharge is positively associated with mean IS only during the growing season (summer and fall) when non-vegetated impervious surface areas most impact the biophysical response to precipitation.

NPS pollutant models indicate that total and storm TSS flux are significantly associated with precipitation and urban soil disturbance in all seasons. Annual NPS total nitrogen flux is significantly associated with both urban and agricultural soil disturbance ($r^2$=0.51). Similar to hydrologic models, seasonal models of total phosphorus flux indicate a significant association of total phosphorus flux with urban soil disturbance, but only during the summer and fall growing season. The significant, positive association of annual storm soluble phosphorus with cumulative mean IS ($r^2$=0.34) suggests that current strategies for stormwater soluble phosphorus reduction in Cub Run may be inadequate. Unvalidated models from this study demonstrate that there is much to be learned in understanding the processes associated with NPS pollutant flux in urbanizing basins.

KEYWORDS: urbanization, impervious surface, LULC, NPS, runoff, regression model

*To be submitted to the Journal of the American Water Resources Association.

## 5.1. Introduction

Urbanization is the conversion of rural land to uses that support higher population and building densities. Urban land typically has less vegetated surface and more impervious surface than rural land. A number of authors (Wheater et al., 1982; Laenen, 1983; Booth and Reinelt, 1993; Schueler, 1994a; and Arnold and Gibbons, 1996) have quantified the hydrologic effects of urbanization such as shorter times of concentration, higher peak flows, larger storm volumes, and potentially lower baseflow volumes. As early as 1968, Brater and Sangal reported the effects of urbanization on peak flows. In 1974, Stankowski developed flood frequencies using indices of manmade impervious cover. The American Society of Civil Engineers (ASCE, 1998) noted that reduced infiltration in urban catchments should theoretically reduce groundwater recharge and dry weather stream flows. However, studies demonstrating lower baseflow volumes, such as the data reported by Simmons and Reynolds (1982), are rare.

Researchers including Omernik (1976), Jordan et al. (1986), Haith and Shoemaker (1987), Osborne and Wiley (1988), Kronvang (1992), and Correll et al. (1999b) have documented the impact of storm events and land use practices on sediment and nutrient fluxes. Although several national studies have modeled nonpoint source (NPS) pollution from urban (U.S.EPA, 1983; Driver and Tasker, 1988; Driscoll et al., 1989) and rural (Clark et al., 2000) sources, research in diffuse pollution that includes both urban and rural sources has been on the fringe of environmental engineering research (Novotny, 1999). 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; Longabucco and Rafferty, 1998). However, few studies have had the long-term precipitation, pollutant discharge, and historic landscape data necessary to analyze basin discharge and pollutant flux as a function of precipitation and land use/land cover (LULC). This paper recognizes that a mosaic of representative LULC descriptors can improve our ability to understand watershed responses to well-known influential factors such as precipitation and impervious surface (IS).

Several authors have argued that IS coverage in a watershed is a good indicator of potential impact on stream health (Randolph, 2004). According to Schueler (1992), changes in urban stream water quality can occur in two phases; 1) an initial construction phase of high sediment loading, and 2) a stabilized period of stream-bank erosion and accumulated washoff. In an urbanizing basin, mean imperviousness is always increasing, but the rate of increase may vary from year to year. During years of increased construction activity, large loading events are more likely to occur due to increased soil disturbance. Theoretically, increased rates of construction and urban soil disturbance are followed by large annual changes in imperviousness. According to Schueler (1994a), adverse water quality effects above the 10 percent mean imperviousness threshold, regardless of rate of development, appear as reduced stream habitat, loss of biodiversity, and increased pollutant loads that end up in receiving water bodies. The four headwater basins in this study drain into the Occoquan reservoir, an environmentally-sensitive water supply and recreational resource for more than one million people in northern Virginia, one of the most rapidly growing metropolitan areas in the United States.

## Objectives of Study

This study develops regression models of long-term hydrologic and NPS pollution flux with the objective to identify significant annual and seasonal relationships between predictor variables (rainfall and LULC) and response variables (basin discharge and NPS suspended solids, phosphorus, and nitrogen flux). The goal of the study is to identify physical processes that affect diffuse pollutant delivery across the four Occoquan headwater basins, with a focus on urbanization. Unvalidated empirical equations are presented as limited descriptors of long-term hydrologic and NPS pollutant flux in the four study basins.

## Study Area Description

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 $km^2$ Occoquan River watershed, located in northern Virginia on the urban fringe of metropolitan Washington, DC (Figure 5-1). The three western basins, ranging in size from 67 to 400 $km^2$, are predominantly forest and mixed agriculture. The fourth basin, the 127 $km^2$ Cub Run watershed, is rapidly urbanizing, with 50 percent of current land use classed as urban (18 percent mean IS). A summary of the physical characteristics for each basin (Table 5-1) 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 5-1). Due to state-mandated wastewater export from Cub Run basin in the 1970s, none of the study basins has significant point source pollutant contributions during the 24-year period that includes water years 1979 through 2002.

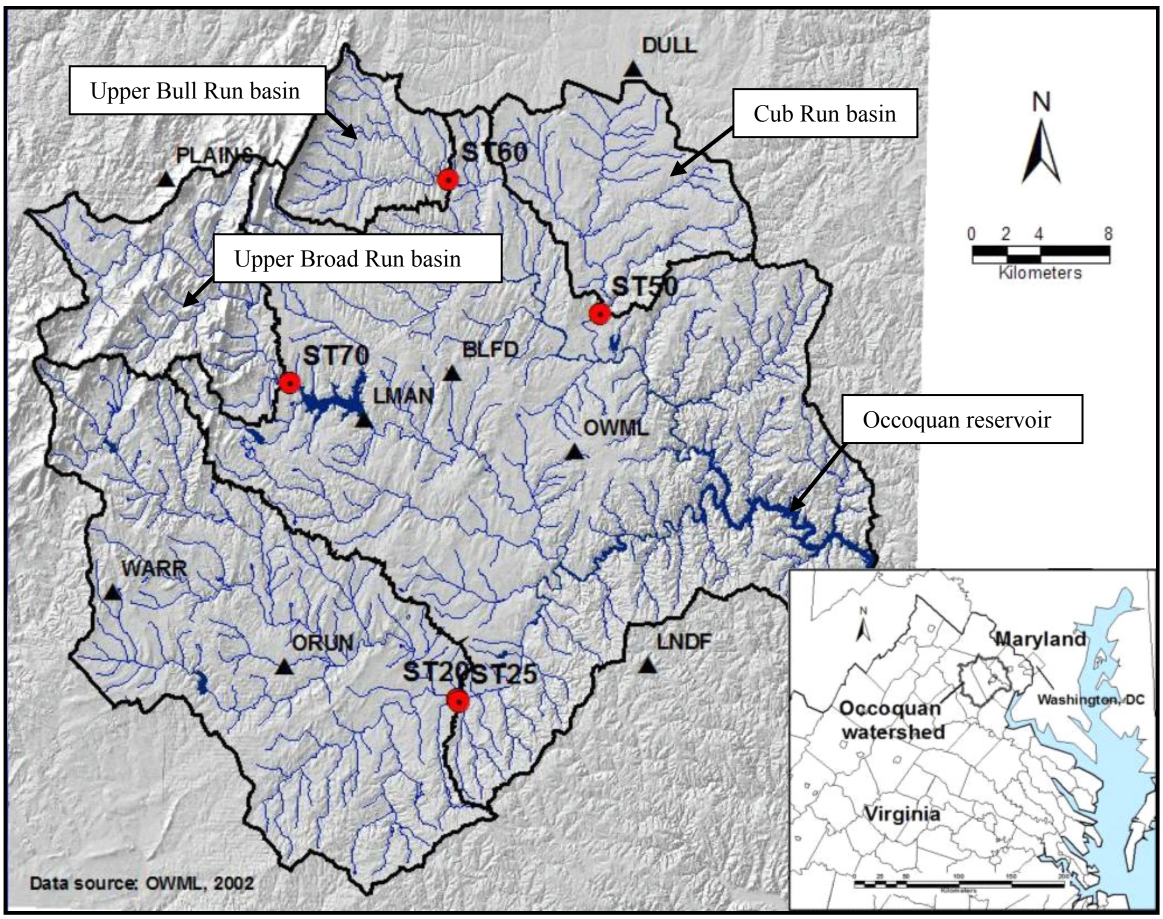


**Figure 5-1.** Occoquan River watershed study area, northern Virginia, USA.

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

**Table 5-1.** 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, sq. km | 398.2 | 127.2 | 66.9 | 130.9 |
| Ave. slope, % | 5.3 | 3.4 | 6.9 | 10.3 |
| Average elevation, m<br>(range) | 114<br>(53-416) | 94<br>(48-154) | 132<br>(75-387) | 194<br>(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).

Land use summaries from 1980, 1990, and 2000 document changing land use in the four Occoquan headwater basins, confirming that Cub Run basin is undergoing quantifiable transformation into an urban landscape (Table 5-2, Figure Q-4). Cub Run basin surpassed 10 percent mean imperviousness in the mid-1980s, outdistancing the other three basins by nearly an order of magnitude (Table 5-3). Randall and Grizzard (1995) reported that most of the increase in new development in the Occoquan watershed occurred after 1984, when a moratorium on building in Fairfax County was lifted. Sources of map-derived land use and satellite-derived IS data are described by Dougherty et al. (in press).

**Table 5-2.** 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 5-3.** 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: GIS analysis of Northern Virginia Regional Commission (NVRC) land use data, calibrated with county-wide planimetric data and Landsat-derived impervious surface estimates.
[1] Linearly interpolated from 1980 and 1990 impervious surface values.
[2] Interpolated proportionately from 1980 and 1990 impervious surface values using annual building numbers from Fairfax and Loudoun County.

## *5.2. Methods*

The following section describes methods of collecting LULC, hydrologic, and NPS pollutant data, as well as the procedures used to develop empirical models and limitations of the data.

### Data Collection

Land use data synthesized at a yearly scale is one of the distinct aspects of this study. Agriculture is a significant land use in the Occoquan watershed (Table 5-2), and is important to this study because of its known association with diffuse pollution (Novotny and Chesters, 1981). Historic land use data provided by the Northern Virginia Regional Commission (NVRC) (Figure Q-2, Figure R-1) is used to develop three agricultural land use classes; conventional tillage, minimum tillage, and livestock/pasture. Conventional tillage agriculture represents row-cropped grains such as corn. Minimum tillage agriculture is a reduced tillage practice that leaves a portion of vegetated residue on the soil surface. Livestock/pasture land represents planted or native legume stands or grasslands that are grazed by livestock and/or cut for hay. County-wide agricultural production data from the National Agriculture Statistics Service (NASS) (U.S. Census of Agriculture, 2002) for 1978, 1982, 1987, 1992, and 1997 are used to annualize NVRC agricultural land use estimates between the years 1980, 1990, 1995, and 2000 (Figure Q-3). Post-2000 agricultural land use estimates are extrapolated using previous 3-5 year trends for each basin.

Complete methods of agricultural land use estimation are described in Appendix R. The following limitations detail the level of uncertainty in the agricultural land use estimates used for regression modeling. The most important limitation is one described by Openshaw (1984) as the ecological fallacy problem, which occurs when a result is applied to individuals who form the zones or groups being studied. In the present study, because county-wide agricultural statistics from NASS are used to characterize land use within specific watersheds (Figure R-3), an inherent assumption is that the distribution of farmland characteristics is homogeneous across the county. However, it is well known that farm management decisions can vary systematically and regionally on a year-to-year and farm-to-farm basis due to market price environment, changing federal farm price subsidies, and changing practices over time. Actual land use cannot be readily verified in the field, and not without high cost. Historic land use is usually more difficult to obtain and often impossible to verify. Therefore, it is quite possible that historic annualized estimates used in this study differ from actual agricultural land use, especially during periods between NVRC mapping (Figure Q-2).

Annualized estimates of IS developed previously (Chapter 3) from historic building polygons (Appendix A) are used to create a new variable called delta IS, which represents the annual change in mean IS for each basin. Delta IS is used in this study as a temporal indicator of urban soil disturbance distinct from agricultural soil disturbance. All land use variables, including delta IS, are expressed as a percentage of the watershed's total area.

*Hydrologic and Stream Sampling Data*

Daily precipitation data provided by OWML staff from eight local rain gages (Figure 5-1) are used to synthesize long-term rainfall estimates for the four study basins. Average daily stream discharge data from OWML records are tabulated from quarter-hour readings taken from stream-gaging equipment at all four monitoring stations. Streams are monitored throughout the study period for characterization of storm and nonstorm flows. Methods of hydrologic data collection and resulting annual/seasonal precipitation and discharge summaries are described in Appendix B through H.

Stream samples are analyzed by OWML personnel for direct and indirect determination of total suspended solids (TSS), total nutrients (TP and TN), total soluble nutrients (TSP and TSN), and particulate nutrients (PartP and PartN) at known stream discharge rates. During nonstorm flow, basin outlets are monitored with weekly or biweekly grab samples and continuous daily discharge records. During storm discharge events, stream volume and composite samples are taken automatically with flow-proportional, volume-integrating storm samplers. Data collection methods and resulting annual and seasonal NPS pollutant summaries are described in Appendix I, J, K, M, and N.

*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, and eleven seasonal intervals (Table L-1) are excluded from seasonal analysis.

## Stepwise Regression

Multivariate linear regression models are fit to annual and seasonal hydrologic and NPS pollutant flux summaries using forward stepwise procedures to find a parsimonious subset of explanatory variables (Insightful Corp., 2001). The selection procedure begins with a base model that includes precipitation and an IS term, terms that are assumed to be central to any model considered. An exhaustive forward selection procedure considers all additive subsets beyond the base model, adding at each step the independent variable that gives the largest reduction of residual sum of squares (Neter et al., 1996, pp. 348-353), resulting in the largest increase in coefficient of determination, $r^2$. Linear regression assumptions are evaluated using graphical diagnostic procedures, with evaluation of model coefficients based on scientific and statistical relevance. The uncertainty of annualized agricultural and land use estimates in this study is recognized and discussed in appropriate sections. Although soil type, slope, and area vary across the four study basins, preliminary investigation finds these variables are not significant as explantory model terms, likely due to the small number of basins modeled.

Since the goal of this study is to describe collective relationships for each hydrologic and NPS pollutant flux response, a statistical test is needed to confirm that a single model fitted across all basins is better than four basin-specific models. A comparative F-test of individual regression coefficients (Montgomery and Peck, 1992, pp. 138-143) uses a null hypothesis that the single model of an observed response provides a better fit than four basin-specific models. Although basin-specific models contain information regarding processes within specific basins, only single models (those with a comparative p-value > 0.05) are included in this study. Subsequent statistical tests of single models for auto-correlation identify some undesirable serial correlation in hydrologic response variables, which is reported. Significant serial correlation between adjacent years, when present, indicates that the underlying assumption of independence in the response variable (from year to year and season to season) is compromised.

Although cause-and-effect relationships can not be derived from this strictly observational study, the use of unvalidated empirical models to estimate future hydrologic and NPS pollutant fluxes in the Occoquan headwater basins is discussed. Regression models explaining less than one-third of the variability in the response ($r^2<0.33$) are presented but not discussed in detail, since factors other than those used in this paper are contributing to hydrologic and NPS pollutant flux response.

*Hydrologic Models*

Annual and seasonal stepwise regression models are developed for six hydrologic responses including unit flow and runoff ratio, partitioned into total, storm, and nonstorm components. All hydrologic response models are tested using the following predictors; precipitation depth, mm (P), percent impervious surface (IS), percent minimum tillage (MinTill), percent conventional tillage (ConvTill), percent livestock/pasture (Pasture), percent total agriculture (TotalAg), percent urban (Urban), and percent forest (Forest). No interaction terms are included, since preliminary testing of this model did not support their inclusion. For the six hydrologic responses, the base model has the form

$$\text{Hydrologic response} = P + IS. \qquad \text{(eqn. 1)}$$

Only one of the hydrologic response models (storm runoff ratio) rejected the null hypothesis for a single model (p-value < 0.05) in favor of separate models for each basin, and is not discussed further in this paper.

*NPS Pollutant Flux Models*

Annual and seasonal stepwise regression models are developed for 21 NPS pollutant fluxes, including TSS and total, soluble, and particulate nutrient fractions, each partitioned into a total, storm, and nonstorm response. Predictors for all NPS pollutant flux responses are the same as hydrologic models, with the addition of delta impervious surface, percent (delta IS) and National Atmospheric Deposition Program wetfall inorganic N flux, kg $ha^{-1}$ (NADPN) (Appendix N). Similar to hydrologic response models, no interaction terms are included. NPS pollutant responses are evaluated using two base models representing two different hypotheses:

NPS pollutant flux response = P + IS (eqn. 2)

NPS pollutant flux response = P + delta IS (eqn. 3)

The first form of the model (equation 2) asks the question, "Is NPS pollutant flux significantly associated with mean annual IS across the four study basins?" The second form of the model (equation 3) asks a different environmental question, namely, "Is NPS pollutant flux significantly associated with annual change in mean IS (i.e., urban land disturbance) across the four study basins?" All *nonstorm* regression models rejected the null hypothesis for a single model (p-value < 0.05) in favor of separate models for each basin, and are not discussed further in this paper.

## 5.3. Results

This section describes estimated LULC data developed for this study, as well as significant hydrologic and NPS pollutant flux predictors identified by regression modeling.

### LULC Data

Annualized estimates of agricultural land use and basin IS are graphed as a function of year (Figure 5-2). Irregularities in agricultural land use estimates may be a result of the gross generalizations used to interpolate between dates of available mapping. Nevertheless, certain differences in LULC among the four basins are apparent, with relatively higher percentages of pasture land in Cedar Run and Upper Broad Run basins, and a decreasing agricultural presence in Cub Run basin. Upper Bull Run basin has generally stable agriculture; and Cedar Run is the only basin with an increasing percentage of minimum tillage. Mean IS percent in Cub Run basin increases notably during the mid-1980s, with the highest delta IS value (1.1 percent $yr^{-1}$) occurring in 1985. 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. Time series of historic land use mapping (Figure Q-4) and impervious surface imagery (Figure A-5) document the growth in Cub Run basin.

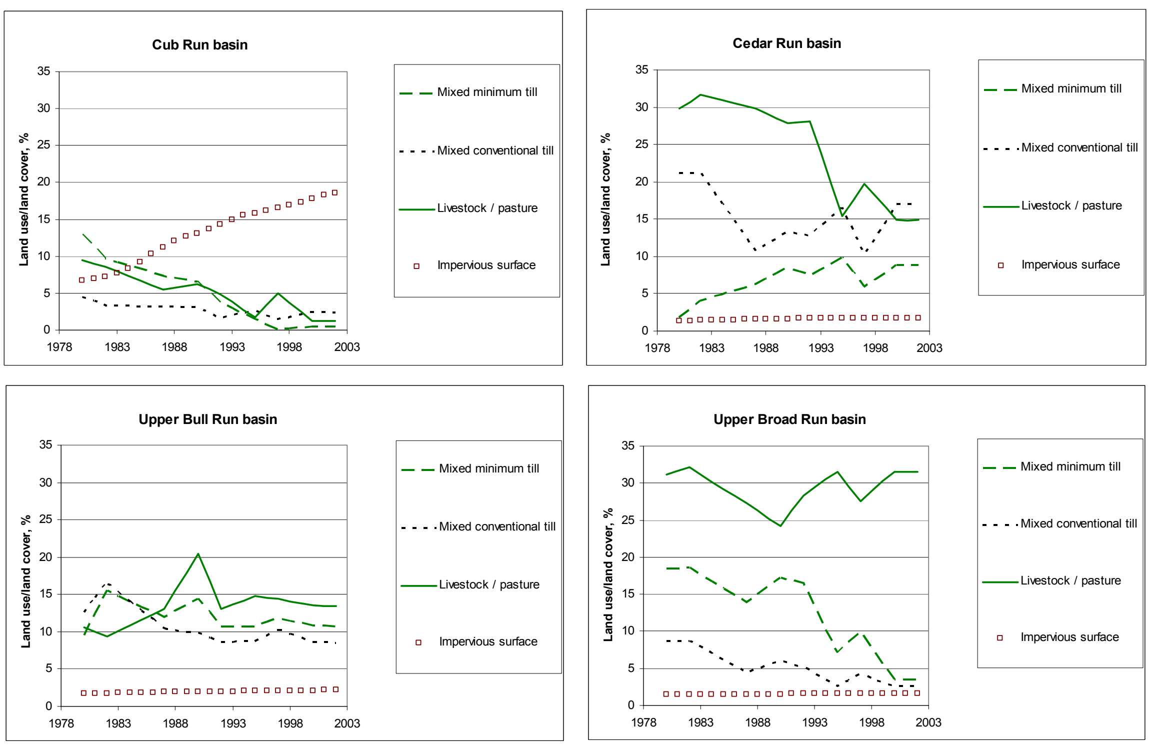


**Figure 5-2.** Impervious surface and agricultural land use, percent of total basin land area, Occoquan headwater basins, 1980 to 2002.

(Source: NVRC land use mapping; U.S. Census of Agriculture; Mid-Atlantic RESAC impervious surface estimates; and Fairfax and Loudoun County building data).

## Hydrologic Response

Annual hydrologic models (equation 1) reveal that both basin discharge and runoff ratio are significantly associated with precipitation and LULC (Table 5-4). Tests for serial correlation identify significant auto correlation (rho, ρ=0.42 to 0.53) in annual nonstorm flow responses. Annual hydrologic models confirm precipitation and IS as significant predictors of total discharge ($r^2$=0.65), storm discharge ($r^2$=0.37), and total runoff ratio ($r^2$=0.30). Seasonal models reveal that unit discharge is significantly associated with mean IS mainly during the growing season, and that spring discharges are a function only of precipitation (Table 5-5). The coefficient of determination for seasonal hydrologic models is higher in spring and winter ($r^2$=0.71 and 0.70, respectively) than in summer and fall ($r^2$=0.62 and 0.54, respectively), indicating a more direct surface discharge response during the dormant season (Tables P-3 through P-6).

**Table 5-4.** Annual hydrologic regression models.

| Dependent variable | $r^2$ | Intercept | Precip (mm) | Impervious surface (%) | Conventional tillage (%) |
|---|---|---|---|---|---|
| Unit flow, total (mm) | 0.65 | -365** | 0.673** | 4.27* | -- |
| Unit flow, storm (mm) | 0.37 | -225** | 0.349** | 3.57† | -- |
| Unit flow, nonstorm (mm)[1] | 0.46 | -83.2† | 0.327** | -2.47 | -5.71** |
| Runoff ratio, total | 0.30 | -8.40E-03 | 3.00E-04** | 4.20E-03* | -- |
| Runoff ratio, nonstorm[2] | 0.21 | 1.09E-01* | 1.00E-04** | -2.60E-03 | -5.90E-03** |

Note: The form of the base model for forward stepwise regression is annual hydrologic response = P + IS.
Example: Unit flow, total (mm) = -365 + 0.673 (*Precip*) + 4.27 (*Impervious surface*).
[1] Significant serial correlation observed in the dependent response variable (p=0.00); ρ=0.42.
[2] Significant serial correlation observed in the dependent response variable (p=0.00); ρ=0.53.
Symbol indicates P-value for the test that the coefficient = 0 (** = p < 0.01; * = p < 0.05; † = p < 0.10; none = p > 0.10).

**Table 5-5.** Annual and seasonal flow responses significantly associated with precipitation, impervious surface, and/or conventional tillage, p<0.05.

| Predictor | Summer | Fall | Winter | Spring | Annual |
|---|---|---|---|---|---|
| Precipitation, mm | T, S, N[1] | T, S, N | T, S, N | T, S, N | T, S, N |
| Impervious Surface, % | T, S | T, S | S | -- | T |
| Conventional Tillage, % | (N) | (N) | -- | -- | (N) |

Model: Unit flow response = P + IS + MinTill + ConvTill + Pasture + TotalAg + Urban + Forest.
[1]T=total flow, S=storm flow, and N=nonstorm flow.
Flow response variables in parentheses have a negative association with the predictor variable.

The annual unit nonstorm discharge model has a highly significant, negative conventional tillage term (Table 5-4) suggesting that increased nonstorm streamflow is associated with higher annual precipitation and lower conventional tillage percent. Impervious surface is not a significant term in either the nonstorm discharge or the nonstorm runoff ratio model. Corresponding seasonal models reveal nonstorm discharge during the summer and fall growing season is associated with increased precipitation and decreased conventional tillage, while spring and winter nonstorm discharges are a function only of precipitation (Table 5-5).

### NPS Pollutant Flux Response

Regressions of annual NPS pollutant flux using the IS base model (equation 2) reveal a consistent, highly significant precipitation effect, as expected. Only six single models of annual NPS pollutant flux are found to be better than basin-specific models (Table 5-6). Regression models indicate that increased storm PartP, storm TP, and total and storm PartN are associated with a decrease in pasture land. Storm PartN is associated with a significant IS term, also negative. Storm TSP flux is the only remaining IS model that is positively associated with conventional tillage and IS, and is the only model explaining more than one-third of the variability in the response. Forest and NADPN are not significant predictors in any model, as they show little variability between basins.

**Table 5-6.** Annual NPS pollutant flux impervious surface (IS) regression models.

| Dependent variable (kg $ha^{-1}$ $yr^{-1}$) | $r^2$ | Intercept | Precip (mm) | Impervious Surface (%) | Conventional Tillage (%) | Pasture (%), Urban (%) |
|---|---|---|---|---|---|---|
| PartP flux, storm | 0.32 | -0.298 | 9.00E-04** | -1.15E-02 | -- | -1.03E-02†<br>-- |
| PartN flux, total | 0.29 | -1.121 | 3.50E-03** | -5.30E-02 | -- | -4.68E-02*<br>-- |
| PartN flux, storm | 0.28 | -0.896 | 3.30E-03** | -6.32E-02† | -- | -5.39E-02**<br>-- |
| TSP flux, storm | 0.34 | -0.209** | 2.00E-04** | 1.52E-02† | 8.20E-03** | --<br>-4.10E-03 |
| TP flux, total | 0.30 | -0.723** | 1.20E-03** | 2.90E-03 | -- | --<br>-- |
| TP flux, storm | 0.30 | -0.054 | 1.20E-03** | 4.85E-02 | -- | -2.27E-02*<br>-2.89E-02 |

Note: The form of the base model is annual NPS pollutant flux response, kg $ha^{-1}$ $yr^{-1}$ = P + IS.
Example: PartP flux, storm (kg/ha/yr) = -0.298 + 9.00E-04 (Precip) - 1.15E-02 (Impervious surface) - 1.03E-02 (Pasture).
Symbol indicates P-value for the test that the coefficient = 0 (** = $p < 0.01$; * = $p < 0.05$; † = $p < 0.10$; none = $p > 0.10$).

#### *Delta IS models*

Stepwise regression of annual NPS pollutant flux using the delta IS base model (equation 3) shows that precipitation is a significant driver of all NPS pollutant models (Table 5-7). Eight of the 13 delta IS models, including total TSS, total and storm PartP, total and storm TSP, total TSN, and total and storm TN are positively associated with both delta IS and cultivated agriculture (conventional and/or minimum tillage). Half of the delta IS models have $r^2$ values above 0.33, and several of these models (total TSP, total TSN, and total TN) have $r^2$ values greater than or equal to 0.50. The storm PartN flux model is excluded as a result of comparison testing with basin-specific models.

Seasonal analysis of TSS and TSP flux reveals a significant delta IS term in all seasons (Table 5-8). Storm TSN flux is significantly associated with delta IS in all seasons except spring. Seasonal models of total and storm particulate N flux reveal significant delta IS terms only in summer and winter. Total and storm PartP and TP flux are significantly associated with delta IS only in the summer and fall growing season (Table 5-8). In the winter, precipitation is the only significant predictor of PartP and TP flux; but during spring, all soluble and total nutrient fractions are dominated by precipitation (Table 5-10). On an annual basis, TP is the only NPS pollutant flux associated solely with precipitation (Table 5-7).

During all seasons, TSP flux is positively associated with both delta IS and agricultural tillage (Table 5-8 and Table 5-9). Storm TN flux is significantly associated with delta IS during the summer, winter, and fall (Table 5-8); but in the spring, storm TN flux is driven only by precipitation (Table 5-10). In the summer, storm TN flux is positively associated with delta IS and conventional tillage. In the winter, total and storm TN flux is positively associated with delta IS (Table 5-8), agricultural tillage (Table 5-9), and pasture. Results for all seasonal delta IS models are presented in Tables P-7 to P-10.

**Table 5-7.** Annual NPS pollutant flux delta impervious surface (delta IS) regression models.

| Dependent Variable | $r^2$ | Intercept | Precip (mm) | delta IS (%) | ConvTill (%), MinTill (%) | Pasture (%), Urban (%) |
|---|---|---|---|---|---|---|
| TSS flux, total | 0.32 | -649** | 0.769** | 550** | -- | -- |
| | | | | | 12.6† | -- |
| TSS flux, storm | 0.35 | -201 | 0.772** | 522** | -- | -14.5* |
| | | | | | 5.92 | -8.77 |
| PartP flux, total | 0.28 | -0.719** | 9.00E-04** | 2.89E-01† | -- | -- |
| | | | | | 1.42E-02† | -- |
| PartP flux, storm | 0.28 | -0.726** | 9.00E-04** | 3.13E-01* | -- | -- |
| | | | | | 1.53E-02† | -- |
| PartN flux, total | 0.30 | -0.706 | 3.50E-03** | 6.27E-01 | -- | -6.00E-02* |
| | | | | | -- | -3.54E-02† |
| TSP flux, total | 0.50 | -0.304** | 3.00E-04** | 2.00E-01** | 9.90E-03** | 3.10E-03* |
| | | | | | -4.30E-03† | -- |
| TSP flux, storm | 0.38 | -0.280** | 3.00E-04** | 1.84E-01** | 9.10E-03** | 2.10E-03† |
| | | | | | -- | -- |
| TSN flux, total | 0.58 | -6.50** | 8.20E-03** | 3.61E+00** | 9.42E-02* | 3.61E-02 |
| | | | | | -- | -- |
| TSN flux, storm | 0.39 | -3.93** | 4.50E-03** | 2.20E+00** | 1.14E-01** | -- |
| | | | | | -- | -- |
| TP flux, total | 0.32 | -0.761** | 1.30E-03** | 2.28E-01 | -- | -- |
| | | | | | -- | -- |
| TP flux, storm | 0.29 | -0.841** | 1.10E-03** | 3.72E-01† | 1.38E-02 | -- |
| | | | | | -- | -- |
| TN flux, total | 0.51 | -8.13** | 1.17E-02** | 3.40E+00** | 1.08E-01† | -- |
| | | | | | -- | -- |
| TN flux, storm | 0.36 | -6.42** | 7.70E-03** | 3.16E+00** | 1.46E-01* | -- |
| | | | | | -- | -- |

Note: The form of the base model is annual NPS pollutant flux response, kg $ha^{-1}$ $yr^{-1}$ = P + delta IS.
Example: TSS flux, total (kg/ha/yr) = -649 + 0.769 (Precip) + 550 (delta IS) + 12.6 (MinTill).
Symbol indicates P-value for the test that the coefficient = 0 (** = p < 0.01; * = p < 0.05; † = p < 0.10; none = p > 0.10).

**Table 5-8.** NPS pollutant flux responses positively associated with delta IS (urban soil disturbance), p<0.10.

| NPS pollutant | Summer | Fall | Winter | Spring | Annual |
|---|---|---|---|---|---|
| TSS | total, storm | total, storm | total, storm | total, storm | total, storm |
| PartP | total, storm | total, storm | -- | -- | total, storm |
| PartN | total, storm | -- | total, storm | -- | -- |
| TSP | storm | total, storm | total, storm | total | total, storm |
| TSN | storm | storm | total, storm | -- | total, storm |
| TP | total, storm | total, storm | -- | -- | storm |
| TN | total, storm | storm | total, storm | -- | total, storm |

Model: NPS pollutant flux, kg $ha^{-1}$ $yr^{-1}$ = P + delta IS + MinTill + ConvTill + Pasture + TotalAg + Urban + Forest + NADP, where delta IS = annual change in mean impervious surface (%) is associated with the NPS pollutant flux in the presence of other variables.

**Table 5-9.** NPS pollutant flux responses positively associated with agricultural tillage, p<0.10.

| NPS pollutant | Summer | Fall | Winter | Spring | Annual |
|---|---|---|---|---|---|
| TSS | -- | -- | -- | -- | total |
| PartP | storm | -- | -- | -- | total, storm |
| PartN | -- | -- | -- | total, storm | -- |
| TSP | total, storm | total, storm | total, storm | total | total, storm |
| TSN | storm | storm | total, storm | -- | total, storm |
| TP | total, storm | -- | -- | -- | -- |
| TN | storm | -- | total, storm | -- | total, storm |

Model: NPS pollutant flux, kg $ha^{-1}$ $yr^{-1}$ = P + delta IS + MinTill + ConvTill + Pasture + TotalAg + Urban + Forest + NADP, where either MinTill = minimum tillage agriculture (%) and/or ConvTill = conventional tillage agriculture (%) are associated with the NPS pollutant flux in the presence of other variables.

**Table 5-10.** NPS pollutant flux responses dominated only by precipitation, p<0.05.

| NPS pollutant | Summer | Fall | Winter | Spring | Annual |
|---|---|---|---|---|---|
| TSS | -- | -- | -- | -- | -- |
| PartP | -- | -- | total, storm | -- | -- |
| PartN | -- | total, storm | -- | -- | -- |
| TSP | -- | -- | -- | storm | -- |
| TSN | -- | -- | -- | total, storm | -- |
| TP | -- | -- | total, storm | total, storm | total |
| TN | -- | total | -- | total, storm | -- |

Model: NPS pollutant flux, kg $ha^{-1}$ $yr^{-1}$ = P + delta IS + MinTill + ConvTill + Pasture + TotalAg + Urban + Forest + NADP, where P = seasonal precipitation (mm) is the only significant variable associated with the NPS pollutant flux.

## 5.4. Discussion

This section discusses identified hydrologic and NPS pollutant flux responses relevant to nutrient and sediment management in Occoquan headwater basins with a focus on urbanization.

### Hydrologic Response

The observed positive effect of annual precipitation and mean IS on total unit flow and runoff ratio (Table 5-4) confirms what is reported in the literature regarding the impact of mean IS greater than 10 percent on surface runoff. During the winter and spring, precipitation is the sole predictor of total flow, dominating cumulative IS effects across study basins (Table 5-5). Higher discharge to rainfall correlations across all basins during the spring and winter are attributed to reduced interception, evapotranspiration, and infiltration during dormant, leaf-off conditions. In the fall and summer, when land surfaces are fully vegetated, IS percent becomes a significant predictor of both total and storm discharge (Table 5-5), indicating that hydrologic impacts due to cumulative IS occur as a result of replacing vegetative cover with IS. The growing season impact of IS on total and storm flow is strong enough that it appears as a predictor in annual models (Table 5-4). Seasonal storm discharge models also provide evidence that precipitation dominates landscape processes in the spring, when all soils (urban and rural) are typically saturated and more susceptible to runoff. For example, unit storm discharge, the most sensitive measure of hydrologic response, is dominated by precipitation only during the spring (Table 5-5).

A negative conventional tillage term in the annual nonstorm discharge model (Table 5-4) provides indirect evidence of significant water consumption from agricultural cropland. Theoretically, reduced agricultural field cropping and lower IS percent should both independently increase nonstorm streamflows. As expected, the IS term in the annual nonstorm discharge model is negative, but not significant (Table 5-4). Seasonal models suggest that nonstorm discharge is associated with increased precipitation and decreased conventional tillage only during the growing season (Table 5-5) providing evidence of seasonal nonstorm streamflow reductions due to cultivated agriculture. Mindful of the uncertainty in the agricultural land use data, this result suggests that headwater streams in this study are more likely to run dry as a result of increased agricultural crop consumption than from cumulative increases in IS.

Hydrologic models for total and nonstorm runoff ratio explain less than one-third of the variability in the response (Table 5-4) and are not discussed further.

### NPS Pollutant Flux Response

Annual regression models that evaluate the impact of cumulative mean IS on NPS pollutant flux (equation 2) are a poor fit, with only one model, storm TSP flux, explaining more than one-third of the variability in the response. Therefore, either other variables are needed to explain the variability in data or the quality of the existing predictor variables must be improved. The negative association of annual particulate nutrient fluxes (PartN and PartP) with both IS and pasture land (Table 5-6) is interesting, since it could be argued that annual particulate nutrient fluxes are linked to land use conversion of pasture to cultivated agriculture, the only remaining non-urban, non-pasture, agricultural land use (percent forest is relatively stable). Although the observed linkage between particulate nutrient flux and cultivate agriculture is weak, the IS and pasture coefficients do match an expected result, that cultivated agriculture is a source of particulate nutrients.

Annual storm TSP flux is significantly and positively associated with both conventional tillage and mean IS, suggesting that conventional tillage agriculture is a source of annual TSP flux in the four Occoquan headwater basins and that the cumulative increase in urban imperviousness is another potential source of soluble phosphorus. The negative urban land coefficient in this model may be identifying the replacement of prime agricultural land with urban land use. The significant association of cumulative IS with annual storm TSP flux indicates the importance of continued urban stormwater and NPS nutrient management efforts aimed at limiting soluble phosphorus deliveries in high impervious sections of the Occoquan basin. Schueler and Claytor (1996) reported that when urban best management practices (BMPs) such as stormwater ponds, wetlands, filters, or infiltration practices are properly installed and maintained, phosphorus loads can be reduced by as much as 40 to 60 percent. Results of the storm TSP flux model suggest that in spite of aggressive urban BMP policies in the Fairfax and Loudoun County portions of Cub Run basin, further performance monitoring of soluble phosphorus removals may be warranted.

*Delta IS models*

Regression models that evaluate the impact of urban soil disturbance on NPS pollutant flux (equation 3) are discussed in the remainder of this section. The following seven models explain more than one-third of the variability in the response; TSS flux (storm), TSP flux (total and storm), TSN flux (total and storm), and TN flux (total and storm). The TP flux model ($r^2$=0.32) is also discussed due to its importance as an enriching nutrient in the Occoquan basin. The above models can be classified into three general groups; TSS models, soluble nutrient models, and total nutrient models, each discussed in turn. Annual particulate nutrient models were all poorly fit ($r^2 < 0.33$) by the methods used in this paper, indicating that improved variables are needed to better explain the annual response. Nevertheless, several interesting results related to seasonal particulate nutrient flux were observed, which are presented.

Total suspended solids: Annual models of total and storm TSS flux provide evidence of two different land use processes driving nonpoint source TSS flux in the Occoquan headwater basins, namely intense urban land development and cultivated agriculture. All annual and seasonal TSS flux models have significant, positive delta IS terms (Table 5-7 and Table 5-8), suggesting a consistent TSS flux response due to urban land disturbance. Increased annual storm TSS flux is associated with decreased pasture land (Table 5-7), but uncertainty in the agricultural land use data reduces confidence in the term. Therefore, although some evidence for cultivated agriculture as a driver of TSS flux exists, it is less direct than that for urban land disturbance.

Particulate nutrients: Annual regression models of total and storm particulate P flux are similar to those for total annual TSS flux. Significant delta IS terms during the summer and fall (Table 5-8) suggest that particulate P flux is associated with urban land disturbance during the growing season, possibly due to the seasonal nature of the construction industry and the occurrence of intense summer storms, but also a likely consequence of increased transport mechanisms in highly-impervious, urbanizing catchments. The positive association of storm particulate P flux with conventional tillage in the summer (Table 5-9) suggests that cultivated agriculture may be a particulate P source in Occoquan headwaters. During the winter, precipitation is the dominant driver of both particulate and total P flux, regardless of LULC (Table 5-10). Delta IS is not a significant term in the annual *particulate* N flux model. This finding, similar to the IS model (Table 5-6), indirectly links agricultural tillage as a possible source of particulate N. More relevant to the topic of urbanization is a significant urban soil disturbance term (delta IS) during the summer and winter that is positively associated with particulate N flux (Table 5-8). Therefore, seasonal regression analysis reveals a significant association between particulate N and urban soil disturbance that is not apparent in the annual model.

Soluble nutrients: Annual regression models of total and storm TSP flux show a highly significant, positive association between soluble P flux, urban soil disturbance, and agricultural land use (Table 5-7), with seasonal models indicating a consistent, positive relationship between the same variables in all seasons (Table 5-8 and Table 5-9). Annual regression models of total and storm TSN flux associate increased soluble N flux with intense urban land development and cultivated agriculture (Table 5-7). The response model for total TSN has the highest fit of any NPS pollutant flux model, suggesting positive, significant associations with annual precipitation, delta IS, and conventional tillage. Seasonal regression analysis reveals that delta IS is a significant model term for storm TSN flux in all seasons except spring (Table 5-8), when precipitation dominates (Table 5-10). Significant conventional tillage terms in the fall, summer, and winter also suggest a positive association between TSN flux and tillage agriculture.

Total nutrients: Precipitation is the only significant predictor of total annual phosphorus flux (Table 5-7), suggesting a dominating influence of precipitation on TP flux in the Occoquan study basins, regardless of LULC. Taken alone, this is an unsettling result, given the phosphorus-limited status of the Occoquan reservoir and many other fresh-water impoundments. However, as in several other models, the *storm* flux model is more responsive to changes in LULC, identifying a significant, positive urban soil disturbance term (Table 5-7). Seasonal models of total and storm TP flux are even more revealing, indicating that urban land disturbance is a significant TP variable only during the summer and fall (Table 5-8). These seasonal results, taken with seasonal hydrologic findings, provide evidence of the well-established linkage between rainfall, runoff, and NPS pollution. Similar to seasonal results for particulate P flux, conventional tillage as a significant, positive term in the summer (Table 5-9) provides another association between total phosphorus flux and tillage agriculture. In fact, it is only during the spring and winter, when denuded land cover is most susceptible to runoff and soils are typically saturated, that precipitation dominates total and storm TP flux (Table 5-10). The results above demonstrate the value of seasonal data to identify NPS pollutant associations not readily apparent at an annual time scale.

Similar to annual models for TSN flux, regression models for total and storm TN flux link increased total nitrogen flux to intense urban land development and cultivated agriculture (Table 5-7). Seasonal regression analysis shows that, like storm soluble nitrogen flux, storm TN flux is significantly associated with urban land disturbance during the summer, fall, and winter (Table 5-8). In the summer and winter, storm TN flux is also associated with conventional tillage (Table 5-9). In the winter, a unique situation occurs as TN flux is positively associated with conventional tillage (Table 5-8), urban soil disturbance (Table 5-9), and pasture land (Table P-10). This finding suggests that flushing of nutrients from disturbed soils (both urban and rural) and pastured lands occurs during high rainfall winters. The positive, significant association of TSP flux with pasture land during the winter (Table P-10) provides additional evidence of winter flushing. In the spring, precipitation is the only significant predictor of total and storm TN flux (Table 5-9), likely due to generally saturated spring soils.

In general, annual and seasonal results suggest that soluble nutrients are more closely linked to agricultural tillage than are particulate nutrients (Table 5-9), which is an unexpected result; and total and soluble nutrient fluxes are impacted most by spring precipitation and soil conditions (Table 5-10). Urban soil disturbance appears to be associated with more NPS pollutant fluxes than cultivated agriculture (Table 5-8 and Table 5-9), with increased urban-disturbed TSS and TP flux response the most prominent examples. Saturated soil conditions in the spring dominate delivery of most NPS pollutants in this study, regardless of LULC.

Uncertainties in agricultural land use estimates provide limited assurance that regression models describe actual farm land use. The large number of models with a low coefficient of determination ($r^2$) indicates that other explanatory factors contribute to variation in annual and seasonal NPS pollutant flux. Modeling results may be improved by using a GIS to selectively extrapolate NASS (U.S. Census of Agriculture, 2002) county agricultural data with layered information such as soil type and slope to isolate spatial boundaries. Through dasymetric mapping, a technique first developed by Wright in 1936 for population density mapping, areas most likely characterized by a specified agricultural practice could be ranked, resulting in improved spatial estimates of agricultural land use. However, temporal errors inherent in the data would remain.

### Limited Use of Models for Prediction

Graphical display of total unit flow in three dimensions (Figure 5-3) helps visualize the individual contributions of precipitation and mean IS on basin discharge, supporting literature regarding increased hydrologic response in urbanizing basins above 10 percent mean imperviousness. Selected regression models characterizing other major hydrologic and NPS pollutant flux responses from this study are listed in Table 5-11, only four of which have an $r^2$ greater than 0.33.

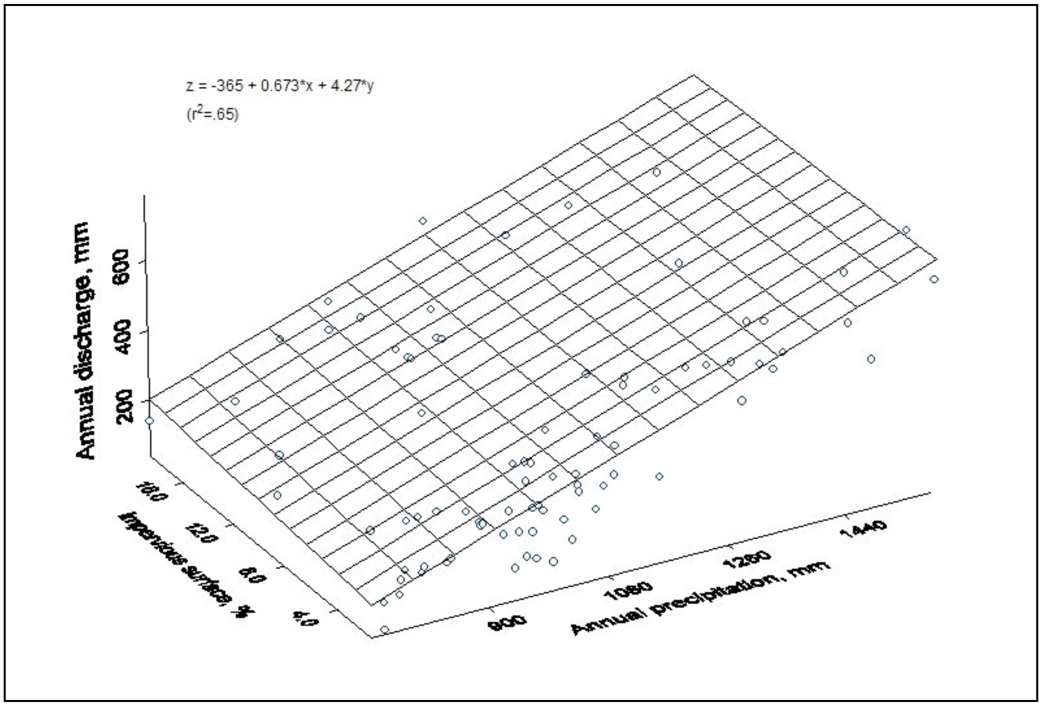


**Figure 5-3.** Annual discharge, Occoquan headwater basins, 1979-2002, mm.
(Source: Occoquan Watershed Monitoring Laboratory, Manassas, Virginia).
(Discharge shown as a function of annual precipitation, mm, and impervious surface, %).

**Table 5-11.** Selected regression equations, Occoquan headwater basins, 1979-2002. (annual hydrologic and NPS pollutant flux response).

| (Equation no.) response | Annual regression model[1,2] | $r^2$ |
|---|---|---|
| Hydrologic flux, mm | | |
| (4) Unit flow, total | -365 + 0.673 (*P*) + 4.27 (*IS*) | 0.65 |
| (5) Unit flow, nonstorm | -83.3 + 0.327 (*P*) – 5.71 (*ConvTill*) | 0.46 |
| NPS pollutant flux, kg $ha^{-1}yr^{-1}$ | | |
| (6) TSP flux, storm | -0.21 + 2.00E-04 (P) + 1.52E-02 (*IS*) + 8.20E-03 (*ConvTill*) | 0.34 |
| (7) TSS flux, total | -649 + 0.769 (*P*) + 550 (*delta IS*) + 12.6 (*MinTill*) | 0.32 |
| (8) TP flux, total | -0.761 + 1.30E-03 (*P*) | 0.32 |
| (9) TN flux, total | -8.13 + 1.17E-02 (*P*) + 3.40 (*delta IS*) + 1.08E-01 (*ConvTill*) | 0.51 |

[1] Regression equations not validated.
[2] P=precipitation, mm; IS=impervious surface, %; delta IS=annual change in impervious surface, %; ConvTill=conventional tillage, %; MinTill=minimum tillage, %.

Multivariate linear regressions in this study were developed to identify processes driving basin discharge and NPS pollutant flux in the four Occoquan headwater basins. Empirical equations of this type (Table 5-11) can also provide a tool for estimating future hydrologic and NPS pollutant response, if limitations of the model are understood. For example, equations (4) and (6) could be used to estimate future basin flow and storm TSP flux, but only within a certain range of IS (1 to 18 percent). Equations (4) and (6) might have utility in estimating the impact of impervious surface build-out in the three less-developed basins of this study. Equations (7) and (9), which use delta IS as a predictor variable, suggest that as IS in these four basins stabilizes (as delta IS approaches zero), precipitation and tillage agriculture become the sole predictors of annual TSS and TN flux. In equation (7), however, the minimum tillage term is unexpected, since the conventional tillage term should theoretically yield a higher TSS flux. Consequently, because of the uncertainty in the agricultural terms, we have less confidence in models (7) and (9) for prediction. Four of the six models presented in Table 5-11 require similar estimates of agricultural tillage (minimum or conventional tillage), making them less attractive as predictive models.

Rather, the greater value of the models presented in this paper lies in what they tell us about the system we are trying to understand. From an investigative research perspective, a flawed model serves as a tool for further scientific inquiry, rather than strictly a predictive equation (Klemes, 1994). The addition of a regresson coefficient for time, for example, may account for variability in model response attributed to changing land management practices, including considerations related to age and maintenance of BMPs. Results of this paper also demonstrate the limitations resulting from less than complete characterization of land use due to incomplete records and spatial lumping. As long as the limitations of the empirical equations presented in this paper are recognized, their value remains.

## 5.5. Conclusions

This paper utilizes long-term hydrologic and NPS pollutant data sets from a rapidly developing watershed on the urban fringe of Washington, DC to model the effects of precipitation and LULC on basin discharge and NPS pollutant flux. Of the four headwater basins included in this study, one is rapidly urbanizing and none contain significant point source contributions during the 24-year study period. Hydrologic regression models indicate that total discharge across the study basins is significantly associated with precipitation and mean IS. Annual change in mean impervious surface (delta IS) is used as an indicator of urban soil disturbance for NPS pollutant flux modeling, with results indicating that all NPS sediment and nutrient fluxes in this study are associated with precipitation and urban soil disturbance at an annual and/or seasonal scale. Annual estimates of forest land and atmospheric deposition of wetfall inorganic nitrogen are not significantly associated with any NPS nutrient flux in the four study basins, likely due to lack of variation in these predictors.

Hydrologic results are in agreement with literature associating increased discharge volumes with mean impervious surface above 10 percent. Seasonal models reveal that increased basin discharge per area is significantly associated with higher mean IS during the growing season (summer and fall), a finding that matches expected theoretical changes in unit discharge due to biophysical response from highly-impervious catchments. Seasonal models of basin discharge show that precipitation generally dominates landscape processes in the spring when all soils (both urban and rural) are typically saturated.

Total and storm TSS fluxes are associated with precipitation and delta IS in all seasons, providing evidence of urban soil disturbance as a significant driver of nonpoint TSS flux in Occoquan headwaters. Seasonal regression analyses reveal a positive association between particulate N and urban soil disturbance that is not identified in the annual model. Increased particulate and total P flux is associated with urban soil disturbance only during the growing season, while soluble phosphorus and nitrogen fluxes appear to be more widely distributed across the year as a function of both urban and agricultural soil disturbance. The finding of a significant, positive association between annual TSP flux and cumulative mean IS during storm flows demonstrates the importance of continued urban stormwater and NPS nutrient management efforts aimed at limiting soluble phosphorus deliveries into Cub Run.

Unvalidated empirical models developed in this study have limited utility as predictive equations, especially given the uncertainties in the agricultural land use data. Regardless, regression equations and model terms provide an indication of the major processes driving long-term NPS pollutant flux in the four Occoquan headwater basins. Results also suggest that recognition of differences between common agricultural practices can improve our ability to understand watershed response to well-established factors such as precipitation and IS, and that much remains to be learned in this area.

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# 6. Conclusions and Recommendations

The principal goal of this research was to quantify long-term relationships between basin land use/land cover (LULC) and hydrologic and NPS sediment and nutrient fluxes in the four headwater basins of the Occoquan River, with a focus on the effects of urbanization. The deficiencies of using average annual runoff ratios and export coefficients for effective NPS pollutant targeting are often discussed; and similar spatial and temporal limitations have been pointed out for various hydrology-driven simulation models. Although the basic concepts of hydrologic response to urbanization are well known, there have been few studies with observed data to verify those expectations, over the long term. Nonpoint source pollution from urban areas has been widely studied on a national scale, but not over long-term periods of intense urbanization. Research described in this dissertation quantified observed precipitation, stream monitoring, and LULC data over a 24-year period of rapid urbanization.

The concept of a watershed is easily understood and therefore a powerful tool for visualizing a watershed as a complex ecological system. However, the lack of information about the relationships maintaining natural ecosystems makes it difficult to assess the impact of human activities when they occur. Therefore, predicting the consequences of land use change is difficult; and professional judgment and adequate science are often used to manage the spatial and temporal nature of environmental challenges within a watershed. The development of data linking certain landscape thresholds such as percent imperviousness to stream degradation in headwater areas has enhanced the potential for land use planning as a tool for stormwater quality management. As a result, the evolving science of watershed management is poised to become a dominating environmental issue.

Empirical models are often used to identify possible indicators or sources of watershed influence on in-stream conditions. However, existing long-term studies in this area are limited by the lack of consistent, historic landscape information or by periodic landscape data that is mismatched with higher resolution water quality data. The present research used empirical modeling at an intermediate temporal scale in an attempt to close the gap between typically high temporal resolution water monitoring data and lower resolution landscape descriptions. Multiple linear regression was used to associate landscape-related processes with hydrologic and NPS pollutant flux across the four study basins, with an emphasis on human activities in urbanizing catchments.

The research goal was achieved by completing the following objectives:

1. Develop methodologies summarizing historic LULC and water quantity/quality in the four study basins.
2. Compare and contrast hydrologic and NPS pollutant summaries across basins, years, and seasons.
3. Identify major physical processes related to LULC that are associated with basin discharge and diffuse pollution across the four study basins.

**The first objective** to develop methodologies summarizing historic LULC and water quantity/quality in the four study basins used spatial and database tools. Twenty-four years of precipitation and stream monitoring records from OWML were used to create integrated time series of hydrologic and water quality data. Daily data were reduced to annual and seasonal summaries partitioned into storm and nonstorm flows, each having separate particulate and soluble nutrient fractions suitable for comparative analysis. None of the study basins contained significant point source contributions during the study period. Nonstorm pollutant loads were calculated using 15-minute daily flow data, along with linear interpolation of weekly and biweekly grab sample concentrations. Stormflow loads were tabulated individually as a time-ordered series at a constant step-loading rate extending from the beginning to the end of each storm flow. Daily nonstorm loads were tabulated separately, and were not included as part of a basin's total load during stormflow.

Spatial LULC information in the form of annualized land use and mean impervious surface (IS) percent were used to characterize the landscape of each study basin and to document LULC changes (Figure Q-1). Land use analysis was completed within a GIS using pre-classified 1979, 1989, 1995, and 2000 land use data from the Northern Virginia Regional Commission (Figure Q-2, Q-3). Agricultural land use was annualized using county-wide data from NASS (U.S. Census of Agriculture, 2002). Three of the four study basins, ranging in size from 67 to 400 $km^2$, are predominantly forest and mixed agriculture. The fourth basin, the 127 $km^2$ Cub Run basin, has urbanized rapidly over the past 20 years with approximately 50 percent of current land area classed as urban and 18 percent impervious surface (Table 5-3). Landsat-derived IS estimates for 1986, 1990, 1996, and 2000 were used as an indicator of urban land cover (Figure A-5). Impervious surface estimates were annualized using building data from Loudoun and Fairfax Counties (Figure A-6).

Because accurate measurement of IS cover is considered an essential indicator of downstream water quality and a critical input variable for many water quality models, this dissertation compared IS estimates from a satellite imagery/land cover approach with a more traditional aerial-photography/land use approach. Both approaches were evaluated against a high quality validation set of the Cub Run basin (Figure 2-4). Results showed that Landsat-derived IS estimates correlated well with planimetric reference data and with published ranges for similar sites in the region. Basin-wide mean IS values (Table 2-5), difference grids (Figure 2-7), and regression and density plots (Figure 2-5) validated the use of satellite-derived/land cover-based IS estimates over photo-interpreted/land use-based estimates. Results of the study (Chapter 2) supported the use of automated, satellite-derived IS estimates for planning and management within rapidly urbanizing watersheds where a GIS system is in place, but where time-sensitive, high quality planimetric data are unavailable.

**The second objective** to compare and contrast hydrologic and NPS pollutant summaries across basins, years, and seasons used descriptive and nonparametric statistics. Hydrologic and NPS pollutant flux summaries have non-normal distributions and contain significant outliers. Consequently, nonparametric comparisons were used to discern statistical difference between central measures of group location. Nonparametric regression was used to identify relationships between annual and seasonal precipitation, basin discharge, and NPS pollutant flux. Loess regression, a nonparametric generalization of multivariate polynomial regression, was used to fit a general smooth surface to annual time series for data visualization.

Results indicate that several hydrologic and NPS pollutant characteristics in the urbanizing Cub Run watershed were significantly different from other basins, and changed over time with increasing urbanization. Observed differences generally corresponded with previous studies, hydrologic principles, and pollutant transport theory. Long-term partitions of water column phosphorus and nitrogen were influenced by season, basin size, and average basin slope, with similarities noted between certain basins. Consequently, results consisted of two major categories of conclusions; 1) general effects demonstrated by all watersheds, and 2) urbanization effects.

General effects demonstrated by all watersheds include the following:

- Storm fluxes made up the majority of total NPS nutrient fluxes from all headwater basins, with between 88 and 98 percent of mean annual TSS fluxes delivered by storm flow (Table M-2).
- Average area-weighted storm phosphorus load for all four headwater basins is twice that of the nonstorm phosphorus load, and is made up mostly of particulate phosphorus, while the average area-weighted storm nitrogen load makes up approximately 60 percent of total NPS nitrogen load, and the soluble fraction dominates (Figure 6-1).
- The majority of TSS and nutrient flux from all basins occurred during winter and spring, seasons which also have the greatest discharge (Figure 4-3, Tables M-12 and M-13).
- Larger basins had lower annual storm particulate/soluble phosphorus ratios, steeper basins had larger annual nonstorm particulate/soluble phosphorus ratios, and higher particulate/soluble nitrogen ratios were observed during the summer and fall growing season, with more inter-basin variability observed in phosphorus compared to nitrogen ratios (Figure 4-4 and 4-5).

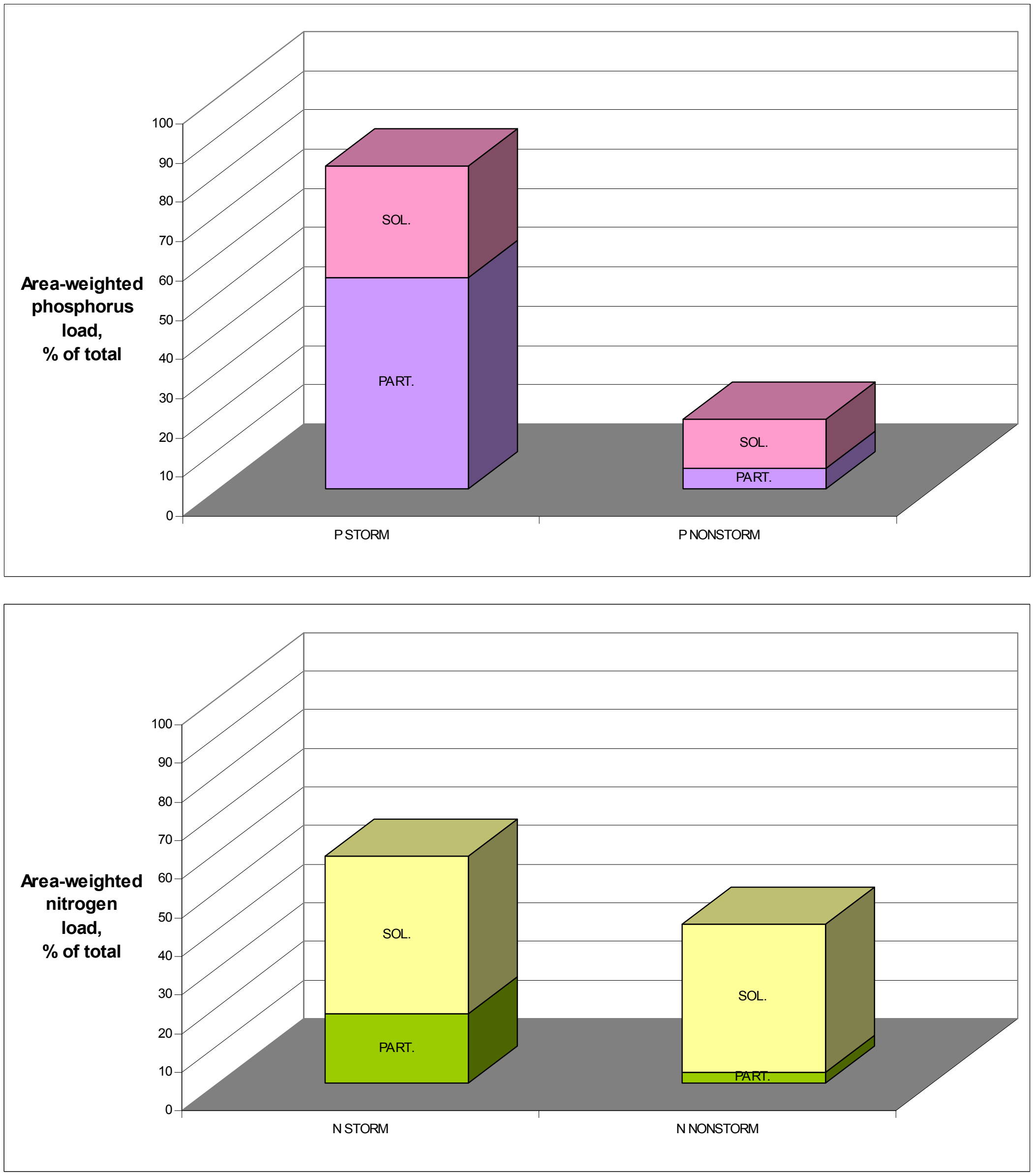


**Figure 6-1.** Area-weighted phosphorus and nitrogen loads, 1979-2002, percent of total. (Area-weighted soluble and particulate fractions include all four Occoquan headwater basins).

Urbanization effects include the following:

- Cub Run had significantly higher long-term annual unit storm discharge and higher annual storm/nonstorm discharge ratio than the other basins (Table 3-5).
- Cub Run had higher post-1983 mean annual unit storm discharge than the other basins (Table 3-6), and significantly lower pre-1984 particulate nutrient EMCs (Table M-6).

- Cub Run had higher post-1984 TSS and nutrient flux than the other basins (Figures 4-6, M-7, M-8, M-9, M-14, and M-15).
- Cub Run had the highest mean annual TSS flux (Figure 4-6, Table 4-7) despite having the lowest average slope of all basins (Table 5-1).
- Cub Run had significantly higher storm runoff response in the summer ($p<0.05$) and in the fall ($p<0.20$) than the other basins (Figure 3-4, Table 3-7), indicating a seasonal hydrologic impact due to urbanization.
- Cub Run median annual TSS and nutrient fluxes during the growing season were twice those of most basins, particularly in the summer (Tables 4-11, M-12, and M-13), providing evidence of a growing season impact due to urbanization.

The finding that Cub Run storm runoff response is higher than non-urban basins during the summer and fall is particularly important, as it agrees with expected reductions in growing season interception, infiltration, and evapotranspiration in catchments with higher imperviousness, and also helps explain elevated NPS pollutant fluxes during these seasons. The mean 20-year IS percent of Cub Run basin during the period of study (12.5 percent) supports literature regarding increased runoff volumes in catchments above ten percent imperviousness. Increased unit-area storm discharge in Cub Run basin during the growing season has implications for seasonal NPS pollutant flux. Higher TSS and nutrient fluxes observed in Cub Run basin during the summer and fall are linked to increased soil disturbance from documented urban construction, but also to increased unit storm volumes and sediment pathways resulting from higher mean imperviousness.

**The third objective** to identify major physical processes related to LULC that are driving basin discharge and diffuse pollution delivery in the four Occoquan headwater basins used annual and seasonal multivariate linear regression models. Annual and seasonal response data for 27 hydrologic and NPS pollutant flux variables were modeled using a precipitation variable, eight LULC predictor variables, and one variable for atmospheric nitrogen input, with annual change in mean impervious surface (delta IS) used as an indicator of urban soil disturbance (Table 6-1).

**Table 6-1.** Variables tested in stepwise multivariate linear regression.

| Response | variable | Predictor | variable |
|---|---|---|---|
| Hydrologic: | Unit flow[1] | Hydrology: | Precip |
| | Runoff ratio | Land cover: | IS |
| NPS pollution flux: | | | delta IS |
| Suspended solids | TSS | Land use: | MinTill |
| Phosphorus | Particulate P | | ConvTill |
| | Soluble P | | Pasture |
| | Total P | | TotalAg |
| Nitrogen | Particulate N | | Urban |
| | Soluble N | | Forest |
| | Total N | Atmospheric wetfall: | NADP[2] |

[1]All response variables are partitioned into storm, nonstorm, and total flow components.
[2]National Atmospheric Deposition Program, kg inorganic N $ha^{-1}$.

Hydrologic models indicated that total annual basin discharge was significantly associated with precipitation and mean IS ($r^2$=0.65), providing further evidence of higher discharge volumes in catchments above 10 percent mean IS. Seasonal hydrologic models revealed that increased basin discharge was significantly associated with mean IS, but only during the growing season (summer and fall) when non-vegetated IS areas most impact the biophysical response to precipitation. Seasonal storm discharge models showed that precipitation dominated pollutant flux processes during the spring when all soils (urban and rural) are typically saturated.

NPS pollutant response models revealed that total and storm TSS fluxes were significantly associated with precipitation and delta IS in all seasons (Table 5-8), providing observed evidence of urban land disturbance as a significant driver of nonpoint TSS flux in Occoquan headwater streams. Annual NPS total nitrogen flux in the four study basins was significantly associated with annual precipitation, delta IS, and conventional agricultural tillage ($r^2$=0.51), demonstrating the environmental impact of both urban and agricultural soil disturbance on annual NPS nitrogen flux. Seasonal regressions revealed a positive association between particulate N and urban soil disturbance that was not apparent in the annual model (Table 5-8). Increased total annual particulate P, TSP, and TSN fluxes were associated with both urban and agricultural soil disturbance. The finding of a significant, positive association between annual soluble phosphorus flux and cumulative impervious surface ($r^2$=0.34) during storm flows demonstrated the importance of continued urban stormwater monitoring and assessment in Cub Run basin. During the spring across all basins, when soils are typically saturated, precipitation was the only variable associated with total and soluble phosphorus and nitrogen (Table 5-10). During the winter, precipitation appears to be the main driver of total and particulate P flux, regardless of LULC. Total and storm TP flux was significantly associated with urban soil disturbance, but only during the summer and fall, which along with hydrologic findings, documents a fundamental seasonal linkage between rainfall, runoff, and NPS pollution.

**The research performed to complete the above objectives** creates an integrated body of knowledge quantifying the impact of precipitation and landscape on long-term basin discharge and NPS pollution flux. Methodologies were developed to summarize historic LULC and water quantity/quality in the four study basins using existing landscape and stream monitoring data. Hydrologic and NPS pollutant summaries were compared and contrasted across basins, years, and seasons, with results indicating that several hydrologic and pollutant flux characteristics in the urbanizing Cub Run basin were significantly different from the other basins, and changed over time with increasing urbanization. Annual and seasonal multivariate regression identified major physical processes related to diffuse pollution in the study basins. Limitations of the method used to characterize agricultural land use, and the impact that had on model performance, were recognized and discussed.

Results of the research were presented in terms of hydrologic and pollutant flux summaries; and linkage between the two classes of results was apparent. Based on twenty-four years of annual and seasonal summaries, the following major conclusions were made: 1) storm fluxes make up the majority of total NPS pollution flux; 2) the majority of TSS and nutrient flux from all basins occurs during winter and spring; 3) particulate/soluble nitrogen ratios are higher during summer and fall; 4) Cub Run had significantly higher annual storm discharge than other basins, and higher storm discharge during the growing season; 5) Cub Run mean annual TSS and nutrient fluxes during the summer and fall growing season were at least twice those of most basins; and 6) Cub Run had the highest mean annual TSS flux, significantly lower pre-1984 nutrient EMCs, and higher post-1984 sediment and nutrient fluxes than the other basins.

Empirical modeling resulted in the following findings: 1) precipitation is the main driver of annual and seasonal basin discharge and NPS pollution flux; 2) increases in cumulative IS affect basin discharge and NPS pollutant flux during the growing season through reduction of vegetated surface; 3) urban soil disturbance is associated with all NPS sediment and nutrient fluxes across most seasons except spring, when precipitation dominates; and 4) total and storm TP flux is significantly associated with urban soil disturbance, but only during the summer and fall growing season. The above results, when taken as a whole, add to the literature that quantifies long-term hydrologic and NPS pollutant response in an urbanizing watershed. Findings provide evidence of the fundamental linkage between precipitation-driven runoff, landscape processes, and NPS sediment and nutrient pollution in an urbanizing landscape.

Changing *seasonal* fluxes across all basins and in the urbanizing Cub Run basin in particular are key to understanding the main findings of this research. As an example, growing season increases in TSS and nutrient fluxes in Cub Run basin highlight the cumulative impact of replacing vegetated surface with impervious surface. Urban impervious surface in Cub Run was found to increase at a rate roughly proportional to population density (Figure A-3). However, the impact of increased IS on basin hydrology is amplified because vegetated surfaces (trees, crop land, and pasture) are being for the most part permanently removed and replaced with an impervious cover that has a drastically different biophysical response.

## 6.1. Contributions

This research has contributed to the body of knowledge quantifying the impact of changing landscape on long-term basin discharge and NPS pollution. The study uses historic data to quantify flux from four mixed-land use headwater basins in the Occoquan watershed. Principal contributions follow:

1) Annual change in mean impervious surface (delta IS) was successfully used as an indicator of urban soil disturbance. High temporal resolution water quality data

was matched with annualized LULC data for integrated watershed analysis at an intermediate scale.

2) Higher annual sediment and nutrient fluxes in Cub Run after 1984, at about the time that mean IS reached ten percent in that basin, link urbanization with higher sustained sediment and nutrient export.

3) Increased hydrologic response to cumulative IS in Cub Run during the summer and fall supports theoretical growing season reductions in evapotranspiration, interception, and infiltration expected from urbanization.

4) Higher NPS pollutant flux observed in Cub Run basin during the growing season in particular was linked to urban soil disturbance *and* significantly increased unit storm volumes.

5) A significant association between TSS flux, precipitation, and urban soil disturbance documents the importance of *urban growth rate* on water quality, regardless of the level of implemented erosion and sediment control.

6) Basin size and slope, as well as seasonal effects, had an observed impact on long-term storm and nonstorm particulate/soluble nutrient ratios.

7) Information related to the composition of TSS and the ratio of particulate to soluble nutrients as a function of discharge makes a contribution to the literature regarding NPS sediment and nutrient delivery from mixed-land use catchments.

## 6.2. Future Research

Numerous questions have been left uninvestigated by this research. Potential research developing from this work can be grouped into immediate and long-term projects.

### Potential Immediate Projects

Several research topics could follow immediately from this dissertation:

(1) For continued modeling work (from Chapter 5), the method of agricultural land use estimation and interpolation should be improved, since agriculture is a major land use in the Occoquan watershed. In addition, a regresson coefficient for time (i.e.,

year) should be tested in order to identify that portion of model variability attributed to changing agricultural and/or urban land use practices within the four headwater basins. If model fit can be improved with the above modifications, several additional models could be run immediately.

(2) The most important models to be investigated are the basin-specific models for Cub Run and the seasonal IS models associated with NPS pollutant response (equation 2, Chapter 5), none of which were tested. It is expected that some results may be forthcoming that were not apparent in this dissertation. For example, additional basin-specific modeling of historic Cub Run data may identify an impact of BMPs and other variables over time; and seasonal IS models may reveal additional NPS pollutant fluxes significantly associated with cumulative mean IS.

(3) Table E-4 of this dissertation, which shows extreme wet and dry periods, can be used to evaluate the expected change in NPS pollutant response during historic high and low rainfall seasons. However, it is recommended that empirical models developed in this dissertation first be improved, as described in (1), above.

(4) An improved set of model variables, as described in (1), above, could also be used to investigate NPS pollutant response as a function of storm size. For example, rainfall/stream flow relationships derived from the OWML database could be used to quantify pollutant flux response to storms smaller than the ten-year storm, the return period commonly used for stormwater facility design.

(5) A more effective measure of directly-connected IS in Cub Run basin could be evaluated using several sources, including; hydrologic and water quality data from OWML, empirical equations developed by Sutherland (1995), historic storm sewer mapping from local jurisdictions, and 30 m satellite-derived IS estimates from the Mid-Atlantic RESAC.

(6) The groundwater component of the water balance for the four headwater basins of the Occoquan has not been investigated. However, if historic estimates of evapotranspiration are developed, annual and seasonal groundwater fluxes as a function of urban imperviousness could be quantified.

## Potential Long-term Projects

Several long-term research topics could follow from this dissertation:

(1) Using additional long-term data, repeat the study described in this dissertation at 5- and 10-year intervals to evaluate the cumulative impact of continued urbanization on hydrologic and NPS pollutant flux in the Occoquan basin.

(2) Of interest would be a study of how long it takes, if ever, to recover from sustained, high NPS pollutant flux (Figure 4-6) in Cub Run basin. To separate the effects of active construction (short-term) from sustained NPS fluxes during more stabilized periods in Cub Run basin, additional long-term data is required. This raises similar research questions,

(3) "When do short-term impacts of urban soil disturbance end, what variables influence short-term versus long-term NPS pollutant flux, and how can the transition period from short-term to sustained long-term NPS pollutant flux be identified?"

(4) A related long-term project could involve a series of studies to quantify the relationship between *rate* of urbanization, as measured in this dissertation, and the *magnitude* of NPS pollutant flux.

(5) Post-1995 decreases in nitrogen and phosphorus particulate/soluble nutrient ratio in Cub Run basin were left unexplained by this dissertation, and should be investigated beyond the the period of drought ending in 2002.

(6) The delta IS variable used in this dissertation as an indicator of urban soil disturbance should be validated, as there are substantial issues related to stream sediment resuspension and basin travel time that may be influencing flux results in Cub Run basin. Long-term monitoring and basin-specific modeling may clarifiy limitations in the use of delta IS as an explanatory variable for NPS pollutant flux.

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