THE SUBURBAN STREAM SYNDROME: EVALUATING LAND USE AND STREAM IMPAIRMENTS IN THE SUBURBS

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Abstract: Development is known to impair stream water quality at moderate to high levels of urbanization, but the effects of low-density urban expansion, the kind occurring on the outskirts of many cities, remain unclear. We examined five suburban headwater streams in Duchess County, New York whose watersheds contained between 4.7% and 34% impervious surface cover. We measured Cl^- and nitrate-N (NO_3-N) concentrations in water samples taken at four to six sites on each stream in winter and summer. Even at low levels of population and impervious cover, concentrations of both Cl^- and NO_3-N exceeded reference levels found in cleaner streams in the region. Chloride levels were elevated in upper reaches and remained elevated or continued to increase downstream, with a linear response to impervious cover. Nitrate-N increased downstream in all watersheds, indicating that NO_3-N inputs exceeded natural denitrification and uptake in both winter and summer. Nitrate-N responded logarithmically to impervious surface cover, with steep increases at low levels of imperviousness. Per-capita inputs were also high in rural areas. Agricultural inputs were not sufficient to explain observed trends in NO_3-N; we interpret inputs to result chiefly from low-density exurban expansion. Widespread residential expansion has significant impacts on water quality that have not previously been acknowledged. [Key words: chloride, nitrate, impervious surface cover, urban watersheds, water quality.]

INTRODUCTION

Land use policies on the periphery of American cities have often allowed or encouraged the expansion of low-density suburbs (USEPA, 2004; Richards, 2006). These conditions lead to changes in the percentage of impervious surface cover

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(ISC) in a watershed, a factor that has the potential to impair water quality in urban streams. In cities and inner suburbs, increasing ISC contributes to higher salinity and nutrient loading compared to forested environments (Groffman et al., 2004; Walsh et al., 2005; Shields et al., 2008). Studies of ISC effects have tended to focus on contrasts between highly developed and undeveloped (e.g., forested) watersheds. In recent decades, however, low-density suburban expansion into exurban areas (beyond both the relatively densely developed urban core and inner suburbs) has been a prominent aspect of land use change in the United States. What are the effects of these low-density developments on surface water quality?

A variety of factors can encourage low-density development. Among these factors are zoning laws that enforce large lot sizes, transportation systems that focus on improving rural highway networks, and road-salting policies that maintain snow-free winter road conditions in snow-belt states, thus facilitating residential expansion outside the urban core. Low-density zoning is supported in part by codes that limit septic density (USEPA, 2004; Richards, 2006). Residential septic systems rely on ecological services such as bacterial decomposition and aeration in soil to decontaminate and take up nutrients from human waste. Low-density codes are designed in part to safeguard health and water quality by maintaining adequate distances between these systems. The rapid expansion of outlying suburbs makes it important to evaluate whether these rules are effective in protecting surface waters.

Impervious surface cover in a watershed has been a useful proxy for multiple aspects of urbanization, such as increasing density of road networks, parking lots, and buildings. These land uses both contribute contaminants to streams and accelerate the movement of contaminants to surface waterways (Doyle et al., 2000; Paul and Meyer, 2001; Feminella and Walsh, 2005). Chloride (Cl^-) levels in streams are strongly associated with percentage ISC, especially where anti-icing road salt is used in winter (Godwin et al., 2003; Jackson and Jobbágy, 2005; Kaushal et al., 2005; Cunningham et al., 2008; Kelly et al., 2008). Elevated levels of nutrients, including nitrate (NO_3^-) are also associated with ISC (Paul and Meyer, 2001; Groffman et al., 2004; Walsh et al., 2005). Because of its contribution to eutrophication in estuaries, NO_3^- is a particular concern in the Hudson River Estuary (Burns, 2006). Watersheds show impairment at 10% impervious surface cover or less (Wang et al., 2001; Kaushal et al., 2005; Wollheim et al., 2005). Recent studies have found effects on biotic health at levels of impervious cover as low as 4–5% (Schiff and Benoit, 2007; Walsh et al., 2007), levels that approximate those of many outlying suburbs. If stream contaminants increase at very low levels of ISC, then low-density residential areas have the potential for disproportionately high per-person impacts on stream health and on the environmental services associated with stream ecosystems. As urban and regional planners consider development and residential expansion in a region, it becomes important to understand whether per-person effects in rural locations are similar to, less than, or greater than per-person effects in urban areas.

To examine the effects of spatially expansive exurban development on stream water quality, we examined water quality and impervious cover in five headwater streams draining directly into the Hudson River in Dutchess County, New York (Fig. 1), an area on the margin of the New York City region. In recent decades, over a

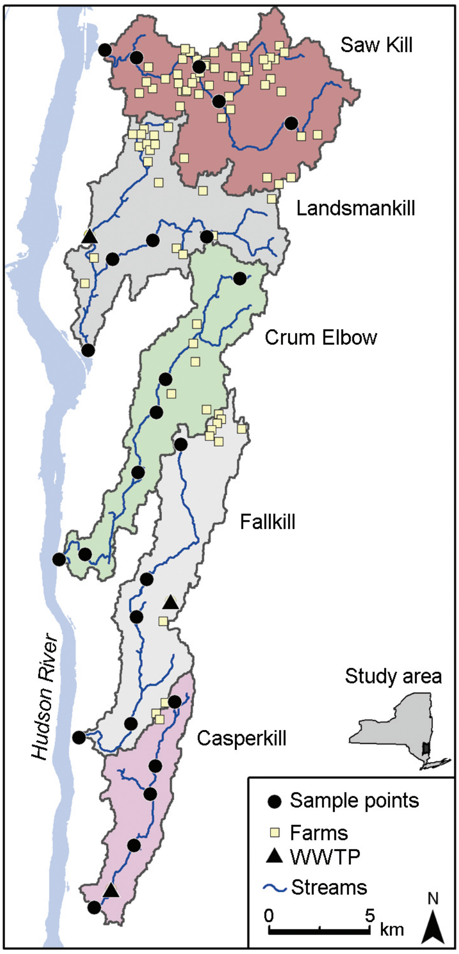

Fig. 1. Sample points on five streams, with farms and wastewater treatment plants (WWTP) also shown. Shaded areas represent watersheds.

third of new buildings in the county have been erected on suburban lots larger than 0.8 hectares (2 acres, Fig. 2). Like many exurban areas of the United States, much of the county is zoned for residential development at densities of 0.8–2.0 hectares (2–5 acres) or more per residence, so the trend of expansive suburban development seems likely to continue. We evaluated the effects of two explanatory factors—basin-scale percentage ISC and settlement concentrations (number of residents in a watershed)—on concentrations of Cl^- and nitrate-N (NO_3-N) in the five streams. We also examined the effect of the farming operations that remain in the watersheds and of wastewater treatment plants (WWTPs) to evaluate whether nutrient levels were more related to ISC or to these other possible sources. To assess severity of impacts, we compared observed levels of Cl^- and NO_3-N to standard levels both

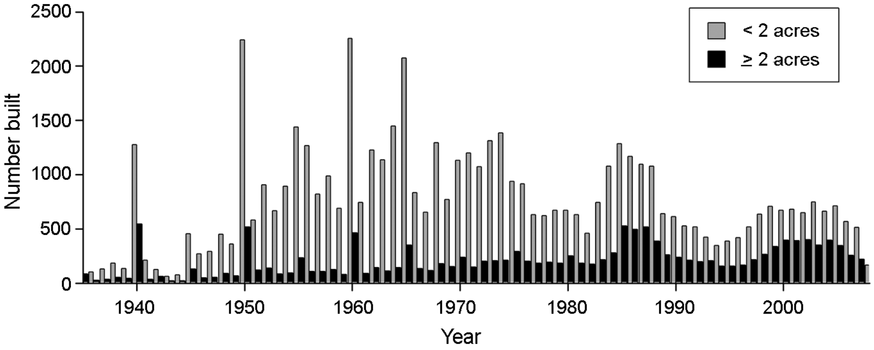

Fig. 2. Number of parcels built on small and large tax parcels, by year, in Dutchess County, NY, 1935–2008.

for highly impaired waters and for pristine waterways. We used longitudinal sampling, with 4–6 sampling sites per stream, to detect whether NO_3-N inputs were greater or less than in-stream potential for denitrification, and to detect changes in streams as watershed-scale land uses changed. We sampled in winter and in summer in order to evaluate seasonal changes in salt and nutrient levels.

STUDY AREA AND METHODS

Study Area

The five Hudson River tributaries have similar watershed areas (30–70 km^2), discharge, topography, and geology, but vary in land use patterns, ranging from highly urbanized to mostly rural. The region has a temperate climate, with rainfall of approximately 1200 mm/yr, distributed approximately evenly through the year, and with snow lasting from approximately December or January to March in recent years. Outside of urban areas, vegetation is dominantly oak-maple deciduous forest, with limited amounts of pasture and orchards. Like many areas on the outskirts of metropolitan areas, Duchess County has seen rapid conversion of rural land to residential development in recent decades. As a result, suburbs have expanded widely beyond the inner suburbs to exurban areas. Low-density development has increased because of local population growth, because of the perceived high quality of life associated with rural residences, and because the area is accessible for New York City commuters. Weekend homes for city residents are also an important part of the local real estate market: in Dutchess County approximately 20% of tax parcels are owned outside of the county.

For each of the five streams we chose four to six sampling sites located at transitions in land cover—for example, downstream of urban or wooded areas—to capture the immediate effect of these changes on cumulative stream conditions. A longitudinal sampling approach allowed us to examine the impact of very low levels of development that occur in upper reaches of watersheds, to determine if threshold effects were detectable, and to evaluate the ability of instream processes either to dilute or to take up nutrients and salts present in the stream.

Land Cover and Population Size

We defined watershed areas upstream of each sample site using the Soil and Water Assessment Tool (SWAT) utility for ArcMap 9.2. This utility delineated watersheds from 1 arc-second digital elevation data taken from the National Elevation Dataset (DiLuzio, 2002; USGS, 2008a). The SWAT utility also delineated stream courses. We used these stream lengths to designate each sample point's distance downstream from the beginning of the stream as designated by SWAT.

We characterized watershed land cover patterns using percentage ISC and the number of farms in the sub-basin upstream of each sampling point. For each subbasin, we calculated the amount of impervious cover from 30 m land cover data acquired from the New York Hudson River Estuary Program and the New York Department of Environmental Conservation Gap Analysis Project (Hudson River Estuary Program, 2005). All GIS analysis was done using ArcGIS 9.2, with percentage impervious calculated using FragstatsBatch for ArcGIS (McGarigal et al., 2002; Mitchell, 2007). We acquired agricultural land use data from county records. County data identified classes of agricultural land use but not intensity of use (e.g., number of livestock). To examine possible impacts of these operations, we calculated the number of agricultural parcels in each sub-watershed recorded as having either livestock (including horses, sheep, poultry, dairy, and other) or crops (row crops, orchards, berry farms, truck farms).

Wastewater treatment plants can also be an important point source of nutrients and possibly salt inputs. We identified wastewater treatment plants (WWTPs) from the New York state listing of the National Pollution Discharge Elimination Systems (NPDES) compliance records (USEPA, 2008). Three WWTPs occurred in our watersheds. To identify sampling points downstream of these plants we geocoded each WWTP according to its latitude/longitude coordinates and mapped these points on watershed maps. Accurate records of the number of households on sewage vs. septic systems were not available in the study area.

To evaluate per capita inputs to streams, we approximated the cumulative population near streams in each watershed area. We selected U.S. Census blocks that intersected a 500 m buffer of stream channels and took the sum of the number of people in those blocks to represent the population within the watershed upstream of a sample point. Because the watersheds were small, the 500 m buffer approximated the lateral extent of the watershed. The cumulative population in all watersheds upstream of a sample point thus represented the cumulative influence of settlement.

Water Sampling and Analysis

Replicate water samples were taken at each site on three separate days within two-week periods in winter (February–March) and summer (mid-June). Samples were taken at close to base flow conditions, based on weather observations and on

USGS streamflow records in an adjacent watershed (Wappinger Creek; USGS, 2008b). Samples were syringe-filtered (Whatman GF/F) in the field into clean 2 mL ion chromatography sample vials. Samples were stored at 4° C and analyzed within two days on a Dionex ICS-3000 Dual RFIC System ion chromatograph for Cl^- and NO_3-N.

Statistical Analysis

Because multiple samples were taken on each stream, we tested for independence among sample sites on any individual stream by including distance from headwaters, nested by stream, in preliminary multiple regression analysis. For both Cl^- and NO_3-N, this nested variable was significant ($p < 0.001$), indicating that differences among sampling sites contributed explanation in addition to other factors and that adjacent sites were statistically independent. We then used multivariate regression to evaluate response of Cl^- and NO_3-N to explanatory factors. These included ISC, number of farms, distance from headwaters (to reflect the effect of downstream changes), season, and stream (to assess differences among streams). Dummy variables were used for the categorical variables stream and season. Continuous variables were log-transformed as necessary to obtain normal distributions. Population was strongly correlated with percentage ISC (Spearman's rho = 0.88, $p < 0.001$), so we excluded population from multivariate analysis. We used stepwise regression, entering terms in order of largest to smallest F statistic, to determine the proportion of variation explained by each of the effects. To examine seasonal differences in levels of Cl^- and NO_3-N, we used ANOVA.

Although population values were excluded from multiple regression because of their correlation with ISC, we were interested in examining the independent effects of population. We therefore calculated per capita inputs of Cl^- and NO_3-N, using population values in the watersheds upstream of each sampling site. We calculated these per capita inputs as:

$$\mathrm{Cl^-/population} = [(\mathrm{mg\ Cl^-/L}) \div (\mathrm{watershed\ population})] * 100, \quad (1)$$

$$\mathrm{NO_3\text{-}N/population} = [(\mathrm{mg\ NO_3\text{-}N/L}) \div (\mathrm{watershed\ population})] * 10{,}000. \quad (2)$$

We then plotted Cl^-/population and NO_3-N/population against percentage impervious cover. We used ANOVA to compare per capita inputs for sub-basins with $< 5\%$ ISC and those with $\geq 5\%$ ISC. Statistical analysis was done using SAS JMP 7.0.

RESULTS

For the five whole watersheds, ISC ranged from 4.7% (Saw Kill) to 34% (Casperkill; Table 1); sub-watersheds ranged from 0.7 to 39.4% ISC. Mean Cl^- levels (mean of all samples for a stream) ranged from 30 to 145 mg Cl^-/L in winter and from 24 to 91 mg Cl^-/L in summer (Table 1). Mean NO_3-N levels ranged from 0.29 to 0.82 mg/L in winter and 0.29 to 0.64 mg/L in summer. Farms were most abundant in the northern watersheds, especially that of the Saw Kill (Fig. 1). Wastewater

Table 1. Mean Levels of Impervious Surface Cover (ISC), Cl^-, and NO_3-N (plus or minus standard error)

			Cl^-		NO_3-N	
Stream	N[a]	ISC[b]	Winter mean [c] (± se)	Summer mean[c] (± se)	Winter mean[c] (± se)	Summer mean[c] (± se)
Saw Kill	5	4.7	30.24 (2.22)	23.90 (2.10)	0.59 (0.10)	0.56 (0.14)
Landsmankill	4	5.4	44.47 (4.75)	30.56 (4.55)	0.46 (0.08)	0.55 (0.19)
Crum Elbow	6	6.0	36.92 (3.37)	26.35 (2.96)	0.29 (0.07)	0.29 (0.06)
Fallkill	5	15.0	54.20 (7.94)	44.47 (9.58)	0.40 (0.08)	0.30 (0.09)
Casperkill	5	34.0	145.79 (39.11)	90.60 (22.18)	0.82 (0.19)	0.64 (0.14)

[a] Number of sites sampled.

[b] Percentage impervious surface cover in whole watershed.

[c] mg/L Cl^- or N, means from three seasonal sampling dates.

treatment plants were located in the lower reaches of three of the watersheds. Levels of ISC, population, Cl^-, and NO_3-N increased from upper to lower reaches of most streams, with the most dramatic increases occurring in the Casperkill, our southernmost and most developed watershed (Fig. 3).

Chloride concentrations were explained primarily by ISC (Table 2, Fig. 4). The categorical variable stream was significant in regression, indicating that the five streams had different patterns of Cl^- accumulation and response to explanatory variables. Number of farms was not a significant contributor to Cl^-. Chloride levels increased linearly with ISC ($p < 0.0001$), and increases were evident even at low levels of ISC (< 5%; Fig. 4). The linear relationship between ISC and Cl^- explains the unusually high Cl^- levels in the Casperkill (Fig. 3), which had about 35% ISC for the three lowest sampling points. Chloride levels increased significantly with distance downstream ($p < 0.01$) for three streams in summer (Casperkill, Fallkill, Landsmankill) and for all streams except the Saw Kill in winter. In a seasonal comparison, Cl^- levels were significantly higher in all streams during the winter ($F = 280$, $p < 0.0001$), with the most significant differences for Crum Elbow, Fallkill, and Landsmankill ($p < 0.005$) and the least for Saw Kill ($\mathrm{p} < 0.03$) and Casperkill ($\mathrm{p} < 0.04$).

Nitrate increases were explained primarily by ISC and distance downstream (Table 2). Farms provided little explanation for NO_3-N and were not significant ($p = 0.52$). For all streams taken together, NO_3-N concentrations increased significantly and logarithmically downstream ($p < 0.001$). When streams were analyzed separately, NO_3-N levels also increased significantly with distance downstream ($p < 0.01$) for all streams in both winter and summer. High NO_3-N levels occurred where wastewater treatment plants were present, but rapid increases occurred upstream of WWTPs, as well (Fig. 3). Seasonally, NO_3-N did not differ when streams were analyzed together ($F = 43$, $p = 0.21$) or when analyzed individually.

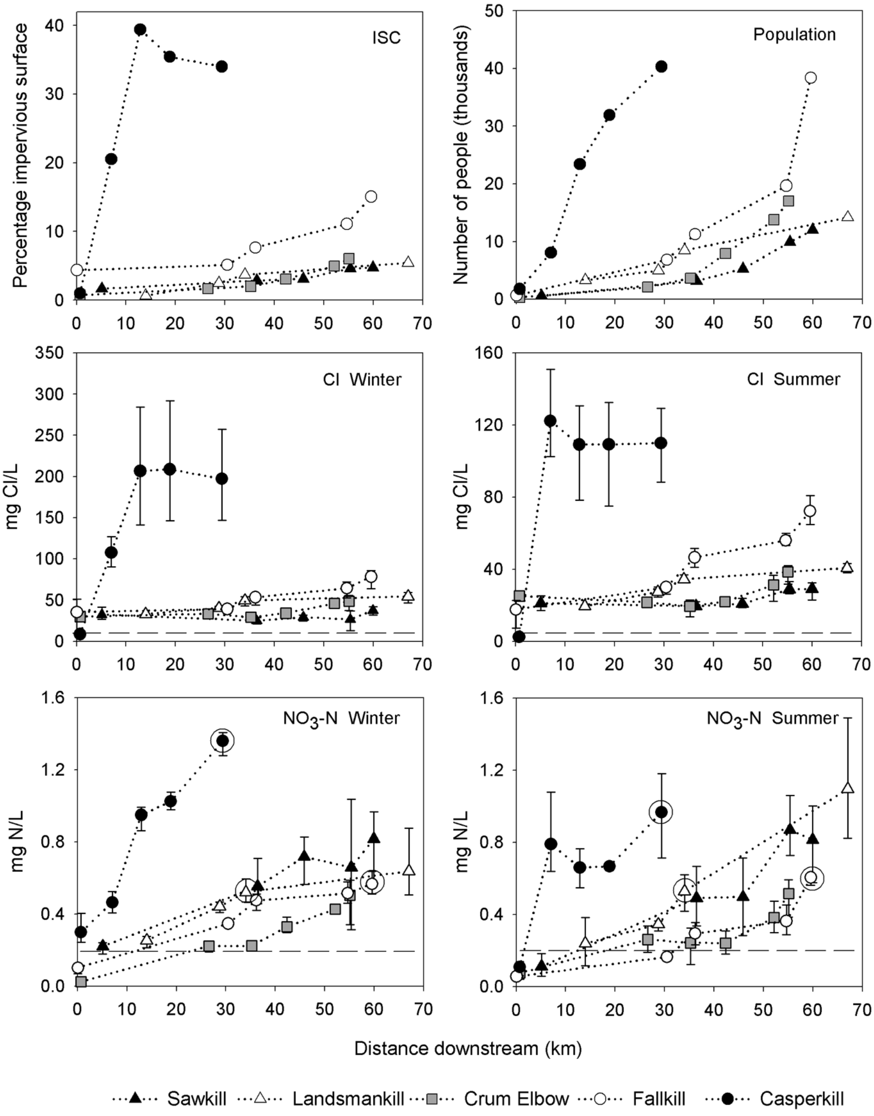

Fig 3. Changes in variables over the length of five streams. Winter and summer graphs show mean values at a site for three sampling days; range bars show maximum and minimum values. Horizontal dashed lines show reference levels of Cl^- and NO_3-N found in clean streams in the region by Dow et al. (2006). Open circles around data points indicate sites directly downstream of wastewater treatment plants.

When examined in terms of inputs/person, concentrations of Cl–/person were significantly higher in areas with < 5% ISC than in areas with higher ISC (ANOVA $F = 11.7$, $p < 0.001$; Fig. 5). Nitrate inputs/person were also significantly higher in areas with < 5% ISC than in areas with higher ISC ($F = 41.6$, $p < 0.0001$).

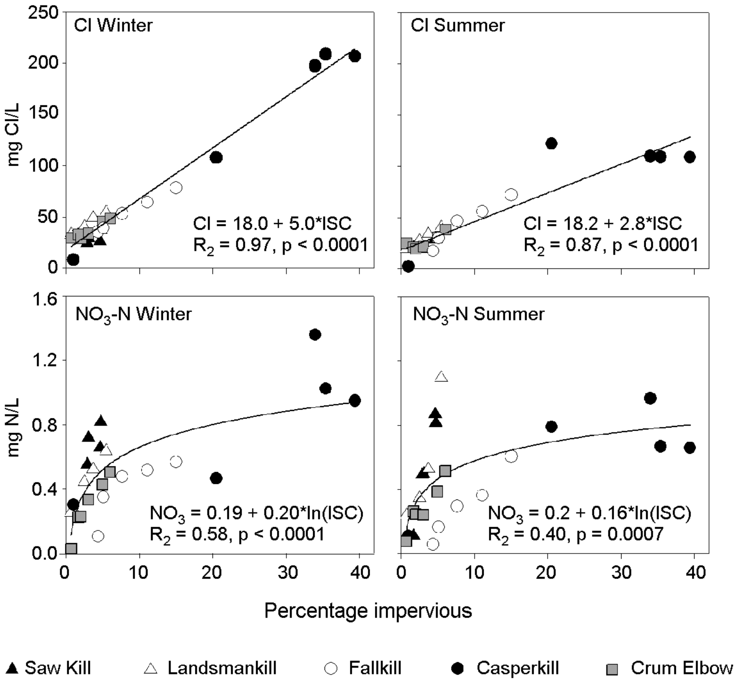

Fig 4. Relationship of Cl^- and NO_3-N to percentage impervious surface cover. Dots show means of triplicate samples from three sampling dates in each season; regression models are shown for seasonal means of all sampling points. Open circles around data points indicate sites directly downstream of wastewater treatment plants.

Table 2. Effect of Explanatory Variables on Cl^- and on NO_3-N

Explanatory variable	Cl^- *F* ratio	*p*	Pct. variation explained	NO_3-N *F* ratio	*p*	Pct. variation explained
Log ISC	377	<0.0001	68.3	38	<0.0001	43.5
Season	48	<0.0001	5.0	5	0.02	0.8
Stream	28	<0.0001	8.1	39	<0.0001	24.8
Distance downstream	12	0.0007	3.2	21	<0.0001	9.1
Log farms	0.3	0.58	<<1	0.4	0.52	<0.1
Overall model	101	<0.0001	84.4	69	<0.0001	80.0

DISCUSSION

Low-density development had a clear impact on stream water quality. Even with ISC levels as low as 1 to 3%, we observed impacts on Cl^- and NO_3-N concentrations. Chloride levels were below the EPA limit for drinking water (250 mg/L Cl^-) in

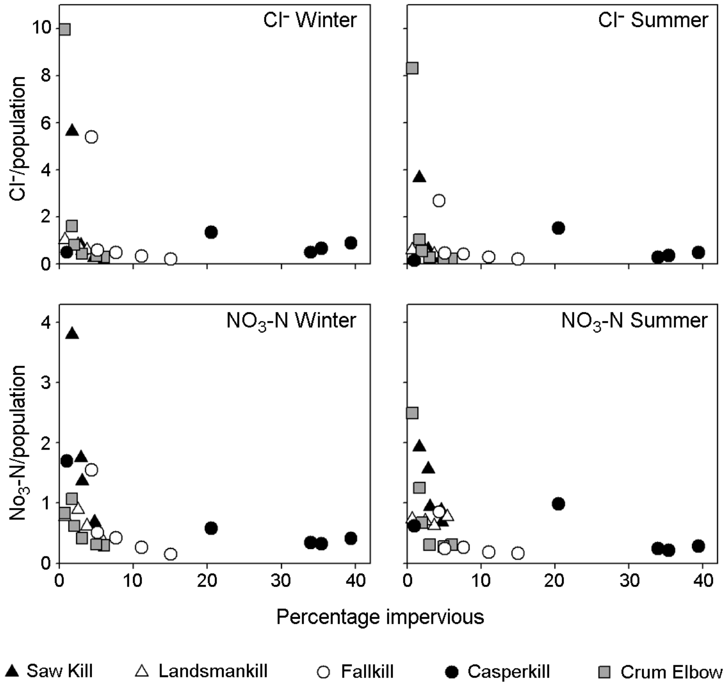

Fig 5. Per-person inputs of Cl$^-$ and NO_3-N, winter and summer, in the five watersheds. Y-axes show mg/person multiplied by an order of 10^2 (Cl$^-$) or 10^4 (NO_3-N).

all but the most urbanized stream (the Casperkill in winter, Fig. 3), but the lowest sample means were above those observed in previous studies of relatively uncontaminated streams in the region. In Hudson Valley streams within the New York City watershed, Dow et al. (2006) reported levels of < 100 milliequivalents Cl$^-$ (< 6 mg Cl$^-$/L) in the cleanest of 10 streams studied in the region. By comparison, all but one of our sites had at least 20 mg/L in both seasons (Fig. 3). For NO_3-N, similarly, our measurements were within the range of EPA acceptable levels (10 mg NO_3-N/L; USEPA 1996), but greater than those in cleaner streams in the area. Dow et al. (2006) found < 0.2 mg NO_3-N/L, and Peterson et al. (2001) reported an average of 0.13 mg NO_3-N/L, in five eastern deciduous forest watersheds. All of the streams had > 0.2 mg NO_3-N/L, except in the highest reaches (Fig. 3).

Taken together, these measures indicate that impairment in these streams is not extreme, but also that impairment is evident even at our lowest levels of development. Findings of elevated salt and nutrient levels are consistent with previous findings for ISC levels at or below 5% (Schiff and Benoit, 2007; Walsh et al., 2007). Our data showed Cl$^-$ and NO_3-N above those of Dow et al. (2006) at $< 2\%$ ISC, suggesting that there is essentially no ISC threshold for water quality (Fig. 4).

Longitudinal sampling can provide useful insights into a variety of water quality questions, despite the potential for spatial autocorrelation among samples. These insights can include evidence of: (1) how responsive streams are to changes in land use; (2) rates of accumulation of contaminants; and (3) possibility of recovery, either by instream processing (N) or dilution (N or Cl^-). In our case, recovery was not evident for either Cl^- or NO_3-N, but accumulation rates differed in important ways, and impairment began very early in the stream courses. These findings would not have been evident if we had sampled the streams only once near their outlets.

Chloride Trends and Sources

Chloride increases occurred in these streams, but in general Cl^- increases were less steep than NO_3-N increases (Fig. 3). For all streams except the Casperkill, our most urban stream, Cl^- increased downstream by a factor of 2, on average (maximum value/minimum value), in both seasons, whereas NO_3-N rose by a factor of 8, on average. The smaller increases in Cl^- apparently results from the extensive road networks that are required in low-density residential areas as well as in high-density areas. Most Cl^- in surface waters in this area has been attributed to road anti-icing salt (Peters and Turk, 1981; Jackson and Jobagy, 2005; Kaushal et al., 2005; Kelly et al., 2008). Higher winter levels of Cl^- also point to road salt as the principal source of Cl^- in these streams. Road salt is a difficult factor to reduce, as drivers from both urban and rural areas have come to expect clear and safe roads in all seasons. The presence of rural-dwelling urban workers seems likely to increase the importance of keeping roads dry in winter, because commuting requires daily travel on a restricted time schedule. Residential development in this region in the past half century has emphasized widely spaced housing without public transportation, while urban areas have been subject to policies of neglect that encouraged out-migration. Consequently, many of the most desirable residential neighborhoods are in remote areas, and families looking for "good" neighborhoods may feel that they have few choices other than suburban living and long commutes on rural roads. Reducing road salt impacts on watersheds may require attention to attitudes about planning policies more than changes in salt use *per se*.

Residential water softeners may be a secondary source of salt in these watersheds, but Kelly et al. (2008) calculated a salt budget for a watershed adjacent to our study area and concluded that less than 3% of salt could be attributed to water softeners. Even if a significant amount of salinity in our streams came from residential water softeners in our watersheds, that would still be consistent with our overall findings that distributed, low-density residential development affects water quality in these streams.

Although we observed higher levels of Cl^- in winter, levels were elevated in summer as well, and concentrations rose with distance downstream in both seasons. These results show that salinity is not just a winter problem. High summer Cl^- levels apparently reflect gradual transport of salt through soil water to streams (Burns, 2006; Kelly et al., 2008). Even our most rural streams (the Saw Kill, Landsmankill, and Crum Elbow; Fig. 3) saw year-round persistence of these high salt levels. This finding underscores the extended temporal, as well as spatial, impacts that road networks can have beyond the urban periphery.

Nitrate Trends and Sources

The non-linear responses of NO_3-N to ISC indicate that NO_3-N was more sensitive to changes in impervious cover in exurban watersheds than in urban watersheds. This difference could represent a shift from septic-dominated systems, which are common with low-density development, to sewer-dominated systems more prevalent in more highly urbanized environments.

The strong correlation between NO_3-N and impervious cover and population (Figs. 4 and 5) suggests that N inputs are mainly anthropogenic. If sources such as atmospheric deposition were chiefly responsible, then more samples should have low levels comparable to those found by Dow et al. (2006) or Peterson et al. (2001). Septic systems are a likely source of NO_3-N in these streams: household septic systems are widely distributed, and many are decades old, if their ages are similar to those of the houses in the study area (Fig. 2). In the urbanized parts of our watersheds, in contrast, city sewer infrastructure removes much of the nutrient load from the watershed by sending it to a wastewater treatment facility (Fig. 4). Lawn fertilizers are another potential source of nutrients, and fertilizer use is another way in which dispersed suburban settlement can input nutrients into the stream system (Robbins et al., 2001; Groffman et al., 2004; Law et al., 2004). A lack of seasonal differences in NO_3-N concentrations also points to septic sources, because septic systems are more likely to be in use year-round. Both septic systems and lawn fertilizers are inputs that can accompany suburban development.

Regardless of whether septic systems or fertilizers are the main inputs to these streams, it is notable that N concentrations rose steadily in the course of all but the most urban stream (Fig 3). Small streams generally have high denitrification potential (Peterson et al., 2001; Triska et al., 2007), but in all the studied streams, in summer as well as in winter, even in areas with low-density development, the current septic density (or other residential sources) apparently contributed NO_3-N to streams at a rate faster than denitrification and nutrient uptake in soils and in-stream biota could remove it from the system. Levels were somewhat lower in summer, probably reflecting more rapid uptake and denitrification than in winter months, but even in summer, NO_3-N levels increased, rather than decreased, in the course of all five streams.

Although farms were present in some of the watersheds, they did not contribute sufficient inputs of nutrients or salts to cause stream impairments commensurate with those from ISC. The lack of effect from farms in these watersheds may reflect the fact that most farms in the study area are small operations, apparently without large numbers of livestock or crop fertilizers. This pattern of small operations may not be unusual on urban peripheries, where recreational and residential land ownership elevate land values, and alternative economic opportunities make large-scale farming less viable than in more concentrated farming areas.

Per Capita Effects

Populations in exurban areas had a disproportionately large per person NO_3-N or Cl^- effect on stream quality compared to more developed areas (Fig. 5). In expansive, low-density development, economic costs of water, sewer, and other infrastructure requirements for each household are widely recognized. Our findings further suggest that the per capita environmental impacts on aquatic systems are also higher in exurban areas. Planning policies that promote in-fill, for example where sewer infrastructure already exists, could reduce these effects. Extensive road networks are needed in lightly populated areas, but exurban residential development further accelerates demands for subdivision roads, for pavement, and for safer winter driving conditions. In terms of watershed impacts, infill in urban and inner-suburban areas is better than further expansion of outlying suburbs.

It is important to note that the watershed scale is not the only scale at which ISC influences stream conditions. Also important (and in some studies more important) are riparian-zone vegetation and soil flora, which can take up NO_3-N and other nutrients (Triska et al., 2007; Walsh et al., 2007). The impacts of ISC can thus be ameliorated by land management approaches, including protection of vegetated stream buffers, maintaining green space along stream courses. Low-impact development strategies, including disconnected storm drainage and on-site infiltration, clustered housing, or bioretention in swales and filter strips (Hood et al., 2007; Dietz and Clausen, 2008), can also be beneficial. In our study area, however, suburban development often follows stream networks, either because stream valleys are relatively level and offer surfaces on which it is easy to build, because road networks follow streams, or because of the aesthetic amenity of streams in the landscape. Thus exurban development often occurs in the zone that is most sensitive for aquatic systems.

There are many arguments in favor of promoting development in already-urbanized areas, including opportunities for walkable communities, lower tax burdens, energy efficiency, community, and conservation of terrestrial and wetland habitat. Our results suggest that additional water quality parameters are likely to benefit from less expansive development patterns. Even the modest levels of rural development, such as those established with 0.8- to 2.0-hectare (2- to 5-acre) zoning, appear to introduce impairments to streams.

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