INFLUENCE OF OPEN SPACE ON WATER QUALITY IN AN URBAN STREAM

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Abstract: Much attention has been given to the impairment of streams in urban areas and to the value of green space in preventing degradation. However, few studies have examined whether green space can remediate water quality downstream of contaminant sources. To assess the degree to which an ecological preserve was able to ameliorate upstream water quality impairments, we examined changes in conductivity, total inorganic nitrogen (TIN), and a family biotic index (FBI) for benthic macroinvertebrates in a partially urbanized stream in eastern New York state, USA. We expected conductivity, which results mainly from road de-icing salt, to decrease in the green space due to dilution from low-conductivity surface runoff. We also expected TIN and FBI to indicate stream improvements in response to increased vegetative cover in the green space. Contrary to expectations, conductivity did not improve in the ecological preserve, although TIN and FBI values did improve. Differences in scales of response explain this contrast in recovery/conductivity responded to basin-wide percentage impervious surface cover (ISC), while TIN and FBI responded to riparian-scale ISC, which declined sharply in the ecological preserve. Conserving riparian green space can aid natural recovery of TIN and FBI. In contrast, controlling conductivity requires watershed-wide management. [Key words: urban watersheds, impervious surface cover (ISC), conductivity, nutrients, riparian buffers, non-point source pollution, water quality.]

INTRODUCTION

The effects of urbanization on water quality in streams have become a growing concern as evidence mounts that distributed, non-point source contaminants derived from roads, parking lots, and other urban land uses can severely degrade

Physical Geography, 2010, **31**, 4, pp. 336–356. DOI: 10.2747/0272-3646.31.4.336

water quality and aquatic ecosystems (Grimm et al., 2000; Paul and Meyer, 2001; Feminella and Walsh, 2005; Walsh et al., 2005b; Cunningham et al., 2009). Urban land uses in a watershed are associated with impairments such as high conductivity (Peters and Turk, 1981; Kaushal et al., 2005; Jackson and Jobbágy, 2005; Conway, 2007), elevated levels of nitrogen and phosphorus (Omernik, 1976; Paul and Meyer, 2001; Groffman et al., 2004), and altered composition of in-stream biological communities (Roth et al., 1996; Wang et al., 2001; Benbow and Merritt, 2004; Roy et al., 2007). Impervious surface cover (ISC) is an easily measured factor that reflects many of the consequences of urban development: impervious surfaces impede infiltration of precipitation, speed runoff from land surfaces to streams, and prevent the uptake of nutrients or contaminants by terrestrial biota. In contrast, vegetated land uses (areas with minimal impervious cover) are important to stream quality both because they typically contribute fewer contaminants than do roads and parking lots and because vegetation and soil microbial activity in the riparian zone can capture nutrients and contaminants and minimize runoff (Zak et al., 1990; McDonnell et al., 1997; Mankin et al., 2007; Triska et al., 2007).

In comparisons of whole watersheds, it is clear that those with little ISC have better water quality than watersheds with high levels of ISC (Cuffney et al., 2005; Walsh et al., 2005b; Morgan et al., 2007; Cunningham et al., 2009). However, few studies have examined responses to changing ISC within the course of a single stream. If watersheds with low ISC have better stream quality than watersheds with high ISC, does it follow that low-ISC areas within a watershed help to remediate impairments already introduced from urban land uses upstream? Studies of ecological resilience in other systems suggest that ecosystems have some ability to recover from disturbance or impairment toward pre-disturbance conditions (Holling, 1973; Gunderson, 2000). The question of resilience has rarely been addressed in the context of watershed studies, but this idea could be useful for understanding both watershed system function and possible effects of land-use planning strategies. For example, evidence of longitudinal recovery would support conservation of green space in a watershed, implementation of riparian buffer management, or planning for clustered development that concentrates impervious land cover in localized areas of a watershed.

Few studies have examined changes in the course of a stream because such a study requires multiple, non-independent samples along a stream to detect downstream changes, and land cover must be analyzed in nested, non-independent subwatersheds. Analyzing non-independent observations can lead to overestimation of the statistical significance of effects, leading to an unrealistic evaluation of the influence of explanatory variables (Diniz-Filho et al., 2003; Hawkins et al., 2007). Comparisons of longitudinal samples are necessary, however, if we are to examine the question of recovery in the course of a stream. As long as conclusions do not hinge on fine differences in p values, this approach may not be inappropriate (Diniz-Filho et al., 2003).

We examined the utility of a longitudinal approach to examine the potential for recovery in conductivity, total inorganic nitrogen (TIN), and a biotic index for benthic macroinvertebrates along the course of an 18 km long stream in southeastern New York state. The stream crosses areas of contrasting land use, including wooded rural areas and a concentrated shopping center development, before entering an ecological preserve and residential neighborhoods. Conductivity values in the local area are strongly associated with the use of road de-icing salt in winter (Peters and Turk, 1981; Godwin et al., 2003; Jackson and Jobbágy, 2005; Kaushal et al., 2005; Cunningham et al., 2008; Kelly et al., 2008; Cunningham et al., 2009), and we anticipated that conductivity levels should decline due to dilution from surface and ground water as the stream passed from areas with highest ISC to areas with low ISC. Nitrogen has many potential sources in the watershed, including effluent from wastewater treatment plants and septic systems, sewer overflows, seepage from landfills, leaf litter, atmospheric deposition, and lawn fertilizers (Valiela and Bowen, 2002; Groffman et al., 2004). Nitrogen generally declines in streams through natural biotic uptake and transformation (Peterson et al., 2001), so we expected improvements in TIN in the green space. However, this might not be the case because the effectiveness of nitrogen removal often declines as nitrogen loads increase (Mayer et al., 2005) and because there are abundant potential sources of nitrogen in an urbanized watershed. Benthic macroinvertebrates respond to cumulative pollutants, nutrient levels, and temperature changes (Hilsenhoff, 1987). We expected the benthic macroinvertebrate (BMI) community to improve with a decline in these contaminant sources in the ecological preserve.

In addition to the question of longitudinal recovery, we examined potential for seasonal recovery in conductivity and TIN. We expected conductivity levels to be lower in summer and fall than during the active salting season of winter. TIN should be higher in winter due to reduced biotic activity and nutrient uptake in the stream ecosystem. Seasonal recovery is an important question in anticipating impacts of winter road de-icing on summer BMI growth and reproduction.

STUDY AREA AND METHODS

Study Area

We sampled 21 points along the Casperkill, an 18 km stream in a partially urbanized watershed in southeastern New York, USA (Fig. 1). The Casperkill has a catchment of 31 km^2 and empties into the Hudson River (41º44´ N, 73º55´ W). Underlying bedrock consists of the Cambro-Ordovician Wappinger Group dolomite and calcareous Hudson River shales. These are overlain by glacial till, with lesser quantities of other glacial sediments. Soils are typically loamy, with silt loams developed on glaciolacustrine deposits and gravelly loams on till. The region's climate is humid temperate, with 1220 mm of precipitation in 2006 and 1100 mm in 2007, distributed approximately evenly throughout the year, although dry months often occur in late summer (National Weather Service, 2007). During the study, average January air temperatures were 1.1 and –0.2°C in 2006 and 2007, respectively; July mean temperatures were 24.2 and 21.9°C. Snow was present from late January to mid-March in both years. Discharge in the stream varies between 0.1 and 4 m^3/s, with an average of 0.4 m^3/s (Minder, 2004). The stream has only one perennial tributary: the 1.5 km Fonteynkill, which drains an urban residential neighborhood. We were not able to identify any other surface or groundwater sources (e.g., springs) that appeared to contribute significant volumes of water that would likely alter stream chemistry

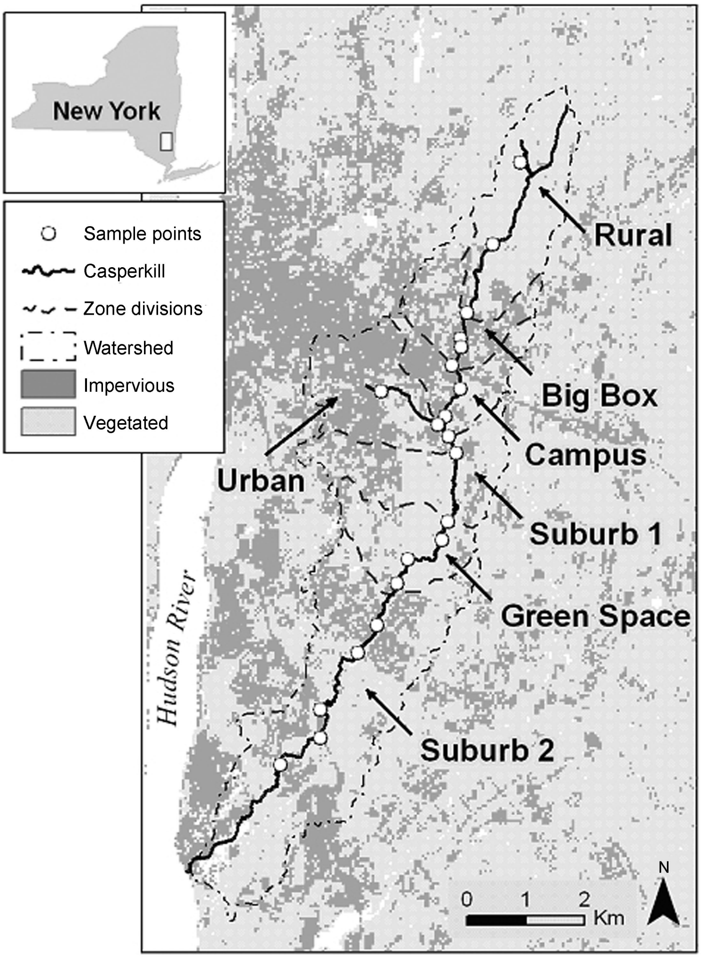

Fig. 1. The study area in southeastern New York state (USA) showing the 21 sample points. The seven zones analyzed in the watershed are delineated with dashed lines. Sub-basins were defined above each sample point.

parameters in this small stream system. Street drains and surface runoff do contribute to discharge along the length of the stream.

The Casperkill passes through seven distinct zones of land use, with varying amounts of impervious cover, before emptying into the Hudson River. Sampling sites were selected at changes in land cover and at distributed points within zones; each land use zone contained two to five sample sites. The uppermost zone ("rural"; number of sampling sites, $n = 3$) comprises woodlands and wetlands, with limited residential and commercial development (Fig. 1). The stream then crosses a zone of expansive shopping centers, parking lots, and government offices, some of which are built atop unlined landfills, a landscape hereafter referred to as the "commercial" zone ($n = 3$). In this zone, segments of the stream are diverted into subterranean culverts and the remainder is confined to a steeply banked, narrow channel lined with rip-rap. Parking lots drain directly into the channel, and a salt storage shed and associated truck-loading area operated by a local department of transportation office lie within 50 m of the stream. Salt has been stored at this site and used on local roads for over 40 years.

Below the commercial zone lies a college campus ("campus;" $n = 2$), where the channel resumes a more normal geomorphic form and a narrow (4–40 m) band of riparian vegetation and tree canopy lines most of the stream. Below the campus zone, the Casperkill is joined by its one perennially flowing tributary, the Fonteynkill, which surfaces from underground culverts about 1000 m upstream of the confluence. The Fonteynkill drains a separate "urban" zone ($n = 2$), which represents a residential portion of the city of Poughkeepsie with impervious surface cover greater than 60%. Despite the high level of impervious cover, the stream channel is bordered by residential lots and a band of trees 4–70 m wide.

Below the confluence of the two streams is an area of suburban residential development ("suburb 1;" $n = 2$) where backyards of homes abut the stream and in which a forested buffer of 20–50 m width has been maintained by most residents. The stream then enters a 110 ha, largely forested ecological preserve ("green space;" $n = 4$), in which it meanders freely across a forested floodplain with a riparian buffer 100–600 m in width before entering another zone of suburban residential neighborhoods with characteristics nearly identical to the first suburban zone ("suburb 2;" $n = 5$). Before entering the Hudson River, the stream crosses a limestone quarry. The lowest sample point was just upstream of the quarry, owing to access limitations.

Sampling for Water Quality and Biotic Indices

We sampled specific conductance (temperature-adjusted conductivity) and nutrients (nitrate, nitrite, and ammonium) at 21 sites along the stream. Sampling was done monthly for 21 months (February 2006–October 2007), in the last week of each month, regardless of weather conditions. At each sample point, in-stream specific conductance (hereafter "conductivity") and temperature were measured using a YSI 556 multimeter probe. Other studies in the region have found conductivity to be strongly related to sodium chloride resulting from road de-icing salt (Kaushal et al., 2005; Kelly et al., 2008). To test this relationship for the Casperkill, we compared conductivity readings from an in-stream sonde (YSI model 6920-S) to chloride levels in water samples collected at the sonde site approximately weekly for 24 months (2007–2009). We tested samples for chloride concentrations using a Dionex ICS-3000 ion chromatograph and then regressed conductivity against chloride. The regression coefficient of determination (r^2) was 0.95 ($p < 0.001$). Consequently, we interpret conductivity to reflect salt contamination, rather than natural sources such as dissolution of dolomite and limestone bedrock.

For nutrient analysis, triplicate samples were collected in 100 ml opaque, high-density polyethylene bottles. Samples were stored at 4°C and analyzed unfiltered within 1 to 3 days. Nitrate levels were analyzed using the copper-hydrazine reduction method (Strickland and Parsons, 1960) and ammonium levels were analyzed using the phenol-hypochlorite method (Solorzano, 1969). We measured nitrite levels using sulfanilamide-naphthyl ethylene diamine (Strickland and Parsons, 1978). For all N species, we used mean values from the triplicate samples. Because we were interested in total nutrient levels and because relative concentrations of the three N species changed seasonally, we summed the N component of the three species and we report total inorganic nitrogen (TIN).

We used kick-net sampling to collect benthic macroinvertebrates. Kick-net sampling was done at riffles, where rocky stream beds provide suitable habitat for stream-dwelling invertebrates. Duplicate kick-net samples (Bode et al., 2002; Barbour et al., 2006) were collected once each summer (June 2006 and June 2007) at the 14 sites with riffles. Collection progressed diagonally upstream from bank to bank for each sample to ensure that the entire stream width and its localized substratum types were sampled. Sampling was conducted for five minutes. Duplicate sample transects were taken 3–5 m upstream to avoid resampling the same disturbed substratum. The entire contents of the net—including pebbles and cobbles that could hold attached animals, woody debris, and dislodged vegetation—was transferred to a labeled bag and preserved with 95% ethanol for subsequent processing. In the laboratory, each sample was examined to separate macroinvertebrates greater than 1.5 mm in body length from other material. When more than 100 invertebrates were collected, individuals were selected for identification by using a random number table and an odd-even accept-reject criterion, with repeated random assessment of all rejected individuals until 100 total individuals had been accepted for identification (Behar and Cheo, 2004). Sample sizes were limited to 100 individuals because overall numbers of invertebrates were low in this stream system.

To evaluate pollution tolerance in the benthic macroinvertebrate community, we used the Hilsenhoff family biotic index (FBI; Hilsenhoff, 1988; Barbour et al., 2006), which assigns tolerance values to all organisms observed. For an urban stream system, this index is more useful than a simpler measure, such as the EPT index (proportion of ephemeroptera, plecoptera, and tricoptera taxa; Barbour et al., 2006) because it differentiates a wider range of species and a wider range of tolerance levels. Invertebrates were identified to the family level and each family was assigned a value from 0 to 9 reflecting its tolerance for high temperature, low oxygen, or contaminants (Hilsenhoff, 1987; 1988); high values represent high tolerance of degraded conditions. FBI (Hilsenhoff, 1988) was calculated by multiplying the number of individuals in each family by the tolerance level, summing the products, and dividing the sum by the total number of individuals. The resulting biotic index had high values (8–10) where highly tolerant families dominated the benthic macroinvertebrate community; low values (0–3) indicated dominance of families intolerant of stream degradation, and thus nearly pristine stream conditions (Hilsenhoff, 1988). We used the mean FBI from duplicate samples for each site in our analysis.

While we were chiefly interested in ISC effects, we also evaluated substrate effects on macroinvertebrates and TIN. Stream-bed conditions should provide significant explanation for both measures because rocky surfaces provide shelter for benthic macroinvertebrates, and periphyton (algae and bacteria on the streambed) provide denitrification and nutrient uptake (Peterson et al., 2001; Hale and Groffman, 2006). We quantified the availability of coarse-grained substrate habitat in the stream (gravel, cobbles, or boulders) by recording the percentage of substrate types (silt/

clay, sand, gravel, cobbles, or boulders) at each footfall while walking back and forth across the stream within the riffle zone until a minimum of 50 measurements were made (Behar and Cheo, 2000). From these data we calculated relative abundance of the different substrates. No sites had exposed bedrock in the substrate. In the present analysis we used only the percentage of silt/clay to represent substrate because of correlations between this and other size classes.

Precipitation data were collected from an airport weather station approximately 2 km from the stream. We calculated the amount of precipitation in previous three days and previous seven days to test for effects of recent precipitation on water quality measures.

Calculating Impervious Surface Cover

Because land cover at multiple scales can influence water quality (Wang et al., 2001; Strayer et al., 2003; Roy et al., 2007), we calculated the percentage ISC at two scales: the sub-basin and riparian zones. We used the ArcView 3.2 interface for the Soil and Water Assessment Tool (AvSWAT; Di Luzio et al., 2002) to delineate sub-basins—that part of the drainage basin upstream of each sampling location—using a U.S. Geological Survey 10 m resolution digital elevation model. Sub-basins were nested: the catchment above the first sample point was included in the catchment above the second sample point, and so on. The last sample point contained the cumulative area of all upstream sub-basins. Within the sub-basin above each sample point, we calculated percentage ISC using land cover data classified from Landsat imagery (date 23 September 1999). Image classification was done with ENVI software (ENVI, 2010). Classified data had a resolution of 30 m and a classification accuracy of 84% for impervious cover (M. Cunningham, unpubl. data).

For the riparian scale, we calculated percentage ISC within a 100 m buffer on either side of the stream, for a distance of 200 m upstream of each sample site. In preliminary analyses, 300 m buffers and 500 m upstream distances were examined, but the 200 m scale explained stream parameters better than did these larger scales, so we show only the 200 m reach in the present analysis. For both sub-basins and riparian zones, we calculated the percentage ISC for each sampling site using the Tabulate Area utility in ArcGIS.

Forest cover and other land cover variables were examined in preliminary analysis. Forest cover was approximately the inverse of ISC but provided less explanation. Other land cover types and urbanization measures (such as area of roads in a sub-basin or in a riparian buffer zone) also provided less explanation than ISC. Thus, we focus on ISC as an explanatory factor in this paper.

Data Analysis

We analyzed both longitudinal and seasonal changes in conductivity, TIN, and FBI using the Tukey- Kramer HSD (honestly significant difference) statistic. The HSD statistic compares means among groups as follows: the program calculates the smallest difference that could be significant between the means of two groups, based on sample sizes and distributions. That least significant difference is then subtracted from the observed difference in group means. An HSD value greater than 0 represents a significant difference between groups (SAS Institute, 2001). For longitudinal changes in conductivity, TIN, and FBI, we compared means of zones. We examined all months separately for conductivity and TIN. Because we were interested in whether stream quality improved downstream from the commercial zone, we report on the significance of differences between two zones: the commercial and green space zones.

To assess whether seasonality affected stream conditions, we compared winter (Dec–Feb), spring (Mar–April), summer (May–Sept), and fall (Oct–Nov) levels of conductivity and TIN using Tukey-Kramer HSD statistics. We did this separately for all seven land use zones, for each year.

To examine the response of dependent variables (conductivity, TIN, and FBI) to ISC at the two scales (sub-basin and riparian), we calculated Spearman's rho rank-order correlation coefficients for each sampling month. We log-transformed continuous variables before analysis.

We evaluated the effects of substrate (percentage sand/silt/clay) on FBI using ordinary least squares regression. Preliminary analysis had indicated that the two summer samples were not significantly different, so we pooled the two summer FBI samples for regression. We also regressed conductivity and TIN against precipitation in the previous three and seven days to assess impacts of recent precipitation on water quality measures. All analysis was done using JMP version 7.0 (SAS Institute, Cary, NC).

RESULTS

Conductivity values across all sample sites and all months varied from 0.03 to 2.02 milliSiemens per centimeter (300–2020 μS/cm; Fig. 2). Among zones, the urban area had the highest conductivity levels in all months. The highest peak conductivity values occurred in winter, but overall we observed no consistent seasonal declines in average conductivity levels. Winter, spring, summer, and fall levels did not differ significantly except for fall 2006, which had lower mean conductivity than the other three seasons that year (Fig. 2; HSD ≥ 0.06, $p < 0.01$).

Total inorganic N levels ranged from < 0.02 to 4.03 mg/L and levels were similar among seasons: only spring 2007 had significantly lower TIN than other seasons (HSD ≥ 0.28, $p < 0.01$). The commercial zone had the highest TIN in nearly all months and the green space had the lowest TIN in all months.

Benthic macroinvertebrate index (FBI) values were statistically the same in the two sampling years, with means (and standard deviation) of 5.9 (1.1) in 2006 and 5.3 (1.1) in 2007. Substrate provided little explanation of FBI values or TIN. For FBI (with the two summer samples pooled), the relationship was marginally significant ($r^2 = 0.20$, $F = 5.47$, $p = 0.03$). When TIN was regressed against substrate, with months evaluated separately, $r^2 < 0.19$, $p > 0.16$ in all months. Precipitation preceding sampling was generally low (median for previous three days was 0.0 mm; for previous seven days, median precipitation was 9.3 mm). Precipitation explained little of the variation in conductivity or TIN ($R^2 < 0.13$ in all cases).

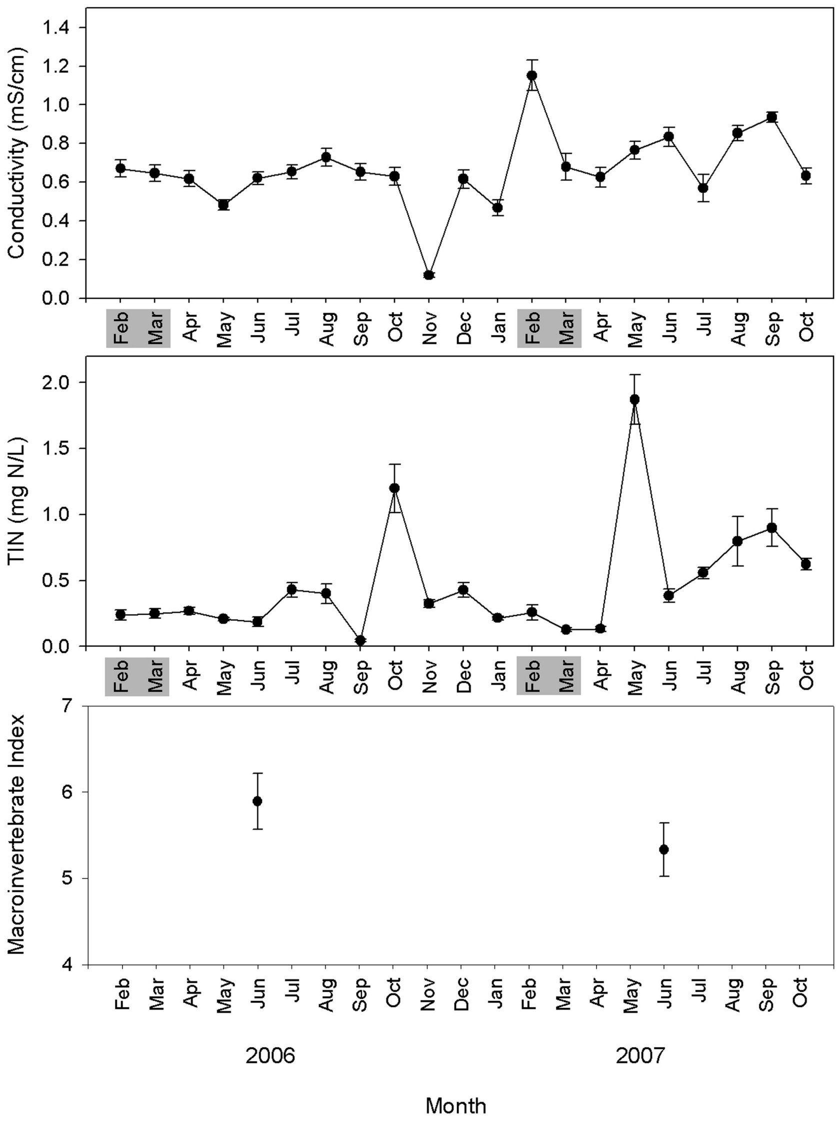

Fig. 2. Monthly mean and standard error for conductivity and total inorganic N at 21 sample sites and for a family biotic index (FBI) of benthic macroinvertebrates at 14 sites. Shaded months had snowfall and road salt applications. Possible FBI values range from 9 (poor) to 1 (excellent).

Downstream Patterns

Conductivity did not decline significantly in the green space zone compared to the commercial zone (in 19 of 21 months, HSD < 0, with $p < 0.01$; for the two months in which the difference was significant, conductivity was higher in the green space zone). Instead, conductivity rose steadily downstream until the stream entered

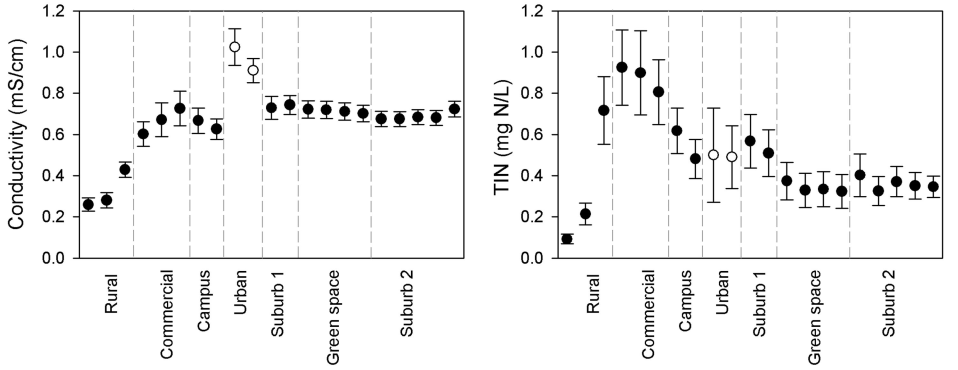

Fig. 3. Downstream variation in conductivity and TIN. Means and standard error are shown for each site for all months. The commercial zone contains a salt storage shed (at second commercial site) and parking lots built on landfills (all three sites).

the commercial zone and then remained approximately stable (500 to 700 μS/cm) for the rest of the stream length. (Fig. 3). This plateau corresponds to the strong relationship between sub-basin ISC and conductivity (Figs. 4 and 5). Highest conductivity and highest ISC were in the urban zone.

Levels of TIN were significantly lower in the green space zone than in the commercial zone for most months (HSD > 0.20, $p < 0.01$ for 15 of 21 months). Levels of TIN also declined between suburb 1 and the green space (Fig. 4). When sites were evaluated separately (Fig. 3), TIN began to increase in the lower rural zone, peaked in the commercial zone, and rose again in the urban and suburb 1 zones, then declined and remained low in the green space and suburb 2.

For FBI values, the green space had significantly lower (better) index values than the commercial zone (with two June samples pooled, HSD = 0.93, $p < 0.01$). Highest (worst) FBI values were in the rural and commercial zones (Fig. 4). Lowest (best) FBI values were in the green space.

The benthic macroinvertebrate community was dominated by pollution-tolerant taxa in the commercial zone (84 percent of individuals), primarily oligochaete worms and midge larvae (Chironomidae, Table 1). These and black fly larvae (Simuliidae) dominated the urban zone as well. In the green space zone, caddisfly larvae were the most abundant group (48%), and 58% of individuals were in the sensitive class. Suburban zones had a combination of pollution sensitive groups (caddisfly larvae) and tolerant groups (Chironomidae).

Scales of Response

The two scales of impervious cover did not vary together. At the sub-basin scale, ISC increased from near 0 percent in the rural zone to level off at approximately 35% below the commercial zone (Fig. 4). Riparian-scale ISC peaked in the commercial zone (> 99%), then declined to ≤ 2% in the green space zone.

Conductivity mirrored the pattern of the sub-basin scale ISC (Fig. 4) and did not decline downstream in any month. There was a strong correlation between

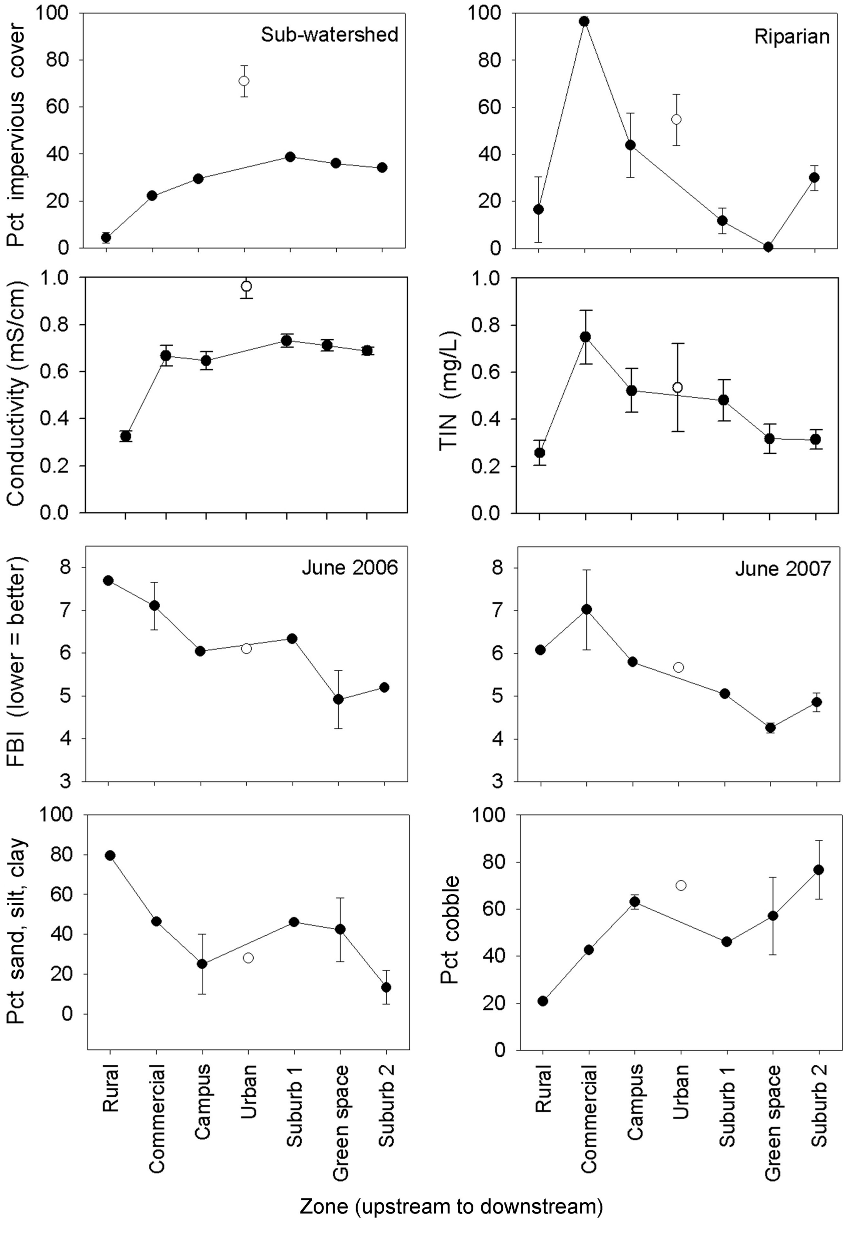

Fig. 4. Mean and standard error values for impervious cover, conductivity, total inorganic N (TIN), a family biotic index (FBI) for benthic macroinvertebrates, and substrate by land use zone. Zones are listed in order from upstream to downstream, and points show means of 2 to 5 sample sites in each zone. Closed circles represent the Casperkill main stem; open circles represent the Fonteynkill tributary.

sub-basin-scale ISC and conductivity in most months (Fig. 5: $\rho > 0.44$, $p < 0.05$ in 17 of 21 months) but not with riparian-scale ISC ($\rho < 0.40$, $p > 0.12$ in all months).

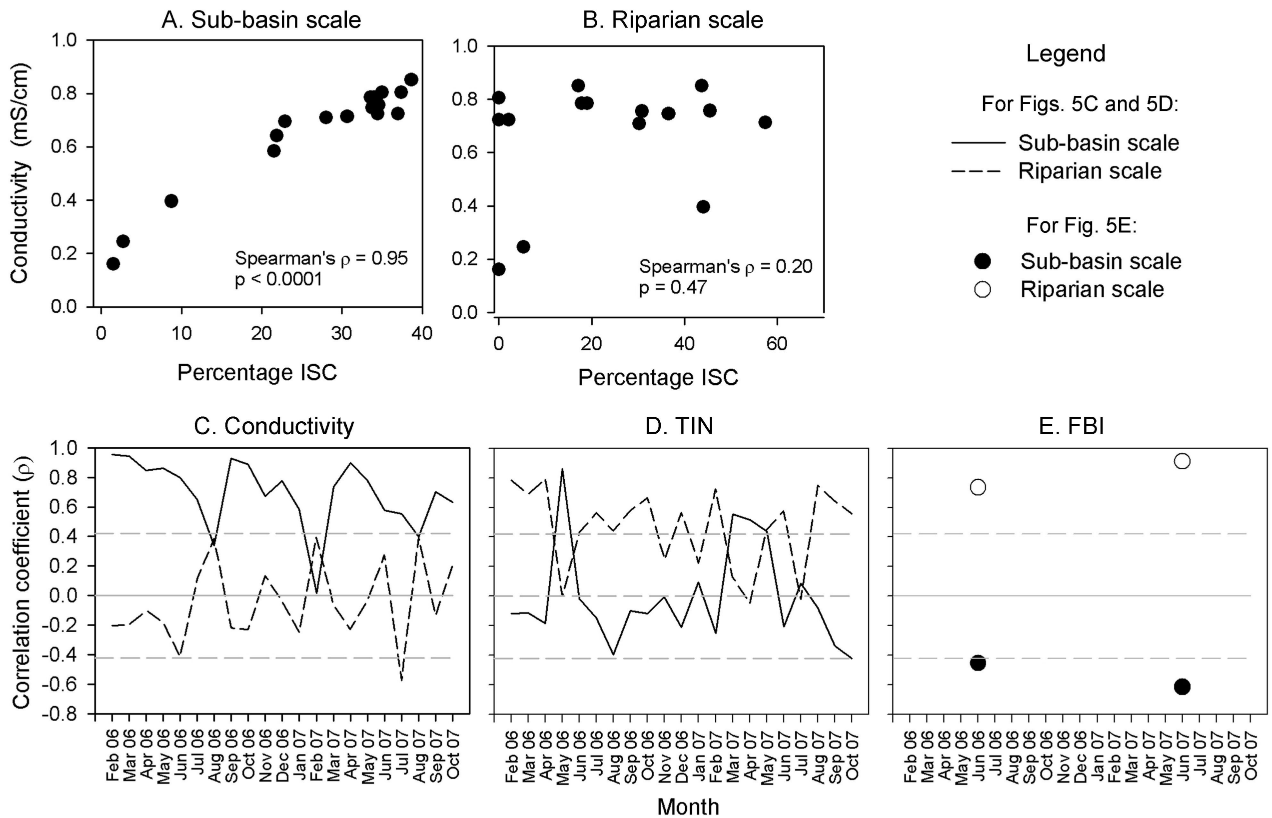

Fig. 5. Comparison of strength of correlation between ISC (at sub-basin and riparian scales) and water quality measures. Correlation coefficients, such as those at top (A and B), are summarized for all months at bottom (C, D, E). Plots show strength of correlation between conductivity and ISC at the two scales for all months (C), between total inorganic nitrogen (TIN) and ISC (D), and between the family-level biotic index (FBI) for macroinvertebrates and ISC (E). Correlation coefficients > |0.42| are significant at $p < 0.05$.

Table 1. Benthic Macroinvertebrate Community Composition by Zones, Shown as Percentage of Total Counts[a]

Sensitivity	Family	Rural	Commercial	Campus	Urban	Suburb 1	Green space	Suburb 2
High	Caddisfly larvae	2.4	3.0	**25.0**	6.0	25.5	47.7	17.4
	Hellgramites (Corydalidae)							
	Mayfly nymphs		0.2					0.5
	Gilled snails (right spiral)		0.3					0.1
	Riffle beetles (Elmidae)	1.2	0.5	2.7		8.7	10.3	7.3
	Stonefly nymphs (Plecoptera)							
	Water penny (Psephenidae)					0.2		2.3
	Other		0.2					0.1
Moderate	Other beetle larvae	0.2	0.2			1.6		0.1
	Clams/mussels	2.0	0.2	10.4	4.3	4.1	2.6	2.9
	Crane fly larvae (Tipulidae)		0.2			1.1	1.9	2.4
	Crayfish (Astacidae)			3.1	0.8	0.2		0.1
	Dragonfly nymphs (Odonata)							
	Damselfly nymphs				0.2			
	Amphipods (Gammaridae)	18.8	6.7	**29.2**	8.9	9.8	12.6	10.1
	Isopods (Asellidae)	19.5	5.0	0.8	0.2	5.0	2.4	6.7
	Fishfly larvae (Corydalidae)						0.2	
	Alderfly larvae (Sialidae)							
	Watersnipe fly larvae (Athericidae)							
	Other					0.5	0.3	0.4
Low	Oligochaete worms	**23.9**	**47.5**	5.0	7.5	7.1	0.3	1.6
	Black fly larvae (Simuliidae)	2.4	2.7		**26.9**	2.7	5.5	5.5
	Leeches (Hirudinea)	19.0	2.1	2.3	1.0	1.6	0.3	1.6
	Midge larvae (Chironomidae)	10.2	**31.0**	**20.0**	**42.7**	**31.4**	15.0	**39.7**
	Left-spiral pouch snails (Physidae)		0.2	0.8	1.4	0.5	0.7	1.3
	Other snails (flattened)	0.2	0.2	0.8	0.2			0.1
	Total number of individuals	410	623	260	517	439	585	1224

[a]Values > 20 % are in bold type.

In contrast to conductivity, TIN and FBI values varied in a pattern similar to that of riparian-scale ISC (Fig. 4). For TIN, correlation with riparian ISC was significant in 15 of 21 months; for FBI, correlation with riparian ISC was significant in both of the 2 years (Fig. 5).

DISCUSSION

Recovery from impairment was evident in the green space for TIN and FBI, indicating that effects of impairments can be reduced even in a short distance (< 2 km between commercial and green space zones) and with a relatively small (110 ha) green space. Moreover, TIN also showed improvement in the suburban zone above the green space, corresponding to an increased amount of vegetated land area in that suburban area. The mechanism for TIN reductions is likely in-stream uptake of N (Peterson et al., 2001), as well as dilution by clean surface runoff and soil/ground water. Given the relatively strong importance of the riparian zone for TIN and FBI (Fig. 5), the value of the green space here appears to have been that it provided one of the few places in which a vegetated riparian zone could reach more than a few meters from the stream for any extended distance, or where a significant reach of the stream was free of major nutrient inputs.

Conductivity levels, however, did not improve in the green space; rather conductivity changed little below the commercial zone. Contrasting responses to the two scales of impervious cover help explain these differences: while TIN and FBI responded to locally changing conditions at the riparian buffer scale, conductivity responded strongly to ISC at the sub-basin scale (Fig. 5), which stabilized at about 35% after the stream entered developed zones (Fig. 4). Vegetated areas in the green space were apparently sufficiently extensive to affect TIN and FBI, but not large enough to provide uncontaminated groundwater or runoff that could dilute conductivity.

Longitudinal Recovery and Land Use

Downstream improvements in FBI (lower values, Fig. 4) were notable because the benthic community is understood to reflect cumulative degradation of in-stream conditions in a developed watershed (see Walsh et al., 2005b, 2007; Wollheim et al., 2005). The riparian-scale response of the FBI helps explain the observed recovery, but this result also indicates the short distance within which the benthic community can change. Riparian vegetation provides leaf litter that benthic macroinvertebrates need (cf. Chadwick and Huryn, 2005), and also helps to shade and cool the stream and to reduce sediment inputs. For moderately sensitive taxa, downstream suburban reaches with moderately dense residential land uses appear to provide enough vegetated cover to help the benthic macroinvertebrate community recover from upstream impairments.

Some previous studies have found the riparian zone most influential for macroinvertebrate biotic indices (Roy et al., 2003; Schiff and Benoit, 2007), while others have found strong responses to whole-watershed impervious cover (e.g., Wollheim et al., 2005, Walsh et al., 2007). Some of this difference involves study site and design. In a comparison of separate watersheds, where urbanization varies from low to high, basin-scale land cover should be highly influential in explaining nutrient loadings. In the Casperkill watershed, persistently high levels of urbanization meant that basin-wide conditions varied little, and the importance of riparian conditions became evident, but both scales had some influence. Contrasting interpretation of results can also produce differences in conclusions. In this largely urbanized watershed, stream conditions improved from badly degraded to moderately degraded with increasing local riparian green space, but few of our sites showed an abundance of extremely sensitive macroinvertebrates. We did not see recovery to pristine conditions, likely because of basin-wide factors such as chronic, year-round high conductivity. Thus, while we found a strong riparian effect (Roy et al., 2003; Schiff and Benoit, 2007), our results do not contradict findings of basin-scale effects (Wollheim et al., 2005, Walsh et al., 2007).

Longitudinal sampling was useful in detecting downstream changes in stream parameters (Dent and Grimm, 1999; Peterson et al., 2001). Longitudinal sampling also allowed us to detect effects of landscape features along the course of a stream. These changes are not detectable in studies that use single sampling points to characterize whole watersheds, but our results suggest that relatively modest landscape changes, such as a 110 ha green space, can modify a stream ecosystem.

The low-gradient, largely urbanized nature of the stream we studied may account for the surprisingly small effect of substrate in explaining FBI or TIN. Substrate varied among sites, but there was abundant fine-grained sediment, presumably originating from roads, construction, and other activities on disturbed surfaces. This situation can be common in urban streams (Paul and Meyer, 2001; Booth and Nelson, 2002; Groffman et al., 2003). Evidently, factors other than substrate dominated the composition of the benthic community. These factors could include the flashy pattern of stream runoff, an absence of riparian vegetation in the commercial zone and other high-impervious areas, and general absence of secure, rocky substrate in the form of bedrock or boulders in the stream, as well as turbidity and high salinity.

High FBI values at our rural sampling site also resulted from the situation of our stream on the edge of an urban area. The rural FBI sampling site is located at the stream's first riffle, which drains a locally degraded environment that includes a wetland containing discarded cars, shopping carts, and other debris, as well as parking lots adjacent to the stream. Such conditions are not unusual on the outskirts of American cities, nor is the presence of the commercial zone in or adjacent to the rural area. Strip-mall and big-box store complexes are typically built on inexpensive real estate near (but not in the middle of) population centers. Thus the commercial location in our watershed, between the rural and suburban residential areas, is likely to be representative of many urban watersheds. The presence of green space and suburban vegetated areas downstream of these areas seems to have contributed considerably to ameliorating their impacts.

The urbanized nature of the watershed may also help explain the lack of consistent effects of precipitation on stream chemistry. The reason for this may be that precipitation both flushes contaminants from impervious surfaces (thus increasing contaminants) and dilutes salt-rich base flow (thus reducing contaminant concentrations).

These simultaneous effects may explain the lack of precipitation effect detection in our data.

Seasonal Recovery

Seasonally, recovery was not evident for either conductivity or TIN. High conductivity persisted year-round and over the length of the stream. For in-stream aquatic health, high summer levels may be especially serious, as most biotic activity occurs in warm months. Kelly et al. (2008) attributed high summer conductivity levels to gradual release of road salt through groundwater, a process that they showed can persist for decades. Cunningham et al. (2008) further showed that in an area with a high density of roads, salt distribution can be ubiquitous in soils; this widespread distribution further exacerbates the spatial extent and the time span of exposures to salt.

Persistently high year-round levels of TIN in the commercial zone suggest that an important source is seepage from unlined landfills that underlie shopping centers, parking lots, and office buildings in that zone. High levels of TIN in the commercial zone comprised mostly NH_4^+ (data not shown), which could indicate an anaerobic landfill source. However, this is not the only source in the watershed, as indicated by subsequent TIN increases in the suburban and urban zones. Secondary high levels in suburban zones (Fig. 3) evidently result from leaking sewage lines and septic systems, which are active year round. Lawn fertilizers, likewise associated with residential development, may also be an important factor (Valiela and Bowen, 2002; Allan, 2004). Thus, residential zones, with septic systems, yard fertilizers, and other nutrient sources, can be an important source of instream TIN, and an absence of residences in the green space may allow for improvements in TIN levels, either through instream nutrient uptake or through dilution by uncontaminated surface runoff.

Implications for Green Space and Riparian Conservation

In the Casperkill watershed, expansive low-ISC riparian areas occurred only in the preserved green space. Elsewhere in this watershed, both residential and commercial development encroached well into the riparian zone. Local riparian protection laws recommend an 8 m (25 ft) protected buffer; but most structures in the watershed predate those laws, and, in any case, that distance may be insufficient. Mayer et al. (2005), for example, found that buffers > 50 m wide were more effective than narrower buffers. In our study area, the green space was the only zone with low impervious cover within 100 m of the stream for all sample points, and stream in this zone consistently had the lowest values for both TIN and FBI. Thus in our system, a healthy riparian zone was possible only where the surrounding landscape was preserved.

For watershed management, it is important to recognize that parameters respond to the landscape at different scales. As a consequence, different remediation strategies will affect different water quality problems. Different scales may also matter in contrasting environments. For example, Walsh et al. (2007), working in systems where basin-scale conditions have strong effects on in-stream conditions, have questioned the effectiveness of riparian-scale remediation. In our system, however, two of the three parameters responded more strongly to riparian than to basin-wide conditions.

Low-impact development and other strategies for minimizing impervious cover can improve the status of TIN and FBI measures by protecting riparian-zone soils and vegetation (Walsh et al., 2005a; Carter and Rasmussen, 2006; Hood et al., 2007). Mitigating the most impervious parts of the watershed—in this case, the commercial parking lots—could be at least partly accomplished by establishing riparian buffers between parking lots and the stream. Reducing conductivity may be considerably more difficult if solutions need to be watershed-wide. However, watershed-wide planning that promotes clustered development can reduce the overall infrastructure and pavement needed to serve a community. In addition to the many economic and aesthetic arguments for concentrating development and preserving open space (Prato and Hey, 2006; Qiu et al., 2006), our results indicate that preservation of open space can help restore the stream system even after impairment.

Acknowledgments: We thank J. Dashnaw, M. Belli, R. Belli, D. Cate, A. Charney, T. J. Fayton, D. Fried, D. Goldie, A. Jost, D. Ketai, J. Monmaney, J. Morris, L. Robbins, A. Schultheis, J. Tsai, and E. Vail for their hard work in the field and in the lab. The comments of two anonymous reviewers have substantially improved this manuscript. We also gratefully acknowledge the assistance and technical support of E. Stout and M. Stewart. This work was funded by the Collins Fund for Environmental Research, Vassar College, the Mellon Foundation, and the National Science Foundation (MRI- 0722813).

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