QUANTIFYING NPS POLLUTANT DELIVERY IN AN URBANIZING HEADWATER BASIN

Mark Dougherty
Randel L. Dymond
Carl E. Zipper
PhD candidate, Civil and Environmental Engineering, Virginia Tech
Assoc. Professor, Civil and Environmental Engineering, Virginia Tech
Assoc. Professor, Crop and Soil Environmental Sciences, Virginia Tech
(mdougher@vt.edu)

KEYWORDS: NPS flux, 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 large mixed land use watersheds, demonstrating the importance of land use management in controlling the magnitude of TSS-related fluxes, and that most TSS fluxes occur during large or intense storm events. However, few studies in literature have the combined long-term precipitation and integrated pollutant discharge data necessary to evaluate NPS pollutant flux as a function of precipitation (Correll et al., 1999b). This research investigates fundamental watershed relationships using a unique assembly of long-term spatial and water quality data.

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 17% impervious surface and 50% of current land use classed as urban.

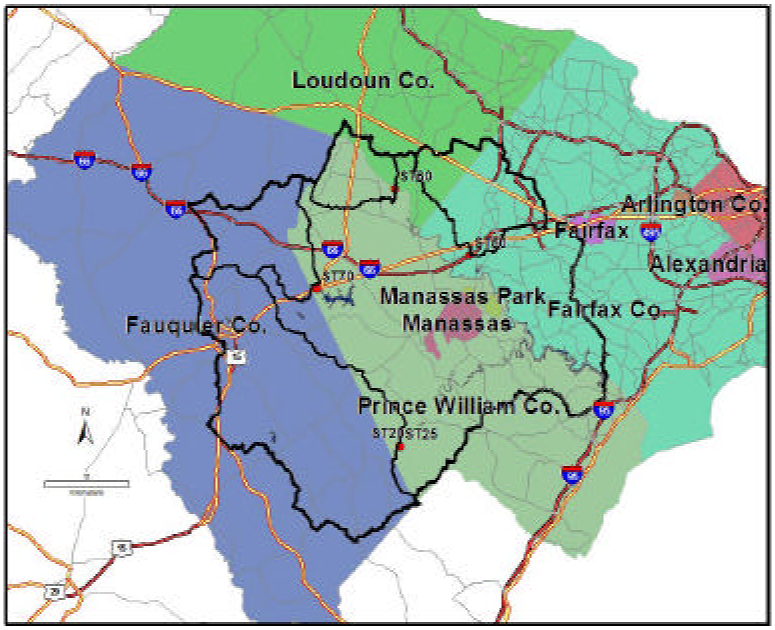

Figure 1. Location Map: Occoquan River Watershed Study Area, Northern Virginia, USA.

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 was begun in 1971 through replacement of the watershed's 11 sewage treatment works with a single advanced wastewater treatment (AWT) plant and the establishment of the Occoquan Watershed Monitoring Program and Laboratory (OWML) (Randall and Grizzard, 1995). Early results from the monitoring program established nonpoint nutrient pollution as a major cause of water quality impairment. The AWT went on line in July of 1978, effectively removing point source contributions in the Cub Run basin. Continued monitoring has demonstrated that ongoing control of both point and nonpoint nutrients is necessary to protect the water quality of the Occoquan reservoir.

The present 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 nine local rain gages; over 30 years of daily stream discharge data; 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).

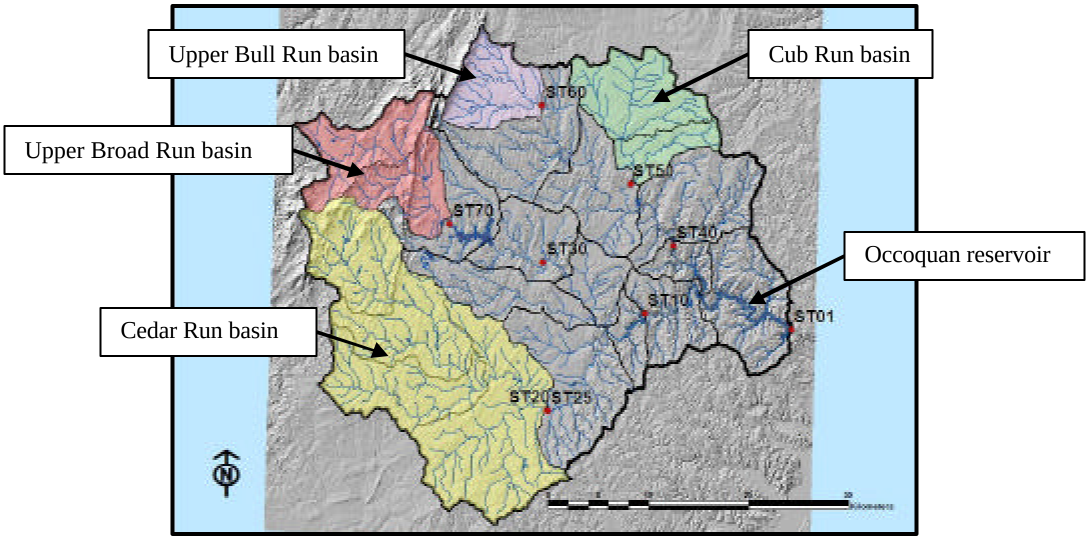

Figure 2. Occoquan Basin (1530 sq. km): Relief Map Showing Four Headwater Basins, Occoquan Reservoir, and Major Water Monitoring Stations.

METHODS

This study analyzes long-term annual precipitation, stream discharge, total suspended solids, total phosphorus, and total nitrogen fluxes in four headwater basins of the Occoquan River. Basins are absent significant, known point source contributions during the 22-year study period (1979-2000). Basin outlets were monitored with automated daily discharge and flow-proportional, volume-integrating storm samplers, and with discrete weekly grab samples for characterization of non-storm flows. A total of 88 basin-years are available for study (4 basins x 22 years). Basin-years with greater than 90 consecutive days of missing water quality samples are deleted. The remaining 76 basin-years have, on average, 33 discrete non-storm samples and 17 composite storm samples per year. Missing flow data is infilled using the drainage area ratio method (Johnston, 1999) with adjacent gaged basins. Missing constituent concentrations are infilled using corresponding seasonal medians for each constituent and basin. Annual NPS pollutant loads are estimated as the product of flow times concentration using a modified OWML method (Johnston, 1999) to sum independently-calculated storm and non-storm loads. Initial load estimates are then adjusted using historic constituent means (table 1) times the difference of total flows from the initial summation and total flows based on records of total daily flow volumes. Precipitation, stream discharge, and NPS pollutant loads are normalized by basin area for further analysis.

Table 1. Historic constituent means for annual load adjustment, mg/L.

Basin	Mean TP	Mean TSS	Mean TN
Cedar Run	0.13	40.27	1.42
Cub Run	0.12	77.68	1.34
Upper Bull Run	0.12	58.88	1.18
Upper Broad Run	0.10	38.96	1.14

In each basin, the relationship of runoff to rainfall is evaluated as a function of season and landscape in order to assess hydrologic patterns across time. Annual NPS pollutant fluxes are plotted against changing precipitation and discharge conditions in order to provide a long-term perspective on the potential for change due to urbanization.

RESULTS AND DISCUSSION

Mean storm flow volume as a percent of total annual flow volume is greater than non-storm flow volume only in Cub Run, the most highly urbanized basin (table 2). Total drainage area from the four headwater basins makes up approximately 47% of the Occoquan basin. Annual loads from the four basins made up, on average, 40% of total Occoquan basin NPS pollutant loads, with total flows and loads generally proportional to basin drainage area (table 3). Comparison of the urbanizing Cub Run basin with the Upper Broad Run basin, however, reveals that Cub Run had more than twice the average TSS load as Upper Broad Run, a similar-sized basin. Cub Run basin had 9% greater average annual flow volumes and 23% and 16% greater annual TP and TN yields, respectively, than Upper Broad Run basin. Average annual TSS yields for Cub and Upper Bull Run basins were significantly higher than the other ag/forested watersheds.

Table 2. Percent non-storm vs. storm flow in Occoquan headwater basins.

Basin	Non-storm flow (% of total)[1]	Storm flow (% of total)[2]
Cedar Run	43.5	41.3
Cub Run	40.4	51.8
Upper Bull Run	48.6	45.1
Upper Broad Run	65.3	27.7

Note 1: represents less than 3058 non-storm samples (10/4/78-5/14/01)

Note 2: represents less than 1523 storm samples (11/18/78-3/29/01)

Table 3. Mean annual loads for four headwater basins of the Occoquan, 1979-2000.

Basin	Area, km^2	Total flow, m^3	TP load, kg	TSS load, kg	TN load, kg
Cedar Run	398	1.60e+08 (402,000 m^3/km^2)	25,200 (63.3 kg/km^2)	11,000,000 (27,600 kg/km^2)	234,000 (587 kg/km^2)
Cub Run	127	4.90e+07 (386,000 m^3/km^2)	7,720 (60.7 kg/km^2)	6,080,000 (47,900 kg/km^2)	69,800 (550 kg/km^2)
Upper Bull Run	67	2.41e+07 (360,000 m^3/km^2)	4,320 (64.5 kg/km^2)	2,790,000 (41,600 kg/km^2)	35,300 (527 kg/km^2)
Upper Broad Run	131	4.64e+07 (354,000 m^3/km^2)	6,480 (49.5 kg/km^2)	2,860,000 (21,900 kg/km^2)	62,400 (476 kg/km^2)

Long-term, Theissen-averaged rainfall for the Occoquan basin is 1008 mm (39.7 in), with 55 percent of the rain falling in spring and summer (March-August). The average annual runoff ratio for each basin ranged from 0.36 to 0.37 (table 4), suggesting deep percolation and/or evapotranspiration. Correll et al. (1999b) reported long-term, average evapotranspiration rates of 807 and 818 mm per year for two ag/forested watersheds in Maryland and West Virginia, respectively. Assuming 813 mm evapotranspiration per year for the Occoquan basin, significant deep percolation appears unlikely. Seasonal runoff ratios reveal generally higher runoff ratios in spring and winter for all basins, probably due to reduced ground cover and evapotranspiration from December to May.

Table 4. Hydrologic averages, Occoquan basin, mm/yr.

	Cedar Run	Cub Run	Upper Bull Run	Upper Broad Run
Predominant land use	forest/ag	urban	forest/ag/residential	forest/ag
Precipitation[1]	1008	1008	1008	1008
Discharge[2]	380	384	376	373
Runoff ratio	0.36	0.37	0.36	0.37
Evapotranspiration[3]	813	813	813	813

Note 1: Basin-wide Theissen average, 1951-2002.
Note 2: Estimated as average annual discharge divided by basin area, 1979-2000.
Note 3: Estimated from similar catchments in Maryland and West Virginia (Correll et al., 1999b).

Regression of annual flow and NPS pollutant flux vs. annual precipitation confirm the strong linkage between precipitation-driven flow and NPS pollutant flux in the four headwater basins of the Occoquan. Correlations of annual constituent concentrations vs. stream discharge demonstrate that TSS and TP concentration is more strongly correlated with storm discharge than TN, due likely to significant particle detachment during storm conditions. Alternately, the relationship between TN concentration and non-storm discharge is stronger than TSS and TP. Storm and non-storm flow partitions suggest that NPS storm fluxes in these mixed land use basins are laden with particulate constituents, while non-storm fluxes are more closely associated with dissolved constituents.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Virginia Water Resources Research Center and the Charles E.Via, Jr. Department of Civil & Environmental Engineering. Collaborative support from the Occoquan Watershed

Monitoring Laboratory, the Northern Virginia Regional Commission, and the Mid-Atlantic Regional Earth Science Applications Center provided the data for this study.

CONCLUSIONS

This research quantifies nonpoint source sediment and nutrient fluxes from four headwater basins in the Piedmont physiographic province of the Chesapeake Bay drainage for up to 22 years. Only one of the basins, the 127 km^2 Cub Run watershed, is rapidly urbanizing. Basin outlets were monitored for characterization of seasonal and annual flows, along with annual fluxes of total suspended solids and total phosphorus and nitrogen. Results indicate strong correlations between annual and seasonal stream discharge and precipitation, annual NPS pollutant loads and precipitation, and TSS and TP concentrations with storm flow. Cub Run basin had disproportionately higher TSS loads and a majority of total flow as storm flow.

REFERENCES

Correll, D.L., Jordan, T.E., and D.E. Weller. 1999a. Precipitation effects on sediment and associated nutrient discharges from Rhode River. *J. Env. Qual.* 28(6):1897-1907.

Correll, D.L., Jordan, T.E., and D.E. Weller. 1999b. Effects of interannual variation of precipitation on stream discharge from Rhode River watersheds. *Journal of the American Water Resources Association*. v 35(1) Feb 1999. p 73-81.

Dougherty, M., Dymond, R.L., Grizzard, T.J., Godrej, A.N., and C.E. Zipper. 2002. Evaluation of land use and population change on pollutant delivery from an urbanizing watershed. In: *Proceedings Virginia Water Resources Symposium 2002,* Nov. 6-7, 2002, Richmond, VA.

Driver, N.E. and G.D. Tasker. 1988. *Techniques for estimation of storm-runoff loads, volumes, and selected constituent concentrations in urban watersheds in the United States*. U.S. Geological Survey Open-file report 88-191, Denver, CO.

Johnston, C.A. 1999. *Development and evaluation of infilling methods for missing hydrologic and chemical watershed data.* M.S. Thesis. Virginia Tech, Blacksburg, VA.

Metcalf & Eddy, Inc. 1970. *1969 Occoquan Reservoir Study*. Completed for the Commonwealth of Virginia State Water Control Board. April 1970.

Novotny, V. 1999. Integrating diffuse/nonpoint pollution control and water body restoration into watershed management. *J. Amer. Wat. Res. Assoc.* 35(4):717-727.

Randall, C W. and T.J. Grizzard. 1995. Management of the Occoquan River basin: a 20-year case history. *Water Science & Technology*. 32(5-6):235-243.

U.S. EPA. 1983. *Results of the Nationwide Urban Runoff Program. Volume I -Final Report*. NTIS PB84-185552. Water Planning Division, WH-554, Washington, DC.