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Urbanization Consequences: Case Studies in the Hudson River Watershed

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Abstract.—Parcel by parcel, urban/suburban development is one of the most active converters of land in the Hudson River Valley in New York State. We are taking an integrative approach to understanding the drivers of and responses to urbanization, by studying how economy drives land use change and how that, in turn, affects downstream indicators of ecosystem state. The ultimate goal of the project is to provide a tool for policymakers, illustrating consequences of different development strategies. In this paper, we discuss synoptic ecological assessments of two major Hudson River tributaries in Dutchess County, the Wappinger Creek and Fishkill Creek watersheds. Physical, chemical, geographic, and biotic indices are compiled, creating a multivariate data set. These data, when set into a geographic information database, provide a spatial response to land use. Application of a regionally calibrated index of biotic integrity showed little relationship to urbanization, although some component metrics indicated a response. Chemical or biogeochemical indicators were more reflective of urbanization gradients. A hierarchy of responses, beginning with physicochemical and moving up to fish assemblages, reflected decreasing responses to urbanization. However, fish densities and the stable isotopic ratios of nitrogen determined in a sentinel species (eastern blacknose dace *Rhinichthys atratulus*) were significantly affected by urbanization. Longitudinal gradients of elevation were identified as strong drivers of development, potentially confounding relationships of land-use attributes and ecological responses.

Introduction

The transformation of land into urban and suburban uses is one of the fastest alterations of the American landscape today, producing cumulative ecological stress. The causes are numerous but generally involve choices made in piecemeal fashion, rather than by some concerted effort such as regional planning. Kahn (1966) referred to "the tyranny of small decisions," which describes the evolution of unintended economic consequences of decisions made on the basis of short-term, marginal gains. Odum (1982) applied this concept to the general problem of environmental degradation, and Ehrlich and Ehrlich (1981) used the analogy of an airplane's loss of structural integrity (the "rivet-popping hypothesis") to the disintegration of ecosystems and consequent loss of species. All point out the mismatch between maximizing individually based, short-term economic benefits and long-term social welfare, including environmental quality.

In this context, we have studied nested economic and ecological systems in the Hudson River Valley of New York State. Our research has focused on characterizing the structure of the economy of Dutchess

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County and understanding how economic and social change affect land development and how these pressures on the landscape may affect the ecological status (physical, chemical, and biological) of two streams, Fishkill Creek and Wappinger Creek. One goal is to elucidate, through integrated studies, the connections between what society does and how, ultimately, ecosystems respond. However, a more pertinent goal is to envision policy options and create tools for decision makers. We hypothesized that ecological integrity would reflect urbanization in the Fishkill Creek and Wappinger Creek watersheds. Although the focus of this paper is to present and discuss the ecological results, we include a brief presentation of the overall methodology. Further details on overall and specific approaches may be found in Erickson et al. (2005). Specific questions we address in this paper include

1. Does an urban-to-rural gradient in ecosystem health occur in the study area?
2. Is the Fishkill Creek watershed, closer to the New York City metropolitan area, more degraded than the Wappinger Creek watershed, as measured by metrics of ecosystem health? and
3. How do natural physiographic factors affect our ability to detect urbanization impacts?

Study Area

Dutchess County, New York (2,077 km^2) is located on the eastern side of the Hudson River Estuary (Figure 1). Within the county, the Wappinger Creek (547 km^2) and Fishkill Creek (521 km^2) watersheds compose more than half of the drainage area. Physiographically, the county and its watersheds belong to the eastern Great Lakes and Hudson lowlands (western county) and Northeastern highlands (eastern county) ecoregions (EPA 2002). Both Wappinger and Fishkill creeks arise in eastern highlands and drain southwest into the Hudson River.

Dutchess County was principally agrarian until the mid-20th century, but today supports a 203-sector economy (Erickson et al. 2005), dominated by large industries such as semiconductors (notably IBM). Development is heaviest in the southwestern part of the county, focused around the cities of Poughkeepsie, Wappingers Falls, and Beacon. New York City, 120 km to the south, is a source of jobs, first and second homeowners, and tourists, serving as another driver of development in southern Dutchess County.

Methods

Economic and Land-Use Change Models

The economy of Dutchess County was described with a social accounting matrix or SAM (Pyatt and Round 1985). This is an extension of the traditional Leontief input–output matrix (Leontief 1966), which tracks the flows of dollars through industrial sectors. The SAM includes household and government transactions, which can be disaggregated to reveal demographic detail as needed. Data for the Dutchess County SAM were obtained from a regional database (IMPLAN or Impact Analysis for PLANning; Minnesota IMPLAN Group, Inc. 2004) and Bureau of Labor statistics (Nowosielski 2002). A geographical information system (GIS) was also developed and coupled to the SAM in order to reference, geographically, where household institutions and businesses occur. Further geographic detail can be built into the GIS.

A drawback of input-output models is that they are static in nature, so tracking the temporal dynamics of an economy is difficult. To explore some of the temporal consequences of economic growth, specifically the development of new residential housing (a major component of sprawl), a probabilistic model of land-use change was developed for the Wappinger Creek watershed (Polimeni 2002); Polimeni did not develop a model for the Fishkill Creek watershed, due to lack of data, but our research group is currently expanding the database to include this second watershed. Land classified as vacant (vacant-residential, agricultural, or private forest tax parcels) in the 2001 tax rolls provided the source for conversion. Change was modeled with a binomial logit regression that took account of both tax parcel and neighborhood characteristics, as defined by census blocks. These included land assessment value, distance to nearest central business district, household income, and population growth. Biophysical data on slope, soils, wetland vegetation, riparian corridors, and agricultural land further refined estimates of “developable” land. Monte Carlo simulations that specified particular constraints (e.g., do not develop wetland parcels) generated probabilities of land conversion (Polimeni 2002; Erickson 2005).

Ecological Assessments

Thirty-three stream sites (Figure 2) were surveyed within the Wappinger and Fishkill creeks in 2001 and 2002, in order to quantify physical, chemical, and biological attributes composing ecological integ-

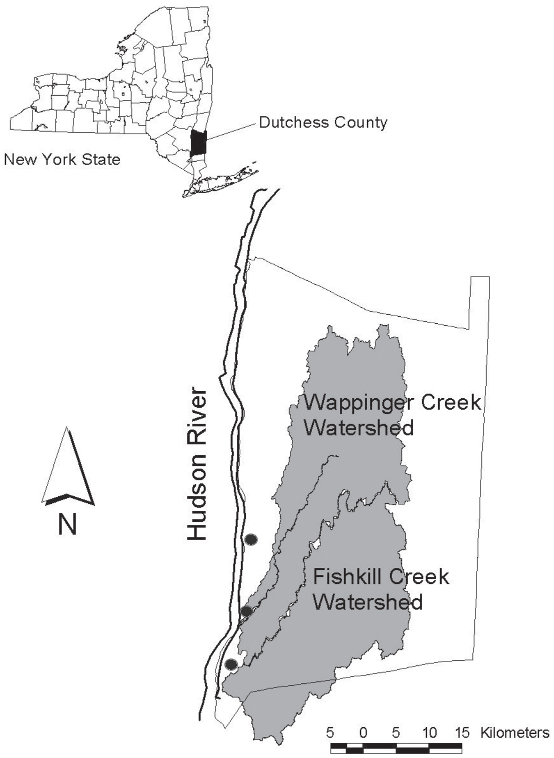

FIGURE 1. Map of Dutchess County, New York, showing the Wappinger and Fishkill watersheds. Major cities, indicated by black dots, are, from north to south, Poughkeepsie, Wappingers Falls, and Beacon.

rity. These included both main-stem sites as well as sites located within subcatchments, generally near their confluences with the main stem. Most were selected in order to make comparisons with earlier studies (Stevens et al. 1994; DCEMC 2000). We followed and modified slightly U.S. Geological Survey (USGS) stream habitat sampling protocols (Fitzpatrick et al. 1998), dividing up a 150-m stream reach into five sections and conducting assessments for stream and riparian zone physical characteristics. Due to limited resources, we made four synoptic surveys of water quality, choosing the period May–August to cover wet and dry months. Chlorophyll-a was quantified by fluorometry (Welschmeyer 1994). Phosphorus was analyzed following Langner and Hendrix (1982) and Clesceri et al. (1998), and total N, NO_2, NO_3, and NH_4 were measured with a Bran-Lubbe autoanalyzer, also following standard protocols (Clesceri et al. 1998). Fish were sampled with a backpack electroshocker, sampling 150 m of stream in a single pass without block nets. All fish were identified to species, counted, and released. Macroinvertebrates were collected by kick-sampling following Barbour et al. (1999), subsampled (combining methods from Barbour and Gerritsen 1996; Courtemanch 1996; Vinson and Hawkins 1996) and identified to family. Insect taxa were used to compute metrics for benthic macroinvertebrate indices (Bode et al. 1996; Riva-Murray et al. 2002).

A number of indices and metrics were used to quantify fish and macroinvertebrate assemblage integrity, sensu Karr (1981, 1991). For both, regionally calibrated indices of biotic integrity (IBI) were computed (Bode et al. 1996; Daniels et al. 2002; Riva-Murray et al. 2002). In addition to the IBIs, metrics were examined individually. For fish, this included species richness, diversity, density (number per area), and percent of assemblage that was composed of centrarchids. For invertebrates, percent dominance of the three most abundant taxa, Ephemeroptera-Plecoptera-Trichoptera (EPT), family richness and diversity (H'), density of organisms, family (Hilsenhoff) biotic index, percent model affinity, and biotic assessment profile were computed (Hilsenhoff 1988; Bode et al. 1996; Hauer and Lamberti 1996; Riva-Murray et al. 2002). Percent model affinity (PMA) is a measure of how closely the assemblage reflects an idealized or "model community"

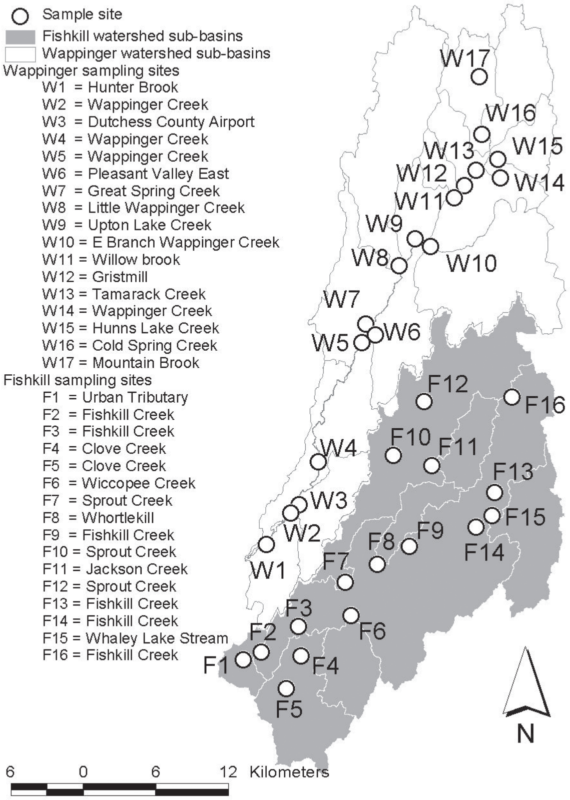

FIGURE 2. Stream sites used for ecological assessments.

in the absence of disturbance, while biotic assessment profile scales and combines results from EPT, dominance, species richness, and PMA.

In addition, a cosmopolitan fish species (eastern blacknose dace *Rhinichthys atratulus*) was assayed as a biogeochemical tracer of anthropogenic N (McClelland et al. 1997) by means of stable isotope analysis. Three to five individuals were collected from as many sites as possible, dried (50°C), pulverized, and analyzed at the Alaska Stable Isotope Facility with a Thermo-Finnigan Delta$^{\text{Plus}}$ mass spectrometer coupled to a Carlo-Erba C:N analyzer. Results were expressed as δ^{15}N, or $[(^{15}\text{N}/^{14}\text{N}_{\text{sample}} \div {}^{15}\text{N}/^{14}\text{N}_{\text{standard}}) - 1] \times 1{,}000$ (Peterson and Fry 1987).

Geographic Analyses

A GIS was developed to delineate catchments, provide physiographical data (e.g., elevation), and incorporate land cover, population density, and highway density to relate to our ecological assessments. Site locations were recorded with a Garmin 12XL geographical positioner. Elevation was derived from Dutchess County 1:24,000 scale quad (30-m resolution) digital elevation maps (DEM) downloaded from the Cornell University Geospatial Information Repository (CUGIR; CUGIR 2003). Site distance from the mouth of each main stem was derived from hydrography shape files downloaded from CUGIR. Stream segments (km) were summed from the confluence of the Hudson River to each sampling site.

Wappinger Creek watershed delineations were obtained from the Dutchess County Watershed Program (DCEMC 2000). Fishkill Creek watershed and subbasin areas (draining to the sampling sites) were delineated, and associated maps were created using Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) within the Automated Watershed Delineation platform (EPA 2001). The BASINS software uses neighborhood operations, where calculations and "decisions" (for water flow direction, inflow, and accumulation) are made for each cell in the DEM based on the values in the eight cells that are spatially adjacent (Jensen and Domingue 1988).

Land use was classified with Multi-Resolution Land Characteristics Consortium (MLRC) National Land Cover Data (NLCD) derived from Landsat-5 Thematic Mapper (TM) satellite imagery. The 1992 NLCD were downloaded from an EPA Web site (http://www.epa.gov/mrlc/nlcd.html) and the 2001 NLCD were provided by M. Hall (State University of New York, College of Environmental Science and Forestry, Syracuse, personal communication). The 2001 NLCD map was created using satellite imagery from three seasons and classified into the 1992 NLCD categories. The satellite images from May 2001 were primarily used to create the map because the April 2001 satellite image was fairly snow-covered; therefore, the analysis omitted leaf-off imagery (important for accurately defining roadways; however, we are confident that this did not unduly bias our estimates of road densities). Distinguishing among agricultural pastureland, row crops, and urban and recreational grasses proved difficult. However, county-level agricultural data showed that crop- and pasturelands in 1992 and 2000 were similar (31,282 ha in 1992 versus 31,404 ha in 2000; NYNASS 1999, 2002). Therefore, as a conservative estimate, we assumed that crop- and pastureland covers were the same in 2001 as in 1992.

Land use areas for 1992 and 2001 were calculated with ArcView 3.3 (Hutchinson and Daniels 1997). Road maps for the year 2000 (road maps were not available for 1992 or 2001 to match the NLCD) were downloaded from the CUGIR. From these maps, we calculated total road length (km) and density (km/km^2) for each subbasin.

Statistical Analysis

Statistical analyses were conducted with Statistica 6.0 (Statsoft 2003). Data were examined for homogeneity of variance and were log-transformed as necessary (e.g., road density). Pearson correlations were performed to explore relationships between anthropogenic disturbance indices (percent of land cover in urban and suburban uses, population density, and road density) and physical, chemical, biological, and biogeochemical parameters. Analysis of variance (ANOVA) was used to test for differences between the Fishkill Creek and Wappinger Creek watersheds; analysis of covariance (ANCOVA) was used when comparisons by watershed involved continuous variables. Linear and nonlinear regression analyses were performed to examine relationships between anthropogenic disturbance indices and ecological response variables. Principal components analysis (PCA) was used to examine relationships among anthropogenic indices, land covers, and physical factors, in order to select a reduced set of explanatory variables. *P*-values less than 0.05 were accepted as significant.

Results

Land use shifted in both watersheds toward increasing urbanization and suburban development over the period 1992–2001. The spatial pattern of land use change over that period is striking (Figure 3) and shows most of the increase in urban/suburban lands in the upper-mid portions of both watersheds. Much of this growth was along the Taconic Parkway, a north–south thoroughfare used to commute to downstate metropolitan centers (White Plains and New York City, primarily). During our field surveys of 2001, we observed dozens of new homes being constructed within a few kilometers of the parkway. Note, though, that urbanization occurred throughout the watersheds, with no subbasin gaining forest or farmland over this period (Figure 3).

Urbanization indices showed some cross correlations, and some habitat variables had significant correlations with highway density (Table 1). However, taken in the aggregate across all 33 field sites, many of the correlations were nonsignificant, even while the sign of correlation was often as expected. For example, percent canopy cover over streams was negatively (but not significantly) correlated with population density, highway density, and percent of land in urban and suburban use. Urbanization indices were all negatively correlated with elevation (Table 1).

Examining chemical and biological response variables, generally more of the chemical indicators responded significantly to urbanization than did biotic ones (Table 2). For example, total N, percent inorganic N (NO_2, NO_3, and NH_4 as a percent of the total, reflecting fertilizers and sewage inputs), total P, and August conductivity (when flows were lowest and dissolved salts highest during our study) all were positively and significantly correlated with urban and suburban land use. Within the indicators of macroinvertebrate assemblage integrity, the EPT index, percent model affinity, and biotic assessment profile were negatively, significantly correlated with urban and suburban land use and positively, but not significantly correlated with percent of the catchment in forest. None of the fish assemblage metrics showed significant correlations with any land use or with other metrics of human activity, such as highway

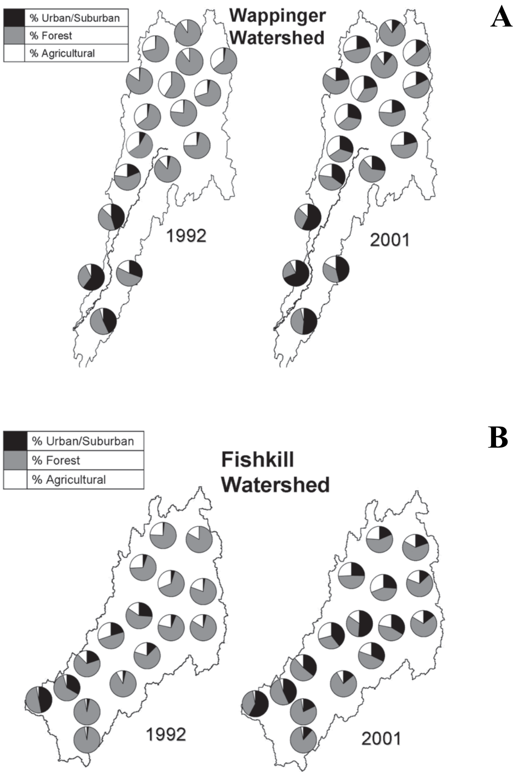

FIGURE 3. Maps showing percentages of land in urban/suburban, agricultural, and forested uses for (A) the Wappinger Creek and (B) Fishkill Creek watersheds, in 1992 and 2001.

density (Table 2). Only one assemblage characteristic, the percent of fishes caught that were centrarchids, showed a significant, negative correlation with elevation. A biogeochemical response variable, the stable isotopic ratios of nitrogen measured in a single, cosmopolitan fish species (eastern blacknose dace), correlated significantly and positively with urban and suburban lands and highway density, and negatively with forested land and elevation (Table 2).

Statistics presented in the aggregate, combining data from both watersheds, conceal detail about how variables respond differently in the two watersheds and how knowledge of particular circumstances helps to explain observed patterns. For example, nitrogen concentrations across the two watersheds (Figure 4) show a complex pattern. Sites F12, F10, and F7, all with moderately elevated N, drain a predominantly agricultural subcatchment (Sprout Creek). Sites W14 and F11 are both located at recreation areas, which receive many visitors in the summer and have restroom facilities near the streams. Site W15 is approximately 1 km downstream from a dude ranch, the horse paddock of which was in direct contact with the stream, and sites W11, W9, and W7 all drain predominantly agricultural subcatchments. Nevertheless, despite the somewhat checkerboard nature of N values reflecting various land uses, total N concentrations tended to increase downstream towards the more urbanized areas (Figure 4).

Other response variables reflected the "individual character" of each watershed. For example, chlorophyll-a values had a stronger correlation with total P than with total N, evidence that P is limiting in the streams, as is generally the case in freshwater (Wetzel 2001). However, the slopes and intercepts of the chlorophyll-TP regressions were different (ANCOVA, $P < 0.01$; Figure 5), suggesting that Fishkill Creek, overall, is less able to use this nutrient in autochthonous production.

Another example of different responses between watersheds is seen in the temperature excursion data (maximum–minimum values recorded in our surveys; Figure 6), which may be interpreted as an index of

TABLE 1. Pearson correlation matrix of elevation (m), three indices of urbanization (population density in people/km^2, highway density in km/km^2 of each subcatchment, and percent of watershed in urban and suburban use), and three habitat indicators (percent embeddedness of the streambed, percent canopy cover, and bank-full stream width (m)) for sites in the Wappinger and Fishkill drainages. Correlation coefficients in bold are significant ($P < 0.05$).

	Elevation	Population density	Highway density	% urban + suburban	% embeddedness	% canopy cover
Population density	**–0.60**					
Highway density	**–0.55**	**0.77**				
% urban + suburban	**–0.59**	**0.77**	**0.67**			
% embeddedness	–0.12	0.19	**0.38**	0.29		
% canopy cover	**0.38**	–0.18	–0.26	–0.30	–0.14	
Bank-full width	**–0.40**	0.16	**0.39**	–0.02	0.19	–0.23

TABLE 2. Pearson correlations of selected response variables on land-use type, highway density, and elevation. Chemical variables are based on May–August means unless otherwise noted. Correlation coefficients in bold are significant ($P < 0.05$). "Transient" species are as defined in Daniels et al. (2002).

Response variable	% forested	% agriculture	% urban + suburban	Highway density (km/km^2)	Elevation (m)
Chemistry					
Total N	**–0.53**	0.07	**0.53**	0.35	–0.35
% inorganic N	–0.35	0.10	**0.42**	**0.41**	–0.10
Total P	–0.22	–0.32	**0.55**	0.30	**–0.58**
August conductivity	**–0.40**	–0.24	**0.71**	**0.52**	**–0.58**
Temperature	0.11	0.06	–0.19	–0.05	–0.16
Max–min temperature	–0.01	–0.16	0.14	**0.42**	–0.21
Chlorophyll-a	–0.16	0.08	–0.005	–0.14	–0.21
Macroinvertebrate assemblage					
Species richness/area	–0.16	0.09	0.35	0.06	0.33
Diversity (H')	0.17	–0.14	–0.26	–0.18	0.01
EPT index	0.34	–0.25	**–0.42**	–0.27	0.05
% model affinity	0.32	0.11	**–0.53**	–0.32	**0.43**
Biotic assessment profile	0.22	0.11	**–0.52**	–0.35	0.31
Fish assemblage					
Species richness/area	–0.27	0.16	0.15	–0.26	0.16
Diversity (H')	0.27	–0.24	–0.31	–0.16	–0.08
Density (#/m^2)	–0.12	0.27	–0.14	**–0.42**	0.27
IBI	–0.18	0.05	–0.20	–0.27	–0.11
IBI, excluding transients	–0.18	0.27	–0.26	–0.31	0.15
% centrarchids	–0.07	–0.02	0.03	0.32	**–0.38**
Eastern blacknose dace δ^{15}N	**–0.61**	0.09	**0.63**	**0.57**	**–0.55**

stream thermal constancy. Temperature differentials (ΔT) in the Fishkill Creek watershed were nearly double those in the Wappinger (Fishkill Creek mean ΔT = 10.4°C ± 0.7 [±SE]; Wappinger Creek mean ΔT = 5.9°C ± 0.7). Most Wappinger Creek sites trended to lower differentials moving away from the Hudson River (and up-elevation), but this was not the case for Fishkill Creek sites (ANCOVA: overall $R^2 = 0.67$, $P < 0.001$). The sites circled in Figure 6 are all located in the region of the county where we observed most construction ongoing in 2001. Site W10, which drains a primarily forested subcatchment, nevertheless is near the Taconic Parkway. Site W16, Cold Spring Creek, ironically was one of the warmest streams in our August survey, and we observed water withdrawals both by truck and farm ponds in the vicinity.

Principal component analyses confirmed covariation of many factors, such as highway density with population density and urban and suburban lands. Hence, a PCA was conducted with only five variables—elevation, highway density, discharge normalized to watershed area, percent agriculture, and percent forest—that were selected as representative of land use, physiography, and habitat. The first principal component, accounting for 41.3% of the variance and representing a gradient of urbanization and elevation, was used as a new independent variable against which fish assemblage metrics were regressed. A significant relationship was found between the first principal component and the N stable isotope ratios in eastern blacknose dace (Figure 7; combined $R^2 = 0.55$, $P < 0.001$). In this case, the regression lines for each watershed had nearly identical intercepts and slopes, with the Fishkill Creek samples being slightly enriched in ^{15}N isotopes. A weaker ($R^2 = 0.17$), but still significant ($P < 0.05$) relationship was found between fish species richness normalized to watershed area and the first principal component as well. None of the other fish assemblage metrics were significantly related to this factor.

Our initial hypothesis was that the Fishkill Creek watershed would be more urbanized and, as such, would show signs of greater ecological degradation. To examine this, we conducted an ANOVA on three

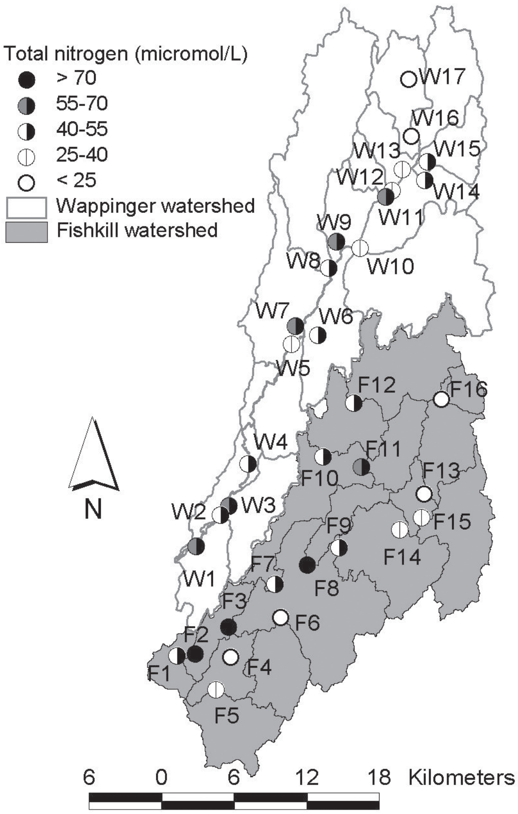

FIGURE 4. Spatial distribution of mean total nitrogen values (μmoles/L).

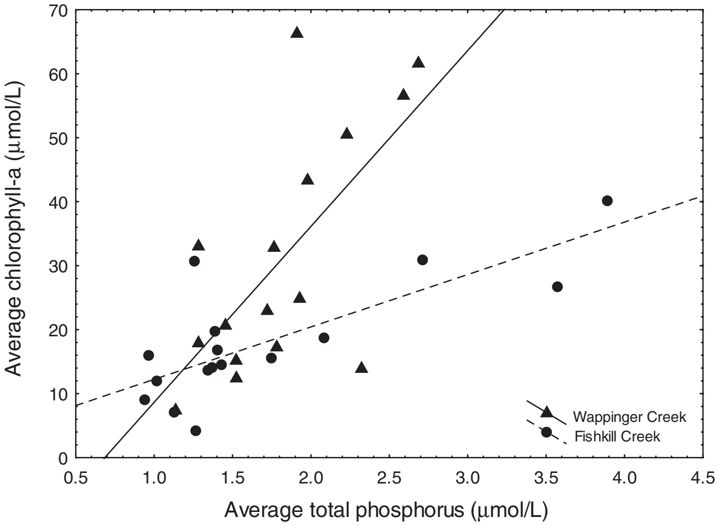

FIGURE 5. Relationship of chlorophyll a (μmol/L) to total P (μmol/L) at Wappinger Creek (triangles) and Fishkill Creek (circles) sites. Mean values, May–August.

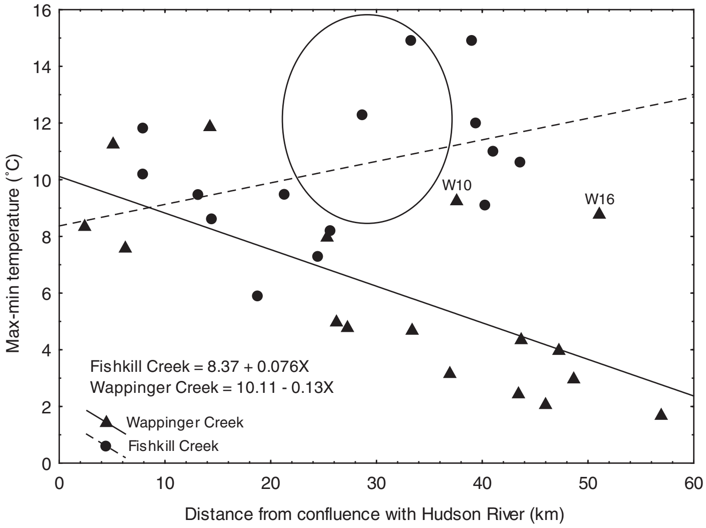

FIGURE 6. Maximum–minimum temperature differentials versus site distance from the Hudson River, Wappinger (triangles) and Fishkill (circles) watersheds.

physical habitat, six chemical, six macroinvertebrate, and seven fish assemblage response variables (Table 3). Most of the means were not significantly different, with a few notable exceptions. Aside from thermal excursions and chlorophyll-a (reported above), three macroinvertebrate assemblage indices were significantly different ($P < 0.05$) and one was marginally significant ($P < 0.053$). All macroinvertebrate assemblage variables showed poorer ecological integrity in Fishkill Creek than Wappinger Creek. Of the fish assemblage variables, only densities showed a significant difference between watersheds, with Fishkill Creek having less than half the mean density of fish seen in Wappinger Creek.

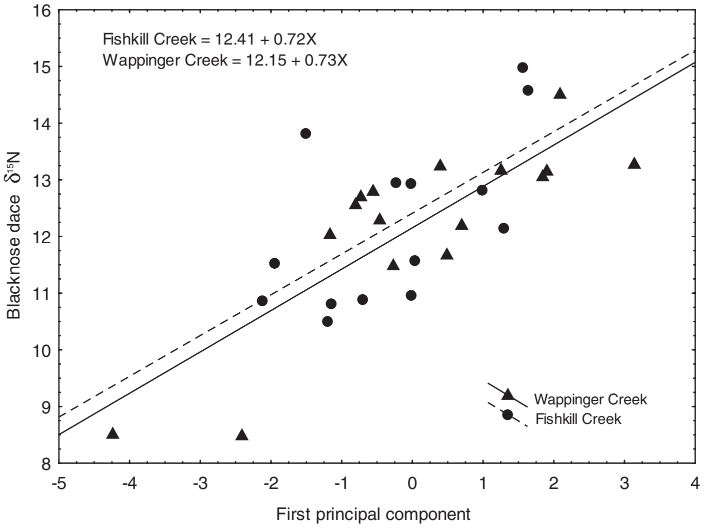

FIGURE 7. Regressions of the nitrogen stable isotope ratios of eastern blacknose dace versus the first principal component from a PCA analysis that examined elevation, highway density, discharge normalized to watershed area, percent agriculture, and percent forest.

TABLE 3. Means, SE, and results of one-way ANOVAs between Wappinger Creek and Fishkill Creek watersheds for selected response variables. Variables with statistically different means ($P < 0.05$) are highlighted in bold.

	Wappinger		Fishkill				
Response variable	Mean	SE	Mean	SE	df	*F*	*P*
Physical habitat							
% silt and sand	17.8	2.97	25.6	3.07	31	3.37	0.08
% embeddedness	44.7	4.15	53.5	4.27	31	2.21	0.15
% canopy cover	69.5	3.25	67.4	3.25	31	0.21	0.65
Chemical							
Max–min temperatures	**5.9**	0.71	**10.4**	0.76	30	18.48	0.001
Chlorophyll-a (mmol/L)	**30.0**	3.68	**18.1**	3.79	31	5.08	0.03
% inorganic N	62.5	4.17	71.0	4.29	31	1.98	0.17
Total P (μmol/L)	2.1	0.24	1.7	0.24	31	0.93	0.34
Total N (μmol/L)	44.2	5.45	49.0	5.62	31	0.38	0.54
August conductivity (mS/cm)	471.7	44.6	502.7	46.1	29	0.23	0.63
Macroinvertebrate assemblage							
% dominance	**61.8**	2.09	**70.1**	2.16	29	7.51	0.01
Diversity (H')	**0.93**	0.03	**0.84**	0.03	29	5.33	0.03
% model affinity	**55.8**	2.42	**48.2**	2.50	29	4.74	0.04
Biotic assessment profile	7.2	0.32	6.2	0.33	29	4.08	0.053
EPT index	52.4	4.69	44.2	4.69	28	1.52	0.23
Taxa richness/watershed area	0.83	0.20	0.63	0.21	29	0.47	0.50
Fish assemblage							
Density (#/m^2)	**0.23**	0.04	**0.11**	0.04	31	5.19	0.03
Species richness/watershed area	0.31	0.06	0.20	0.06	31	1.50	0.23
IBI, excluding transients	36.9	1.82	35.4	1.88	31	0.36	0.55
% centrarchids	10.5	3.49	7.5	3.60	31	0.35	0.56
IBI	37.5	1.87	36.4	1.93	31	0.18	0.67
Diversity (H')	0.65	0.06	0.68	0.06	31	0.16	0.69
Blacknose dace δ^{15}N	12.1	0.38	12.2	0.41	29	0.067	0.80

Some of the ecological data showed nonlinear trends when plotted against urbanization indices, suggestive of a threshold response. We present fish density as an example. Fish densities, when plotted against percent of watersheds in urban and suburban uses, highway density, or population density appeared to show nonlinear, inverse relationships, but the data were scattered. We selected the best relationship (highest proportion of variance explained in nonlinear least-squares regression), which was highway density as the independent variable (Figure 8). Realizing that all these variables were in some way confounded by elevation, we regressed log-transformed highway density on elevation ($R^2 = 0.55$, $P < 0.001$) and used the standardized residuals of this analysis as a new independent variable. This effectively removes the influence of elevation on highway density. The new response also appears nonlinear, but now, Fishkill Creek sites tend to cluster in areas with "higher than expected" road densities (adjusting for elevation), whereas Wappinger Creek sites distribute at "lower than expected" road densities and show more variation in fish density (Figure 9).

Discussion

Over the past two or three decades, land use change in Dutchess County has followed a pattern of economic downturn for farms, reversion of abandoned fields to secondary forest, sale, and development into new housing or, less frequently, commercial property. Most of the new growth is spreading north and east. Housing booms in the mid-1980s, and again in 1998–2001, reflected economic development often tied to industries such as IBM. Downsizing by the IBM corporation was also responsible for a development slowdown in the early 1990s (Lynch 2000). Farmland statistics (NYNASS 1999) show that most of the acreage losses were not from active croplands—which increased slightly over the 1990s—but rather from wooded areas, and areas that had buildings on them. We feel satisfied that our GIS analysis picked

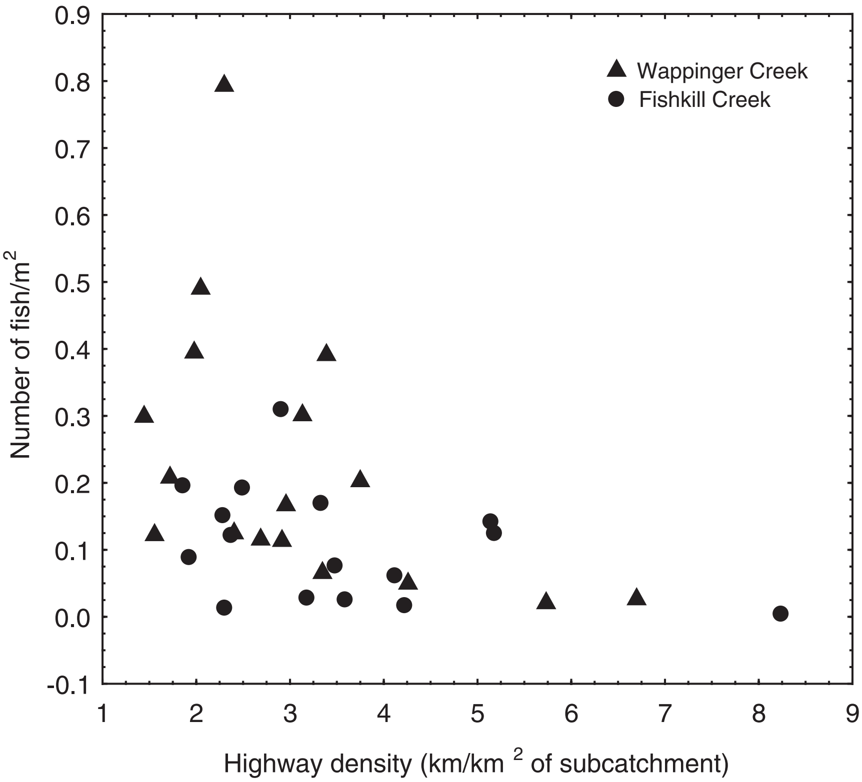

FIGURE 8. Fish densities observed at sites in the Fishkill Creek (circles) and Wappinger (triangles) Creek versus highway densities.

up most of the changes in land use between 1992 and 2001 (Figure 3).

Although suburban growth is clearly happening in many parts of the Wappinger Creek and Fishkill Creek watersheds, the ecological responses were often complex and rarely clear. When plotted against land use, most of the response variables showed much scatter and low, if any, correlations. There appeared to be a hierarchy of responses, going from chemical to organismal, where chemistry reflected land use characteristics, macroinvertebrates did to some extent as well, but fish assemblages (representing a part of the ecosystem that was more displaced from primary production processes) were relatively insensitive.

The regional IBI (Daniels et al. 2002), which had been calibrated, in part, in the Hudson River drainage, appeared relatively insensitive to anthropogenic disturbance, but this could have been due to the limited range of values. Most of our sites fell into the range of IBI scores corresponding to fair to poor conditions. When IBIs are calibrated, care is taken to include sites at the extremes of environmental quality. Our collection of stream sites, while encompassing one or two highly degraded and one or two relatively undisturbed sites, did not possess as clear a gradient of variation in fish assemblage structure. Some of the sites were surprising in their scores: for instance, a site near a county airport, in a suburban area, had the highest IBI score for the Wappinger Creek watershed.

Several of the stream macroinvertebrate indices appeared to be more sensitive to indicators of urbanization. Some of the reasons for the discrepancy may lie in the scale at which fish and macroinvertebrates experience the environment. Stream insects presumably have smaller spatial ranges than do fish, and so their assemblages may be more constrained by streamwater chemistry. Fish, which can move greater distances, can seek refuge from unsuitable conditions. One of the ameliorating factors for the fish assemblages we surveyed may have been the presence of riparian vegetation, and reasonably high canopy cover over the streams, resulting in shading during the record drought of 2001.

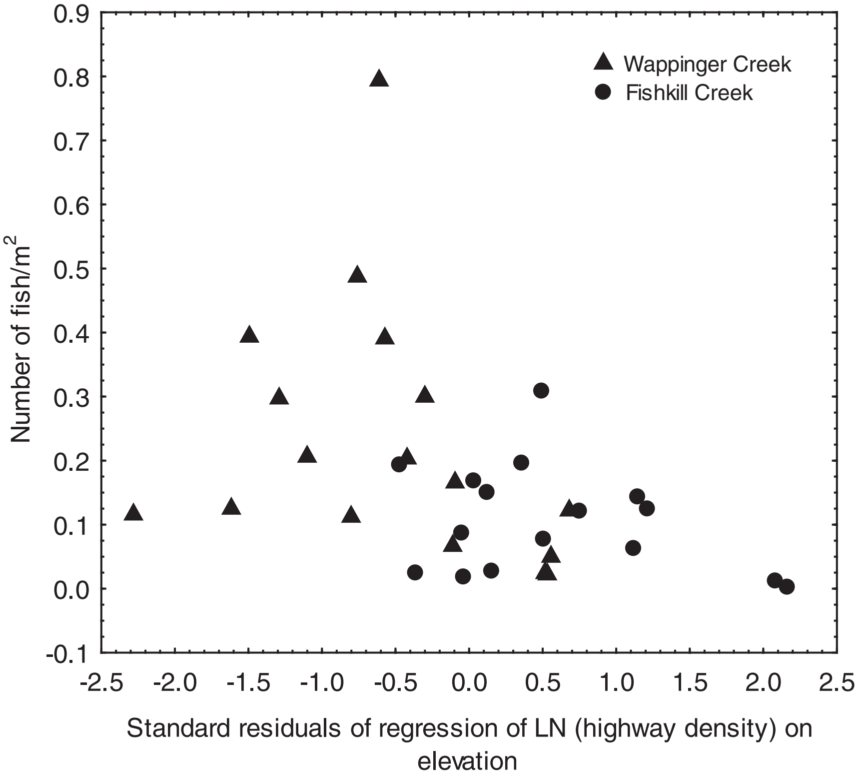

FIGURE 9. Fish densities observed at sites in Fishkill Creek (circles) and Wappinger Creek (triangles), plotted against the standardized residuals from a regression of log-transformed highway densities on elevation.

The strong relationship of eastern blacknose dace nitrogen stable isotope ratios to urbanization indices is in agreement with results obtained in coastal catchments on Cape Cod, where organisms in more urbanized watersheds had higher $\delta^{15}N$ values than those in less disturbed watersheds (McClelland et al. 1997). The heavier, less abundant ^{15}N isotope tends to accumulate in trophic transfers and under circumstances where much N processing occurs; for example, Caraco et al. (1998) found that $\delta^{15}N$ values increased as leaf litter was decomposed and the dissolved inorganic N remineralized. Sewage tends to have elevated $\delta^{15}N$ as well, whereas artificial fertilizers, manufactured by the Haber-Bosch process of fixing atmospheric N, have $\delta^{15}N$ values closer to the atmospheric value of zero (McClelland et al. 1997). Seston and periphyton (unpublished data) also showed increasing $\delta^{15}N$ with urbanization indices, but with more scatter. The weaker relationships probably resulted from different sources of organic matter contributing to the seston and different species of periphyton. Thus, standardizing on a particular species, as well as a particular life stage (we chose adult eastern blacknose dace, although juveniles were occasionally assayed as well), is useful.

Eastern blacknose dace was a sentinel species in our study, and this represents a novel combination of the sentinel species and the stable isotopic methods for impact assessments. Eastern blacknose dace are cosmopolitan in Hudson Valley streams and, thus, provide a useful species to track. Fraker et al. (2002) used eastern blacknose dace as an indicator species in the Baltimore, Maryland vicinity, finding that fish in more urbanized areas put on most of their growth and matured in the first year of life, while fish in more rural environments continued to grow through age 2, and most matured in that year as well. Fitzgerald et al. (1999) also found utility in the sentinel species approach because their sentinel organism (creek chub *Semotilus atromaculatus*) was sensitive to water quality and was also ubiquitous in the small streams they were surveying.

A nonlinear, inverse response of fish densities to highway densities was detected. Similarly, Limburg and Schmidt (1990) found an inverse response of larval fish density and percent of land in urban and suburban use in 16 Hudson River tributaries studied in the late 1980s. The ultimate cause may only be speculated on, but could relate to the effects of impervious surface, which affect hydrology, chemistry, and geomorphology of streams (Klein 1979; Walsh 2000; CWP 2003). Reviewing the ecological effects of roads, Forman and Alexander (1998) noted that increased peak flows occur at road densities greater than 2–3 km/km^2, promoting more scouring and erosion. Within our own data set, 16 sites had road densities greater than 3 km/km^2, but consistently low fish densities occurred at sites where subcatchment highway densities exceeded 4 km/km^2 (Figure 8).

Fish densities may vary as a function of position in the watershed, with increases in smaller, higher elevation streams confounding urbanization indices. Therefore, further exploration of this relationship included an attempt to adjust highway densities for the observed, nonlinear decline in highway densities with elevation (a proxy for many other geographic factors, such as distance from the river mouth and stream order), by extracting the standardized residuals of the latter relationship and using them as a new independent variable. In this analysis, a new pattern emerged, showing that the Fishkill Creek watershed had higher than expected road densities and low densities of fish and that the Wappinger Creek watershed sites had lower than expected road densities and generally higher densities of fish. In a sense, then, the Fishkill Creek watershed is “over-built” and the Wappinger Creek watershed is “under-built,” and in the road-denser drainage, fish densities were lower. The historic pattern of settlement by humans in this part of the Hudson Valley follows longitudinal gradients, with access to the Hudson River (for trade) at one end and higher elevation lands, with upland soils less suited for agriculture, at the other. This pattern is likely common to many areas and implies that urbanization trends may be conflated with strong, longitudinal gradients.

In this study, as in many others (this volume), complex and often diffuse patterns of ecological response to urbanization appear to be the result of historical contingencies (Harding et al. 1998), patchworks of land uses, and unexplained variation, presenting challenges that even multidisciplinary approaches find difficult to resolve (Nilsson et al. 2003). Some of the uncertainty may ultimately be explained by zoning regulations, as these are implemented town by town on individual tax parcels, implemented as parcels come up for sale and new regulations take effect. The spatial configurations of urban and suburban land development may also produce different ecosystem responses (Kleppel et al. 2004). Thus, more work could focus on the relationship of zoning and ecological responses, but would entail site-specific knowledge of what regulations apply.

The approach used here indicates that Fishkill Creek is the more ecologically degraded of the two, but also that moderate impact is occurring to Wappinger Creek as well. Given that most growth in the Wappinger watershed is predicted to occur in its northern and eastern parts (Polimeni 2002), planners and citizens there might take note of the Fishkill watershed as a vision of the “business as usual” development trajectory.

Future work in our project will include more historic ecological comparisons with data from the 1980s, as well as further integrating the ecological, economic, and land use change studies. At a very practical level, we are currently working with planners and an intermunicipal citizens’ council to develop a new policy tool, using Multi-Criteria Decision Assessment (Erickson et al. 2005). This is a stakeholder-based approach that helps to elicit their preferences, whether explicit or hidden, and work towards compromise in conflict resolution. We will test the approach for its value as a means for managers and citizens to come together for prioritizing watershed management goals.

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