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Elevated Nitrogen and Phosphorus Concentrations in Urbanizing Southwest Washington Streams

Abstract

In southwest Washington, rapid population growth and associated land use change have resulted in elevated stream nutrient concentrations. To evaluate the extent and nature of human alterations to stream nutrient concentrations in this region, we compiled four water years of total phosphorus (TP) and dissolved inorganic nitrogen (DIN) data from two long-term monitoring programs. We also quantified watershed characteristics likely to affect aquatic nutrient loading, and tested for correlations between these characteristics and stream nutrient concentrations. Average nutrient concentrations in study streams were significantly elevated relative to EPA recommended nutrient criteria in all sites for DIN and in nine out of 14 sites for TP. Of the watershed characteristics investigated, percent “impervious” (+) and percent “forested” (-) were the best predictors of TP concentration ($R^2 = 0.41$ and 0.64, respectively, + and – indicate the slope of the regression). Percent “developed” (+) and percent “forest and woody wetland” (-) were the best predictors of DIN concentration ($R^2 = 0.75$ and 0.73, respectively). In urban streams, the mean dry season DIN concentration was significantly higher than the mean wet season DIN concentration, but this pattern was reversed in less urban watersheds. Urban streams also had significantly higher DIN than non-urban streams. The strong relationship between DIN and “developed land” suggests that as southwest Washington’s population continues to grow, targeted N management will become increasingly important. The strong negative relationship between “forest and woody wetland” and both TP and DIN concentration suggests that this land use type is particularly important in reducing stream nutrient loading.

Keywords: Nitrogen, phosphorus, watershed, land-use, urban

Introduction

Over the last several decades, high levels of nutrient loading and associated degradation of water quality have been extensively documented in freshwater systems across the United States (USEPA 2006, USGS NAWQA 2010). This pattern can largely be attributed to human activities, which have more than doubled the rate at which biologically available nitrogen (N) and phosphorus (P) are mobilized across the landscape (Vitousek et al. 1997, Bennett et al. 2001, Galloway 2008). At the global scale, anthropogenic sources of biologically available riverine nutrients exported to the coastal zone are now greater than natural sources (Seitzinger et al. 2005). Within the United States, 47% and 39% of wadeable streams exhibit elevated total N (TN) and total P (TP) concentrations relative to reference conditions respectively (Herlihy and Sifneos 2008).

Anthropogenic sources of N and P include organic and inorganic fertilizers, human sewage, detergents, and (for N) fossil fuel combustion and N fixing crops. While these nutrients are produced and applied largely to the terrestrial landscape, they are mobile and can leach from soils to surface or groundwater if the rate or timing of application is not optimized for biotic uptake. Alterations to the landscape associated with urbanization and agricultural practices often affect hydrologic flow paths, thereby directly influencing the timing and magnitude of nutrient transport to surface waters. For instance, impervious surface cover has been directly related to increases in overland flow (Arnold and Gibbons 1996) and resultant erosion of sediment and associated nutrients. A similar phenomenon is also seen in pasture systems where grazing and associated soil compaction has been

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shown to cause increased sediment and P loss in runoff (Hart et al. 2004). Increased overland flow associated with impervious or compacted surface cover has also caused urban streams to exhibit a flashier hydrology than reference sites (Arnold and Gibbons 1996), and severe stream channel incision in a number of systems (Walsh et al. 2005). Stream incision combined with urban storm water systems can also result in an urban hydrology that acts to cutoff contact between the stream and its rooted riparian zone, thereby minimizing the retention of upslope nutrients (Bernhardt et al. 2008). Urbanization may also cause fundamental changes to within-stream ecosystem function, resulting in a reduced capacity for nutrient removal (Paul and Meyer 2001, Meyer et al. 2005).

In addition, human alteration to the landscape can be strongly correlated with stream nutrient concentrations due to patterns of N inputs associated with particular land use classes (e.g., fertilizer application on agricultural lands). At the county level, the interplay between land use and water quality should be of particular interest to local managers who make zoning decisions that may directly affect stream nutrient concentrations.

In southwest Washington, an understanding of the dominant relationships between land use and stream water quality is particularly important given the rapid rate of land use change this area is currently experiencing. Clark County's (County) population has grown 205% over the past 35 years and is projected to rise from 432,000 (US Census Bureau 2009) to above 0.5 million in the next 15 years (Clark County 2007); much of this increase is expected to occur in the suburbs and as a consequence will result in conversion of agricultural land to suburban, developed land. Importantly, eight of the 14 watersheds in this study occur in a national nutrient ecoregion that is relatively data-poor with respect to small stream water quality (Herlihy and Sifneos 2008). The national nutrient ecoregions referenced here are aggregations of Omernik III ecoregions used by the US EPA to develop recommended nutrient criteria for streams, rivers, lakes and reservoirs (USEPA 2000, 2001), and are described in Herlihy and Sifneos (2008).

In this study, we examine four years of monthly water quality data (spanning October 2003 to September 2007) from 15 storm water-influenced streams in Clark County, WA, in order to: (1) assess the nutrient status of selected wadeable streams in Clark County relative to recommended nutrient criteria, (2) relate nutrient concentrations at sampling stations to watershed characteristics, (3) examine seasonal patterns in stream nutrient concentrations, and (4) place our findings in a regional context.

Study Area

Study watersheds are located in Clark County, southwest Washington (Figure 1). Land use in this region varies and includes relatively undisturbed natural areas on the eastern side of the county as well as agriculture, pastureland, housing developments, and light industry on the western side. Mean annual precipitation is 92 cm (30 year average; Western Regional Climate Center). Precipitation falls mainly during the wet season (November to June). The soils in this region are mostly alluvial terraces; however volcanic foothills do populate the eastern margin of the county (McGee 1972). The bedrock is primarily volcanic and volcaniclastic (Evarts 2004).

Methods

Stream Data

For this study we used stream monitoring data collected from 15 sites on 12 creeks by the Clark County Water Resources Department (Figure 1) during four water years (2004 to 2007). The 15 sampling locations were selected by the County to be representative of a wide range of conditions across the county. Ten of these sites were monitored through the Long-Term Index Sites (LISP) program and are intentionally located on small streams, which are more likely to be influenced by storm events (Schnabel 2004). The other five sites were part of the Salmon Creek Monitoring Program (SCMP) and were all located along the main stem of Salmon Creek (Schnabel 2003).

The Clark County Clean Water Program collected nitrate-nitrite, ammonium, and TP samples

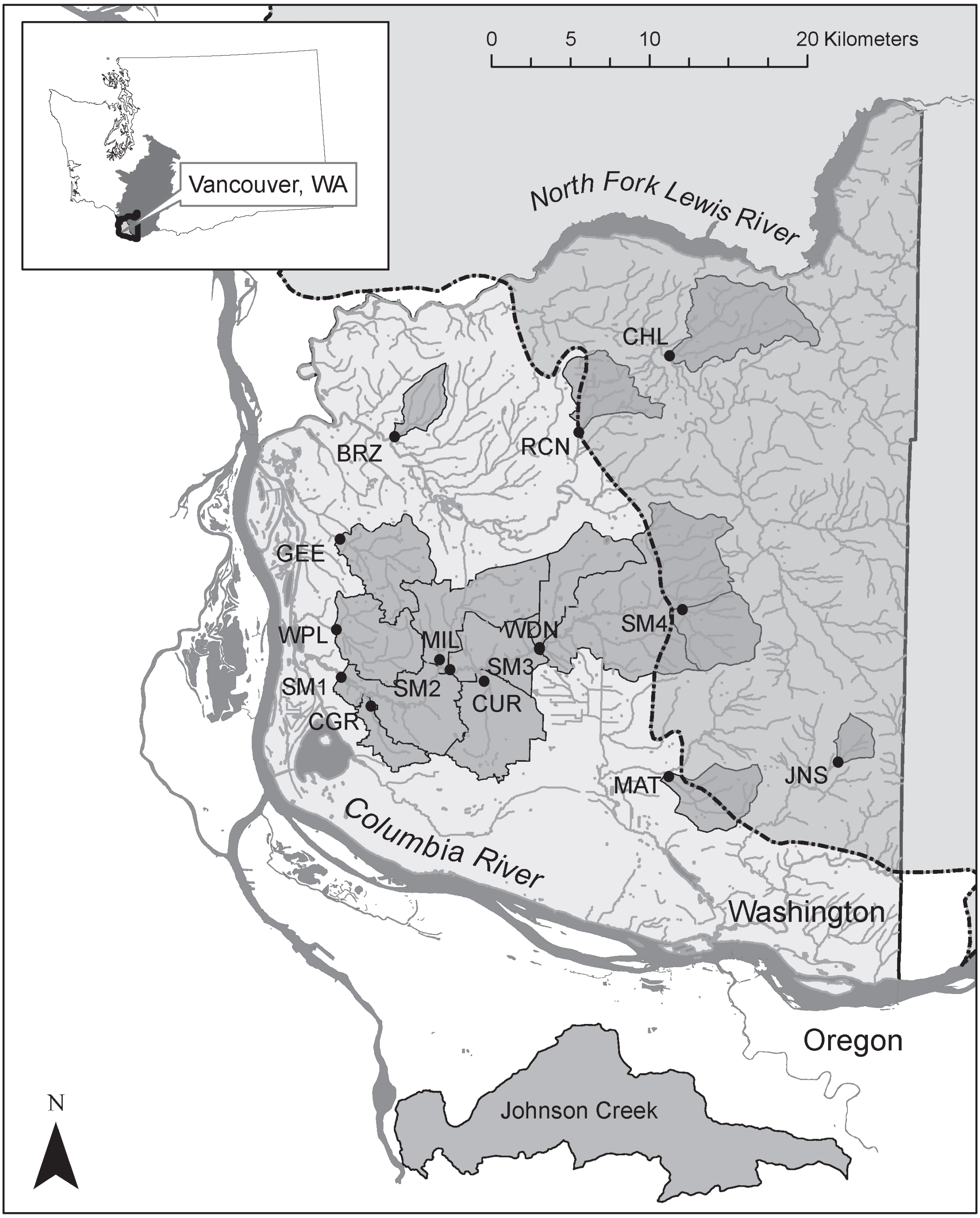

Figure 1. Map of 15 study sites (marked by dots with corresponding three letter station codes), watershed areas (shaded), and streamlines. Inset map shows the location of Clark County (thick black outline) in Washington State (thin black outline) as well as the national nutrient ecoregions represented in this study (ecoregion I in light gray and ecoregion II in dark gray). Ecoregions are also delineated by a dotted line on the main map, where the darker shading to the right of the map is ecoregion II. The Columbia River is the boundary between the states of Oregon and Washington.

at all LISP and SCMP stations on a monthly basis. Samples were stored on ice or refrigerated and transported within 24 hours to North Creek Analytical Laboratories in Beaverton, Oregon for analysis. All analyses were performed according to a Washington State Department of Ecology-approved quality assurance program using EPA colorimetric methods (Schnabel 2003, 2004). Detection limits were 0.05 mg L^{-1} for ammonia, 0.01 mg L^{-1} for nitrate-nitrite, and 0.02 mg L^{-1} for TP (Schnabel 2003, 2004). DIN concentration was calculated as the sum of nitrate, nitrite, and ammonia concentrations.

We compared DIN and TP in streams monitored by Clark County with the 25th percentile of data found for TN and TP from national nutrient ecoregions I and II, which are aggregations of Omernik level III ecoregions (US EPA 2000, 2001). Nutrient ecoregions were developed by EPA to facilitate the development of nutrient criteria by state agencies, and group regions with similar geology, climate, and geomorphology. The majority of the watersheds in this study were located fully or partially within nutrient ecoregion I, the Willamette and Central Valleys (Figure 1). The 25th percentile values of EPA found data for nutrient ecoregion I are 0.310 mg L^{-1} N and 0.047 mg L^{-1} P for TN and TP, respectively (US EPA 2001). Three watersheds were located fully within ecoregion II, the Western Forested Mountains, and three watersheds were located partially within ecoregion I and partially within ecoregion II (Figure 1). The 25th percentile values of EPA found data for nutrient ecoregion II are 0.120 mg L^{-1} N and 0.010 mg L^{-1} P for TN and TP, respectively (US EPA 2000). Since TN concentrations were not available for our study streams, our comparison of DIN concentrations to TN reference concentrations is a very conservative assessment.

Watershed Land Cover

Most of the watersheds assessed in this study were previously delineated and provided to us by Clark County Geographic Information Systems, Vancouver, WA. In cases where there was a discrepancy between the water quality monitoring site and the county watershed delineation, we edited polygons manually in ArcGIS 9.2 (ESRI, Redlands, CA) using the Washington Department of Natural Resources watercourse data set (WDNR, 2005). Areas of watersheds were calculated in ArcGIS 9.2.

We used the 2006 National Land Cover Database (NLCD) to determine land cover percentages within each watershed. The NLCD is an image-based dataset of land cover, imperviousness, and tree canopy at 30 m resolution developed by the Multi-Resolution Land Characteristics Consortium (MRLC) (Fry et al. 2011). The percent of each land cover class described below was calculated in ArcGIS 9.2.

For our analyses, we combined the NLCD classes into several different functional classes. The "developed, open space," "developed, low intensity," "developed, medium intensity," and "developed, high intensity" were combined into a single classification of "developed." Similarly, the forested land classes (deciduous, evergreen, and mixed) were combined into a "forested" class. We also combined the three forested land classes with "woody wetland" as has been done in at least one study (King et al. 2005) to account for functional similarities between forests and woody wetlands. In addition, we quantified the percent of each watershed in "cultivated crops" or "pasture hay."

Percent impervious surface was calculated for each watershed using NLCD classifications. The imperviousness dataset gives a value for the percent of each 30-m x 30-m pixel that is covered by impervious surface. We summed impervious area within each watershed and divided by total watershed area to determine the percent impervious surface. Some land uses are double-counted in our percent land use classifications (i.e., "wetland," "forested," and "forested and woody wetland") such that total percent cover for a watershed is sometimes greater than 100%. In other cases, total watershed cover may be less than 100% due to the omission of several land cover classes (i.e., open water and barren land).

Population density was estimated in each watershed using parcel information from the county assessor in GIS format (Clark County GIS). The number of "units," or dwellings, was multiplied by the persons per household for that particular unit and these numbers were then summed within each watershed using GIS. The total number of people per watershed was divided by watershed area to obtain a population density for each watershed.

Statistical Analysis

For our analysis we selected the water years (WY) for which there is consistent monthly data for the largest number of the 15 sampling stations (WY 2004 to 2007) and calculated four-year simple averages of [DIN] and [TP] (n = 48 for each watershed). If more than one month of nutrient data were missing for a particular water year, the sampling location was omitted from the analysis.

In order to assess stream nutrient status, a one-sample, one-tailed t-test was used to determine if individual stream average DIN or TP concentration was significantly greater than reference levels ($\alpha = 0.05$). All data were tested for normal distribution using the Ryan-Joiner normality test and, if necessary, were transformed to meet normal distribution assumptions. DIN concentration, watershed area, population density, and percent impervious surface were all log transformed. TP concentration and the remaining percent cover classifications did not need to be transformed to meet normal distribution assumptions. We treated watersheds located partially in both nutrient ecoregions conservatively by comparing measured nutrient concentrations to the higher of the two ecoregion reference levels. Bonferroni corrections for experiment-wise error rate were not included in this analysis. Readers are advised to consider this in their evaluation of the results.

To assess seasonal variation, we compared mean monthly DIN and TP concentrations in the wet months (November to June) to those in the dry months (July to October). Seasonal DIN and TP data could not be successfully transformed to meet normality assumptions, so a non-parametric Mann-Whitney test was used ($n = 4$ for dry season and n = 8 for wet season).

Linear regression analyses were performed to determine the predictive capacity of watershed characteristics with respect to nutrient concentrations. Watershed characteristics, including log population density, log watershed area, log percent impervious, percent developed, percent wetland, percent forested, percent forested and woody wetland, percent cultivated crop, and percent pasture hay were regressed against average stream nutrient concentrations (TP and log DIN). All statistical analyses were performed in Minitab15 (Minitab Inc., State College, PA).

Results

Stream Data

Mean stream nutrient concentrations were generally elevated relative to reference conditions for the Willamette Valley and Western Forested Mountains nutrient ecoregions (Figure 2). DIN concentrations averaged 1.15 mg L^{-1} ($n = 13$) and TP concentrations averaged 0.06 mg L^{-1} ($n = 12$). All of the sites ($n = 13$) had average DIN concentrations that were significantly higher than the EPA recommended criterion for TN. Nine of 14 sites had average TP concentrations that were significantly higher than the EPA recommended criterion for TP. There was a large range in nutrient concentrations between the study sites (Figure 2). The lowest four-year average concentrations of both DIN (0.27 mg L^{-1}) and TP (0.021 mg L^{-1}) were observed at Jones Creek. The highest four-year average TP concentration in our dataset (0.15 mg L^{-1}) was recorded at Gee Creek while the highest four-year average DIN concentration in our dataset (2.55 mg L^{-1}) was at Cougar Creek.

Seasonal patterns in average monthly DIN and TP concentrations were observable across watersheds (Figure 3). Stream TP concentrations tended to peak in May and then declined steadily through the following April (Figure 3). Seasonal patterns in stream DIN concentration varied by watershed. Cougar and Curtin creeks, the two most urban watersheds, had significantly higher average DIN concentrations than the other streams (Mann-Whitney test, $P = 0.000$). These streams also had significantly higher DIN concentrations during the dry season than during the wet season ($P = 0.000$, Figure 3). In contrast, non-urban watersheds showed significantly higher DIN concentrations during the wet season ($P = 0.023$, Figure 3).

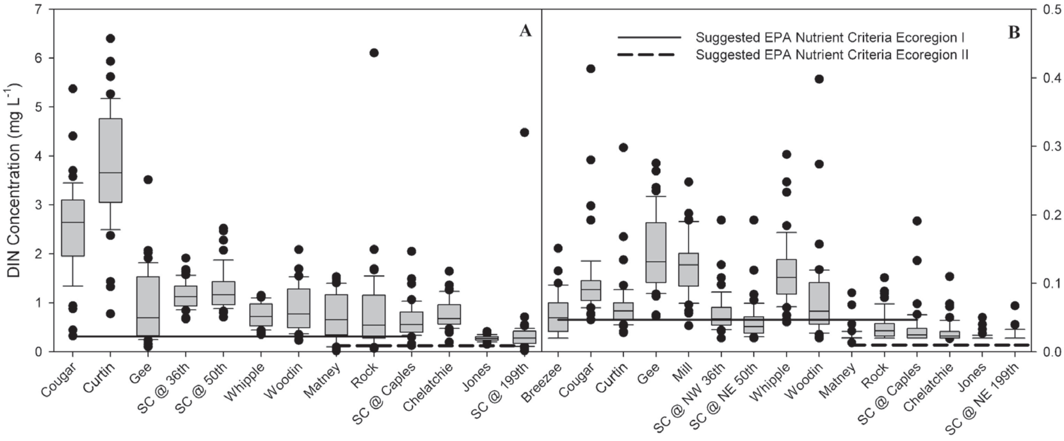

Figure 2. Box and whisker plots of (A) average DIN concentration (mgNL^{-1}) and (B) average TP concentration (mgPL^{-1}), for water years 2004-2007. Lines within the boxes indicate median concentrations. Boxes demarcate the 25th and 75th percentile of data, whiskers demarcate the 10th and 90th percentile, and dots plot data points outside of this range. Solid horizontal lines indicate the recommended nutrient criteria for nutrient ecoregion 1 based on the 25th percentile of EPA found data: 0.310 mg L^{-1} for TN and 0.047 mg L^{-1} for TP. Dashed horizontal lines indicate the recommended nutrient criteria for nutrient ecoregion II based on the 25th percentile of EPA found data: 0.120 mg L^{-1} for TN and 0.010 mg L^{-1} for TP. Matney, Rock, and Salmon Creek 3 straddle the two nutrient ecoregions. Note that in panel A the criterion is for TN while only DIN is plotted. TN values would almost certainly be higher.

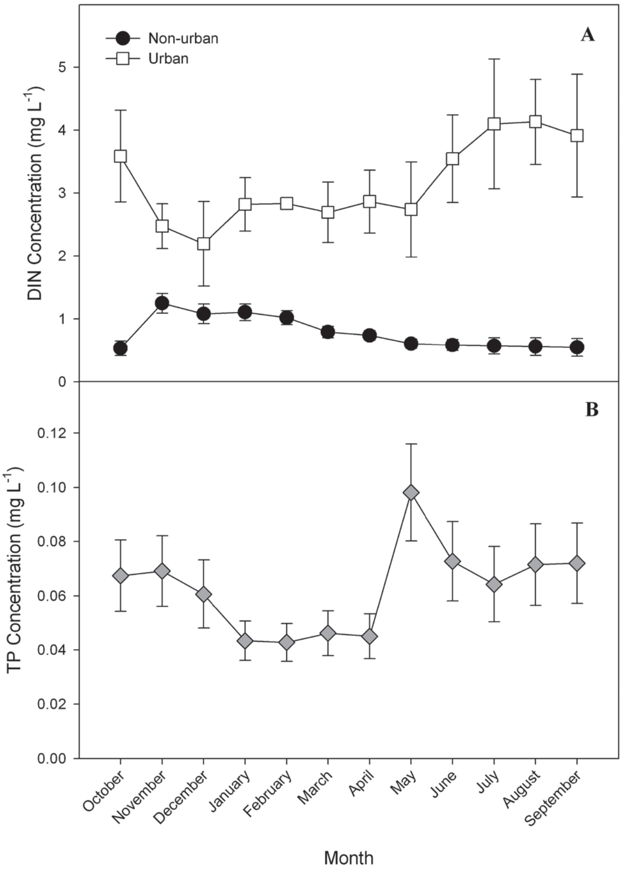

Figure 3. Mean monthly (A) DIN and (B) TP concentrations (mg L^{-1}) for WYs 2004-2007. Different seasonal patterns in DIN concentrations were observed for urban (open squares) and non-urban (closed circles) watersheds. Seasonal patterns for TP concentrations were consistent for all watersheds. Error bars indicate standard error ($n = 15$, $n = 11$, and $n = 2$ for TP, non-urban DIN, and urban DIN respectively).

Watershed Land Cover

While Clark County has a strong agricultural legacy, only one watershed was dominated by agricultural land use (Gee Creek) and none of the watersheds in this study exceed 43% agricultural land (pasture hay + cultivated crops; Table 1). Within the study area, the agricultural land is mostly pasture hay. Cultivated cropland is a minor use of land in this region, and constitutes less than 5% of the total surface area in all but one watershed. Cougar Creek and Curtin Creek were the only two watersheds that had $\geq$ 75% developed cover, while Jones Creek was the only watershed that had $\geq$ 75% forested cover.

Other watershed characteristics also varied widely among study watersheds, including watershed area (6 to 227 km^2), population density (5 to 1452 persons km^{-2}), percent pasture (0 to 37%), and percent forested (1 to 84%) (Table 1).

Linear Regression Analysis

Seven watershed characteristics were significant predictors of TP while five watershed characteristics were significant predictors of DIN (Table 2). Developed land was significantly positively correlated with stream DIN and was the best predictor of stream DIN ($R^2 = 0.75$, $P = 0.000$) (Table 2). Population density and percent impervious surface, two other indicators of urban land use, were also significantly positively correlated with DIN ($R^2 = 0.62$, $P = 0.008$, and $R^2 = 0.55$, $P = 0.02$, respectively). Percent forest and woody wetland was the strongest inversely related predictor of DIN ($R^2 = 0.73$, $P = 0.000$). Percent cultivated crop and percent pasture were not significant predictors of DIN. For TP, percent forest was the best predictor of stream TP, with more forestland in a watershed corresponding to lower TP concentrations (Table 2, $R^2 = 0.64$, $P = 0.003$). Percent impervious surface was the strongest positively related predictor of

TABLE 1. Watershed station codes, size, and land use. Data from the 2006 National Land Cover Database, the Washington Department of Natural Resources water course data set (WDNR 2005), and the Clark County assessor GIS data set (Clark County).

Sampling Station	ID	Watershed Area (km^2)	Population Density persons/km^2)	% Impervious	% Wetlands	% Forest	% Forest and Woody Wetland	% Developed	% Pasture Hay	% Cult. Crops
Brezee Creek	BRZ	9	183	4	8	35	43	12	30	3
Chelatchie Creek	CHL	33	37	1	7	49	56	6	19	1
Cougar Creek	CGR	8	1452	44	0	2	2	97	0	0
Curtin Creek	CUR	33	798	27	1	1	2	79	14	1
Gee Creek	GEE	25	108	8	7	8	14	33	37	6
Jones Creek	JNS	6	5	0	1	84	85	1	0	0
Matney Creek	MAT	17	126	4	5	44	49	21	11	1
Mill Creek	MIL	31	389	13	5	5	9	48	35	2
Rock Creek	RCN	17	87	2	12	40	51	14	8	2
SC @ 36th	SM1	227	464	15	4	20	23	50	16	1
SC @ 50th	SM2	160	301	11	4	27	30	41	15	2
SC @ Caples	SM3	92	110	5	4	40	44	27	10	1
SC @ 199th	SM4	19	64	1	1	60	61	4	0	0
Whipple Creek	WPL	23	592	13	8	14	21	44	26	4
Woodin Creek	WDN	20	528	15	6	21	25	51	15	1

TABLE 2. Linear regression statistics for non-nested watersheds (n = 12 for TP and n = 10 for DIN). Significant P values (α = 0.05) are in bold. "Coefficient" refers to the slope of the regression.

	Total Phosphorus (mg L^{-1})			Log DIN (ug L^{-1})		
Factor	R^2 adjusted	*P*	coefficient	R^2 adjusted	*P*	coefficient
log watershed area	0	0.85	-	0	0.52	+
log population density	0.25	**0.03**	+	0.62	**0.008**	+
log % impervious	0.41	**0.02**	+	0.55	**0.02**	+
% wetland	0	0.77	+	0	0.67	-
% forest	0.64	**0.003**	-	0.70	**0.000**	-
% forest & woody wetland	0.63	**0.004**	-	0.73	**0.000**	-
% developed	0.29	**0.04**	+	0.75	**0.000**	+
% cultivated crop	0.37	**0.02**	+	0	0.89	+
% pasture hay	0.36	**0.02**	+	0	0.67	+

stream TP ($R^2 = 0.41$, $P = 0.02$). The capacity for percent forest and woody wetland cover to predict both DIN and TP makes this land use category a useful predictor of overall stream nutrient status.

Discussion

The impact of urban and urbanizing areas on surface waters is important to understand. Most of the world's cities are located near water and, for the first time ever, more people on earth live in cities than in the countryside (United Nations 2010). Although a number of studies have found that stream water quality can be predicted by land use parameters, the specific impacts of urbanized areas on water quality are far from fully understood. This study suggests that, in Clark County, WA, TP and DIN sources are predominantly urban/suburban in nature, and that such sources can substantially increase DIN and TP concentrations in streams draining urban watersheds.

Although N and P levels in this study were not exceedingly high by national or global health standards, they are clearly elevated above baseline conditions. The US EPA drinking water standard for NO_3^--N is 10 mg L^{-1}, and none of the samples from Clark County streams exceed this threshold. However, the average DIN concentration in this study was 1.15 mg L^{-1}, which is about double the national background TN concentration of 0.58 mg L^{-1} (USGS 2010), and quadruple the regional reference of 0.310 mg L^{-1} (EPA 2001) used in this study. Chronic concentrations at this level can certainly affect ecosystem function in streams (Bernot and Dodds 2005). Similarly, the mean TP concentration in this study (0.06 mg L^{-1}) was nearly double the national background levels of 0.034 mg L^{-1} (USGS 2010) and 25% above the regional reference of 0.047 mg L^{-1} (EPA 2001) used in this study, suggesting that TP in Clark County streams is high by national standards. The elevated nutrient concentrations observed in urbanizing Clark County streams is consistent with national patterns of elevated TN and TP concentrations in urban streams. The National Water Quality Assessment reports a median TN concentration of 2 mg L^{-1} and a median TP concentration of 0.25 mg L^{-1} in urban streams (USGS 2010).

While comparing our regional results to national and ecoregion-specific nutrient criteria is a necessary first step in assessing nutrient status, it should be noted that environmental heterogeneity poses significant challenges to the reference site approach (Herlihy et al. 2008). Ideally, several reference, or least impacted, sites would have been included in the Clark County dataset, but county-wide monitoring efforts were specifically focused on sampling storm water influenced or otherwise impacted streams. Of all watersheds studied, Jones Creek probably provides the best reference site because it is only 1% developed

(Table 1). Here we use a proxy for reference condition based on the 25th percentile of all regional found data compiled by the US EPA in their initial assessment of nutrient status of the nation's rivers and streams (US EPA 2000, 2001). As stated earlier, this approach is less desirable than setting reference conditions based on data from least impacted sites; however this is the best estimate of reference conditions available due to a limited sample size for reference streams in this region (Herlihy and Sifneos 2008).

Although nutrient source attribution is beyond the scope of this study, insights from linear regression and seasonal analyses may serve as a springboard for future studies. The positive correlation between TP and impervious cover suggests that runoff from urban areas is a source of stream TP. However, the high TP concentrations observed during the dry summer months suggest an additional source of phosphorus that is independent of runoff, such as point sources, leaky sewage pipes or septic systems, or groundwater inputs with high P, as is seen in the Tualatin basin of northwest Oregon (Wilson et al. 1999). Additional information on groundwater P concentration as well as sewage infrastructure and point sources, would help tease apart the relative importance of these potential sources of phosphorus.

Both linear regression analysis and seasonal analysis suggest an important link between urbanization and stream DIN loading. While developed land was positively correlated with TP, it was a much better predictor of DIN (Table 2). Other indicators of development—population density and percent impervious surface—were also positively related to DIN concentrations (Table 2). The difference in the seasonal patterns of DIN between the two most developed watersheds and the rest of the sampled watersheds highlights an important difference in the N dynamics of urban and non-urban systems. The non-urban watersheds exhibit seasonal patterns in N concentrations typical for temperate climates. N concentrations appear runoff limited, wherein the highest concentrations are seen in the fall and winter as the landscape is wetting up and nitrate that has accumulated during the dry season due to the microbial mineralization of organic matter and subsequent nitrification is flushed from the terrestrial system to the river network. Additionally, biological uptake in the streams is low in the winter due to temperature and light limitations to primary productivity, resulting in even higher dissolved nutrient concentrations during the winter months. In the most urban systems in this study, however, highest [DIN] is observed during the dry summer months, when stream flows are lowest. This suggests that sewage inputs, or possibly some other source such as runoff from irrigated fertilizer or residential lawns, is concentrated during the summer when flows are low and is then diluted by relatively nutrient-poor runoff during winter runoff events.

In contrast to our study, nutrient sampling along a nearby rural to urban gradient in the urbanizing Johnson Creek watershed in Portland, Oregon revealed higher N concentrations in the rural and agricultural upper regions of the watershed (Sonoda et al. 2001). In fact N concentrations at rural Johnson Creek sites were comparable to N concentrations at urban Clark County sites, whereas N concentrations at urban Johnson Creek sites were comparable to rural Clark County sites. Higher N concentrations in the rural regions of Johnson Creek may be due to differences in N-use intensity between the two sites. The rural regions of the Johnson Creek watershed consist primarily of open grazing land and nurseries that are likely heavily fertilized whereas agriculture was almost never the dominant land use in Clark County sites. Higher [DIN] concentrations in the urban areas of Clark County may result from differences in sewage or storm water management. Regardless of the mechanism, it is clear that the relationship between land use and water quality can vary on regional spatial scales.

The elevated stream nutrient concentrations observed in this study, the projections for further population growth in Clark County, and the relationship between DIN and developed land observed in our linear regression analysis suggest the need for targeted management of N loading. The strong negative relationship between "forest and woody wetlands" and both DIN and TP suggest that this land use class plays an important role in maintaining good water quality in urbanizing watersheds of this region. In addition to being a small source of N and P, forest and woody wetlands likely function to remove nutrients via plant uptake, denitrification, and soil sorption processes. If these land use types are placed downslope of nutrient sources in regions that are hydrologically connected to the river network they may serve to intercept N and P (King et al. 2005, Alberti et al. 2007). The role of forest and woody wetlands in the retention and removal of N and P should therefore be the subject of additional studies and perhaps the focus of regional conservation efforts.

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