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Landscape template of New York City's drinking-water-supply watersheds

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Abstract. New York City (NYC) receives >99% of its drinking-water supply from streams, rivers, and reservoirs north and northwest of the city (east or west of Hudson River [EOH or WOH, respectively]). As part of a large-scale enhanced water-quality monitoring project (the Project) in NYC's drinking-water-supply watersheds, 60 stream and 8 reservoir sampling sites were established in the water-supply area (30 WOH and 30 EOH) and sampled from 2000 to 2002. Our study describes watershed characteristics (including climate and hydrology, land use, human population, and known point-source discharges) at each study site and provides an analysis of differences in land use quantified at 3 scales: 1) watershed, 2) riparian (30 m on each side of entire stream network upstream of a site), and 3) reach (same as riparian, but truncated 1 km upstream of the study site). Regression analysis was used to determine relationships among scales, and principal components analysis was used to describe spatial differences in watershed characteristics across the study region. EOH sites are on smaller streams than WOH sites because the WOH region is much larger than the EOH region. EOH sites had smaller mean annual area-specific discharges than WOH sites, reflecting differences in precipitation and in watershed hydrologic retention that were related to surficial geology and the presence of wetlands, lakes, and reservoirs. Population densities, point-source discharges, and flows from those discharges were higher in EOH watersheds than in WOH watersheds. Landuse values in the EOH watersheds ranged from 87% forest to 57% urban. Agricultural land use exceeded 16% in only one watershed. Landuse values in WOH watersheds indicated either largely forest (several sites near 98%) or agriculture and grassland (many near 25%, largely in pasture). Urban landuse values were never >11%. Values for most landuse categories were strongly correlated (most $R^2 > 0.75$) between the watershed and riparian scales. In WOH watersheds, values for categories indicating human land use (e.g., agriculture, urban) were greater at the riparian than at the watershed scale, indicating that human land use was concentrated along the stream network. In EOH watersheds, values for categories indicating human land use were lower at the riparian than at the watershed scale. Values for most landuse categories were not correlated (typically $R^2 < 0.50$ or not significant) between the reach and watershed scales, indicating that local landuse values described statistically different conditions than watershed- or riparian-scale landuse values.

Key words: land cover, land use, watershed, riparian, reach, forest, agriculture, urban.

Land use influences hydrology (Lull and Sopper 1966, Booth and Jackson 1997, Rabalais et al. 2002), chemistry (Dunne 1979, Bolstad and Swank 1997, Johnson et al. 1997), biology (Lenat and Crawford 1994, Richards et al. 1996), and functional attributes (Niyogi et al. 2004, Sweeney et al. 2004, Bott et al. 2006c) of freshwater ecosystems (Allan 2004). (In our paper, land use implies both land use and land cover.) Landuse information is now widely recognized as a good indicator of human impacts on riverine systems (Gergel et al. 2002). Therefore, a complete inventory of land use and point sources in the watershed is a critical component of a watershed monitoring program aimed at understanding sources of pollutants to streams, lakes, and reservoirs (National Research Council 2000).

In their assessments of the relationship between landscape factors and riverine systems, Gergel at al. (2002) and Allan (2004) suggested that the type, extent, and proximity of land use can differ in their relationships with stream water-quality response variables. For example, the types and extents of land use that influence the nutrient and sediment content of streams are different from those that influence macroinverte-

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brate or fish communities. One way to test the influence of landuse type, extent, and proximity is to summarize these variables at different spatial scales to determine which scale best describes differences among sites (e.g., Sponseller and Benfield 2001, Strayer et al. 2003).

We described the landscape template (including land use, soils, geology, and climate and hydrology) of the New York City (NYC) drinking-water-supply watersheds, which occur in 2 geographically distinct regions (see below). This description serves as important background material that provides the spatial context for understanding the results of a large-scale enhanced water-quality monitoring project (the Project) conducted in the watersheds from 2000 to 2002 (Blaine et al. 2006). Our primary objective was to quantify land use at 3 scales (reach, riparian, and watershed) that captured land use from different proportions of the watershed upstream from each sampling site. Landuse variables were compared among scales. A secondary goal of our analysis was to compare and contrast watershed characteristics in the 2 regions over which our study occurred. We focused on 3 questions regarding land use: 1) Are reach- and riparian-scale land uses reflective of watershed-scale land uses? 2) Are certain landuse categories more or less prevalent at watershed, riparian, or reach scales? 3) Do scale–landuse relationships differ between regions?

Study Regions

Our study was done in 2 regions (fig. 1 in Blaine et al. 2006) encompassing ~5066 km^2: 1) the east of Hudson River region (EOH), also known as the Croton/Kensico system (971 km^2), and 2) the west of Hudson River region (WOH) that includes 2 headwater systems (the Catskills [1479 km^2] and the upper Delaware [2616 km^2]). The WOH includes 6 primary watersheds and 6 reservoirs that drain either to the Hudson River (Schoharie, Esopus, and Rondout creeks) or to the Delaware River (Neversink and East and West Branches of the Delaware River) (Fig. 1). The EOH includes 12 reservoirs, 3 controlled lakes, and numerous tributaries that drain to the Hudson River (Fig. 2). Water for drinking is withdrawn from all WOH reservoirs and from several EOH reservoirs.

The Delaware and Hudson watersheds were covered by dense mixed-hardwood or hardwood-conifer forests prior to European settlement (Jackson et al. 2005). Vast proportions of both watersheds were clear cut in the late 18th and 19th centuries and, today, forests in these watersheds are dominated by sugar and red maple, yellow birch, American beech, several species of oak, eastern hemlock, and white pine.

Surficial geology

Surface geology in the 2 regions is the result of past glaciation by the Hudson–Champlain Lobe of the Laurentide Ice Sheet. In the Catskills, glacial history is complicated by the occurrences of both the Laurentide Ice Sheet and local mountain glaciers (Isachsen et al. 2000). The WOH generally can be separated into 2 distinct geologic regions: 1) the southeast (Neversink, Esopus, and upper Schoharie watersheds) is primarily bedrock outcrop mountain tops with till, kame (steep-sided mounds of sand and gravel deposited by meltwater from a glacier), and outwash sand and gravel deposits in narrow valleys; and 2) the northern and western areas have more till and deeper soils on the ridges and side slopes and valleys with recent alluvium, outwash sand and gravel, and kame deposits. In the EOH, surficial geology is predominantly glacial till riddled with kame deposits throughout with bedrock outcrops and swamp deposits more prevalent in the north.

Bedrock geology

Bedrock geology of the WOH (Isachsen et al. 2000) has roots in the Late Devonian Period (~375 million years before present [ybp]) and is mostly sedimentary (quartz-dominated shale, sandstone, siltstone, and conglomerates). Different formations (Oneonta, Lower Walton, and Upper Walton) occur from north to south and east to west within the WOH, but rock composition remains relatively similar throughout the region. Geology in EOH watersheds is a mosaic of sedimentary, metamorphic, and igneous rock formations defining 2 distinct geologic regions (Isachsen et al. 2000), the Hudson Highlands (Middle Proterozoic ~1100 million ybp), and the Manhattan Prong (~500 million ybp). The Hudson Highlands region, which crosses the northwestern portion of the EOH, is composed of layered and unlayered metamorphic units, which are highly resistant to erosion and contain biotite, magnetite, mica, quartz, and feldspar gneiss. The Manhattan Prong dominates the southern portion of the EOH and also is found in the northeastern tip of the region. Its metamorphic rocks include Fordham, Yonkers, Pundridge, and Bedford gneiss, and Inwood (to the south) and Stockbridge (to the north) marble. A pocket of limestone, dolostone, and siltstone occurs near the northern tip of the EOH.

Soils

Soils in the 2 regions are primarily Udept Inceptisols (suborder/order) that are moderately to highly acidic (NRCS 1994). Inceptisols usually occur on relatively active landscapes, e.g., mountain slopes and river valleys, where the processes of erosion actively expose and deposit relatively unweathered material (Brady and Weil 1999). Udepts, which extend from southern New York through central and western Pennsylvania, West Virginia, and eastern Ohio, are freely drained Inceptisols and often have only thin, light-colored surface horizons. Some Udepts in southern New York and northern Pennsylvania are naturally unproductive because of low organic content and have been used for silviculture and pasture/grazing activities after earlier periods of crop production (Brady and Weil 1999). Aquepts (fluvially deposited wet Inceptisols) and Fluvents (fluvially deposited wet Entisols that are younger and less developed than Inceptisols) also are present in EOH and WOH valleys. These organically rich soils are too wet for crop production without artificial drainage. Saprists, wet Histosols of well-decomposed plant material usually associated with wetlands, are limited in extent in the WOH but occur throughout the EOH and account for up to ~5% of soil surface area in some watersheds.

Methods

Site selection

In spring 2000, 60 stream and 8 reservoir (Bott et al. 2006b) sampling sites were established in major watersheds of the 2 regions (Table 1, Figs 1, 2). Thirty sites were selected in each of the regions (EOH and WOH) based on the following criteria: 1) a range of land uses (forested, agricultural, suburban, and urban), 2) a range of underlying geology/soils, 3) availability of US Geological Survey (USGS)-gauged stream-flow data (Table 1), 4) availability of background data (e.g., nearby historic or current New York City Department of Environmental Protection [NYC DEP] sites, Table 1), and 5) feasibility of studying the various elements of the Project (Blaine et al. 2006).

Study sites were separated into 50 *targeted* sites and 10 *integrative* sites (Blaine et al. 2006). Targeted sites occurred throughout the regions on streams of varying size (Table 1). Integrative sites occurred sufficiently downstream in a watershed to integrate effects of land use and other factors on stream water-quality and functional processes. In some instances, downstream distance was constrained by feasibility of one or more of the study elements of the Project.

Watershed, riparian, and reach delineations

Sampling sites were located using a Trimble GPS Pathfinder™ ProXR receiver. Geographic data were manipulated using ArcMap™ (version 9.0, Environmental Systems Research Institute, Redlands, California). Watershed boundaries provided by NYC DEP that did not precisely match our sample locations were modified by on-screen digitizing using USGS 1:24,000 topographic maps (6.1-m contours).

Land use, population density, road density, and known point sources were quantified and summarized at 3 spatial scales. Watershed boundaries defined the watershed scale. Thirty-meter buffers around each side of all streams or water bodies in the stream network upstream of each sampling site defined the riparian scale. These riparian-scale buffers were clipped at a distance of 1-km upstream from each sampling site to define the reach scale. The reach-scale delineation included tributaries (where present) but the mainstem stream received the greatest proportion of the 1-km length. Two sites (59 and 60) located on small streams with mapped channel lengths <1 km (0.71 and 0.95 km, respectively) were retained in all analyses.

Landscape variables and data analyses

Precipitation.—Daily precipitation data for the study region were compiled from the National Oceanic and Atmospheric Administration (NOAA), National Climatic Data Center (NCDC), Cooperative Summary of the Day (TD3200) CDROM containing period-of-record data through 2001. Additional 2002 data were downloaded from http://ols.nndc.noaa.gov/plolstore/plsql/olstore.prodspecific?prodnum=C00314-TAP-S0001. NOAA sites were selected by importing the site coordinates in decimal degrees for NY climate divisions 2 and 5 and all sites in Connecticut into a Geographical Information System (GIS) layer using ArcMap™. All sites within a 10-km buffer around the entire study area were considered, and 21 sites (14 WOH, 7 EOH) were finally selected by keeping those sites with ≥2 y of data in the 2000 to 2002 period. Daily precipitation data were summed by month and year for the study period for each NOAA site.

The period from 1964 to 1999 was the longest period of overlapping and continuous USGS streamflow monitoring data used to summarize hydrological trends across the study region (see below). Therefore, precipitation data for the period from 1964 to 1999 were collected from a subset of the NOAA sites that had adequate historical data to provide a temporal perspective for the study period. For any given site, a single year's data record was omitted if it was incomplete. Thus, the number of years of data for the NOAA sites used for historical analysis ranged from 20 to 34. A spatial perspective for precipitation throughout the study period was obtained by com-

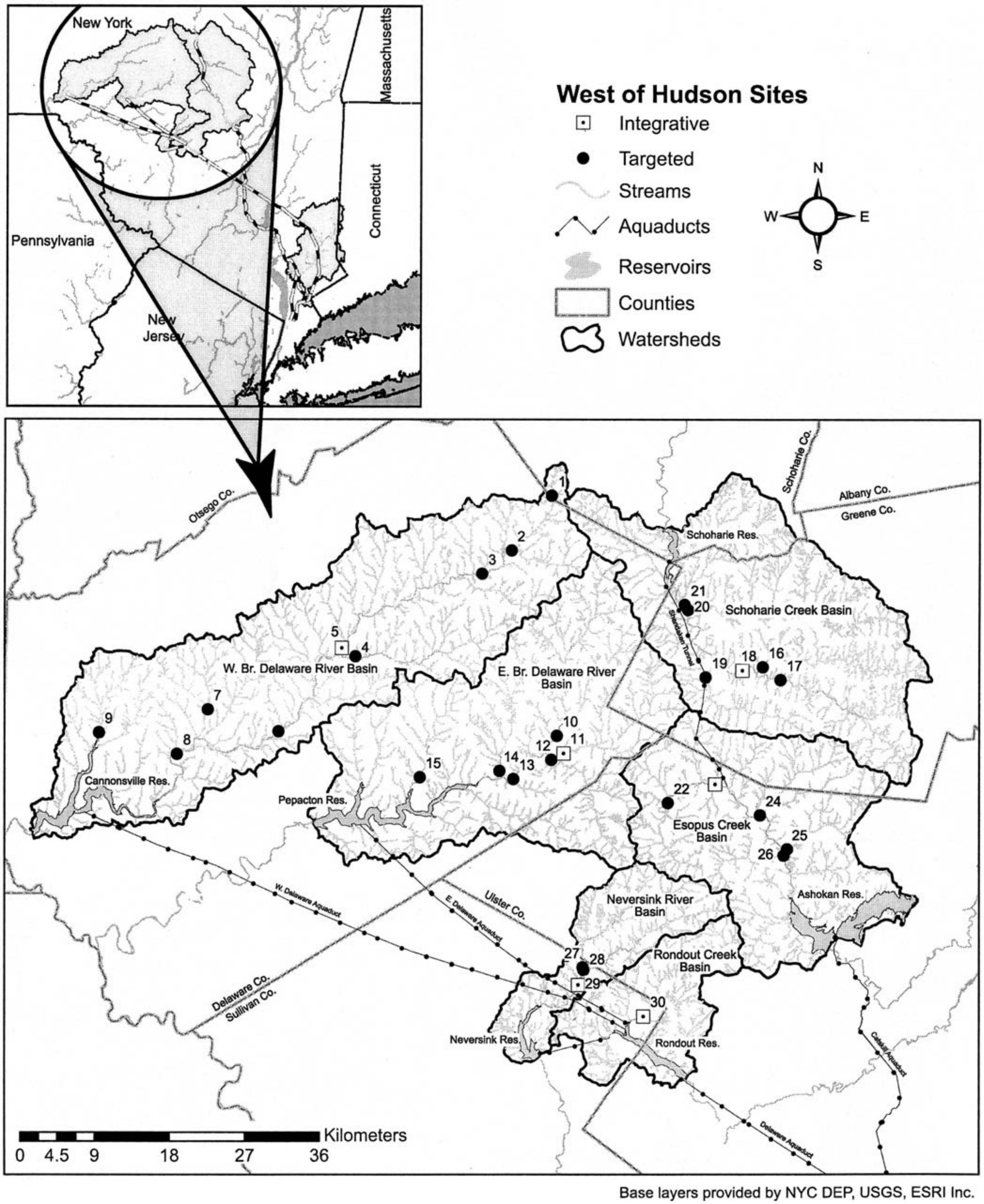

FIG. 1. Stream monitoring sites in southeastern New York (inset) located west of Hudson River (WOH) in headwater watersheds of the West and East Branch Delaware River (to Delaware River), Neversink River (to Delaware River), Schoharie Creek (to Hudson River), Esopus Creek (to Hudson River), and Rondout Creek (to Hudson River).

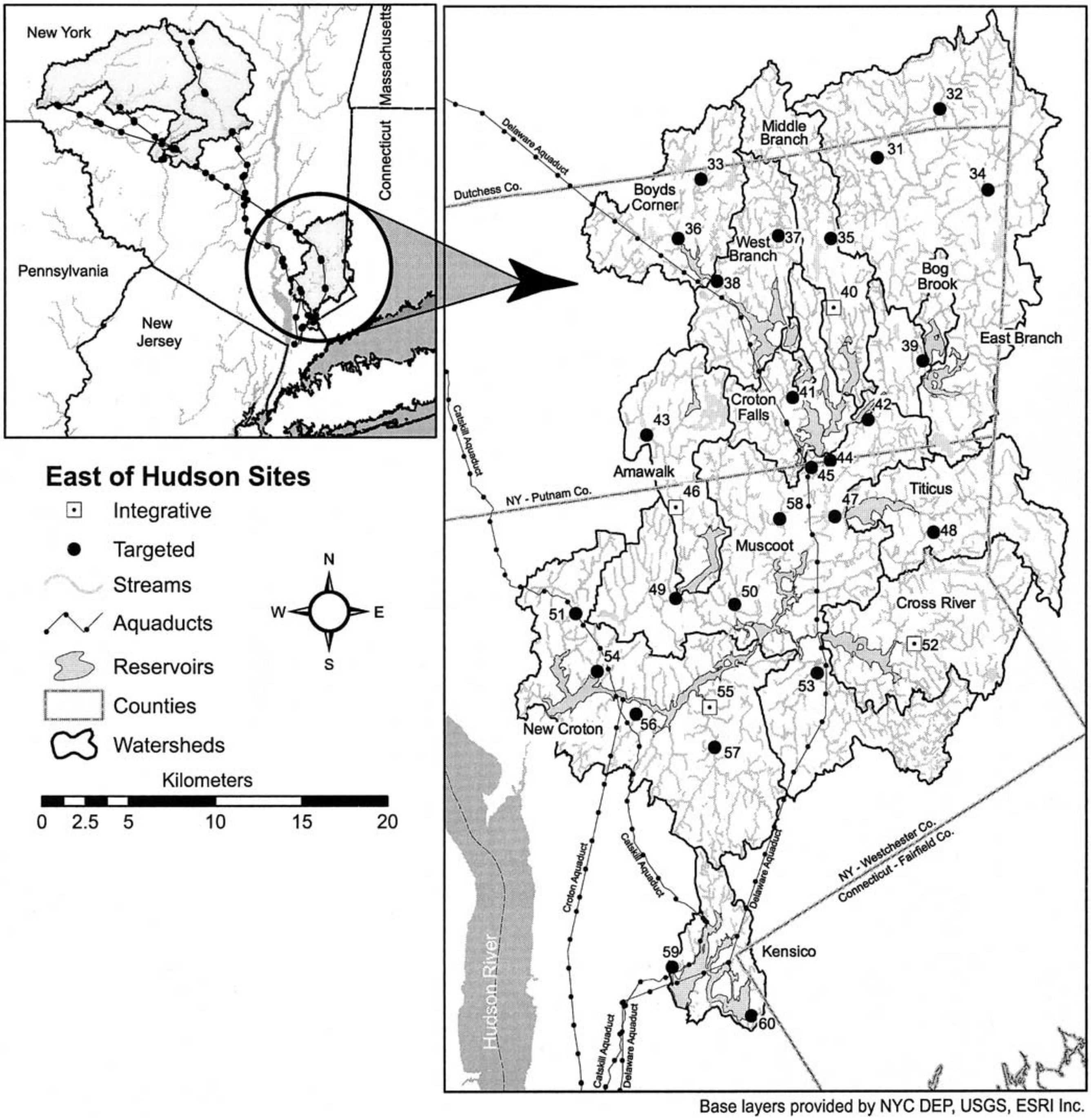

FIG. 2. Stream monitoring sites in southeastern New York (inset) located east of Hudson River (EOH) in headwater watersheds of the Croton and Bronx River (Kensico Reservoir) systems (to the Hudson River).

paring average annual precipitation between WOH and EOH sites.

Hydrology.—Published streamflow data were available for 61 USGS sites located throughout the study regions (http://waterdata.usgs.gov/ny/nwis/sw). Ten of these sites were influenced either by reservoir/lake outlets or by interbasin transfers (based on USGS site information) and 2002 data were unavailable for one site. Data for the entire period of record through September 2002 were obtained for the remaining 50 USGS sites. Daily mean discharges were converted from ft^3/s to $cm^3/cm^2/d$ (cm/d) by dividing discharge by watershed area to generate area-specific discharge rates, which facilitated com-

Table 1. Stream monitoring study sites in west of Hudson River (WOH) and east of Hudson River (EOH) regions of New York City (NYC) drinking-water-supply watersheds. Site numbers are specific to the Stroud Water Research Center (SWRC) database. Watershed identifiers are: WBD and EBD = West or East Branch Delaware River, SCH = Schoharie Creek, ESP = Esopus Creek, NVR = Neversink River and Rondout Creek, EMC = East and Middle Branch Croton River, WBC = West Branch Croton River, MNC = Muscoot River and other sites north of Croton Reservoir, TCS = Titicus, Cross, and Stonehill rivers, KSC = Kensico Reservoir and other sites south of Croton Reservoir. E = east, W = west, R = river, Trib = tributary, Br = branch, Brk = brook, Cr = creek, nr = near, T = targeted site, I = integrative site, WB = winter baseflow samples, S = stormflow samples, Q_{Ave} ions = mean discharge ($n = 3$) at time of baseflow water chemistry (summer) sampling, Q_{Ave} inverts = mean discharge ($n = 3$) at time of benthic macroinvertebrate (spring) sampling.

Region	SWRC no.	Watershed	Site name	Latitude (decimal °)	Longitude (decimal °)	Type	Watershed area (km^2)	Q_{Ave} ions (m^3/s)	Q_{Ave} inverts (m^3/s)
WOH	1	WBD	W Br Delaware R nr Stamford	42.427723	–74.617441	T WB	5.9	54.4	150.8
	2	WBD	Town Brk nr Hobart	42.368793	–74.676987	T WB	41.4	371.3	986.0
	3[a]	WBD	W Br Delaware R at South Kortright	42.343674	–74.719800	T	122.6	1836.8	3037.3
	4	WBD	Little Delaware R nr Delhi	42.259438	–74.928044	T	135.4	1261.0	2457.6
	5	WBD	W Br Delaware R nr Delhi	42.260172	–74.927666	I	372.3	3467.7	6758.5
	6	WBD	W Br Delaware R at Hawleys	42.175484	–75.018290	T WB S	663.9	10,218.4	13,510.0
	7	WBD	W Brk nr Walton	42.198677	–75.121183	T	34.8	322.6	982.6
	8	WBD	W Br Delaware R nr Walton	42.150651	–75.165521	T WB	878.6	7739.3	18,614.5
	9[a,b]	WBD	Trout Cr nr Trout Cr	42.173769	–75.279433	T	53.3	748.8	1232.5
	10	EBD	E Br Delaware R nr Arkville	42.169880	–74.611514	T WB	181.6	1942.8	4038.7
	11[a,b]	EBD	Bush Kill nr Arkville	42.150721	–74.601627	I WB	121.1	934.6	3134.1
	12[a,b]	EBD	Dry Brk nr Arkville	42.144399	–74.619285	T WB	211.9	1567.3	5647.6
	13	EBD	E Br Delaware R nr Dunraven	42.123772	–74.674938	T WB	448.2	5426.4	7715.0
	14[a,b]	EBD	Platt Kill at Dunraven	42.132560	–74.695428	T	90.7	831.7	1670.9
	15[a,b]	EBD	Tremper Kill nr Andes	42.126101	–74.811702	T	77.8	1233.1	2543.1
	16[a,b]	SCH	East Kill nr Jewett Center	42.242467	–74.310366	T WB	93.1	254.9	2220.5
	17	SCH	Schoharie Cr nr Jewett Center	42.228239	–74.284268	T WB	133.2	364.8	3543.4
	18[b]	SCH	Schoharie Cr nr Lexington	42.238506	–74.339876	I WB	250.1	793.0	6032.2
	19[b]	SCH	West Kill nr Lexington	42.231837	–74.393246	T	74.4	203.7	1917.9
	20[a]	SCH	Batavia Kill nr Prattsville	42.303657	–74.418487	T WB	189.4	518.6	4460.5
	21	SCH	Schoharie Cr nr Prattsville	42.309343	–74.423210	T WB	589.0	1612.8	13,410.8
	22[a]	ESP	Esopus Cr nr Big Indian	42.096036	–74.449983	T WB	76.7	777.4	1783.4
	23[a,b]	ESP	Esopus Cr nr Allaben	42.116905	–74.380218	I WB	163.4	2265.6	4072.4
	24[a]	ESP	Stony Clove Cr at Phoenicia	42.083290	–74.315735	T WB	83.5	846.2	1880.9
	25[a]	ESP	Beaver Kill at Mount Tremper	42.046748	–74.276543	T	64.5	653.2	1451.9
	26[b]	ESP	Esopus Cr nr Mount Tremper	42.039750	–74.281761	T	438.8	13,280.4	21,361.2
	27[a,b]	NVR	W Br Neversink nr Claryville	41.920402	–74.574486	T WB	87.1	1161.1	2605.4
	28[a]	NVR	E Br Neversink nr Claryville	41.917600	–74.573459	T	71.1	1334.8	2014.0
	29[b]	NVR	Neversink R nr Claryville	41.901204	–74.581408	I WB S	165.9	3689.0	4902.8
	30[a,b]	NVR	Rondout Cr nr Lowes Corner	41.866889	–74.486683	I WB	100.3	1312.2	2539.4
EOH	31	EMC	W Patterson Cr nr Patterson	41.511920	–73.622452	T	11.0	25.8	131.3
	32[a]	EMC	Brady Brk nr Pawling	41.541332	–73.570024	T WB	17.7	40.4	211.8
	33	WBC	Leetown Stream nr Farmers Mills	41.502004	–73.744515	T WB	8.4	19.2	95.1
	34[a]	EMC	Haviland Hollow Br at Haviland Hollow	41.494381	–73.546416	T	25.1	107.1	350.8
	35	EMC	Trib to Middle Br Croton R	41.470629	–73.655240	T	26.9	62.9	320.8
	36[a,b]	WBC	W Br Croton R nr Allen Corners	41.471733	–73.760774	T	28.4	29.0	336.1
	37[b]	WBC	Horse Pound Brk nr Lake Carmel	41.472510	–73.691475	T	10.3	14.3	145.4
	38	WBC	W Br Croton R nr Kent Cliffs	41.449613	–73.734348	T	58.2	137.0	641.2
	39	EMC	Trib to E Br Croton R nr Brewster	41.406456	–73.593218	T	1.5	3.6	14.8
	40[a,b]	EMC	Middle Br Croton R nr Carmel	41.434762	–73.654275	I WB	35.5	68.9	509.8

TABLE 1. Continued.

Region	SWRC no.	Watershed	Site name	Latitude (decimal °)	Longitude (decimal °)	Type	Watershed area (km^2)	Q_{Ave} ions (m^3/s)	Q_{Ave} inverts (m^3/s)
EOH	41[b]	WBC	W Br Croton R nr Crafts	41.388429	–73.683238	T	117.1	670.2	689.1
	42	EMC	Holly Stream nr Deans Corner	41.376373	–73.631460	T	11.9	24.1	139.0
	43	MNC	Secor Brk at West Mahopac	41.370157	–73.784534	T WB	6.8	14.0	71.8
	44[b]	EMC	E Br Croton R nr Croton Falls	41.355717	–73.658092	T	238.3	1708.6	2048.5
	45[b]	WBC	W Br Croton R nr Butterville	41.352213	–73.671042	T	209.1	1038.4	2190.1
	46[a,b]	MNC	Muscoot R nr Baldwin Place	41.332659	–73.764970	I WB	35.1	394.6	385.2
	47[b]	TCS	Titicus R nr Purdys Station	41.327014	–73.655407	T	63.9	271.9	896.8
	48	TCS	Crook Brk nr Grant Corner	41.318073	–73.587466	T	5.3	6.2	52.9
	49[a]	MNC	Hallocks Mill Brk nr Amawalk	41.285831	–73.766065	T WB	29.5	35.2	291.7
	50[a,b]	MNC	Angle Fly Brk nr Whitehall Corners	41.282468	–73.725124	T	7.7	2.7	73.6
	51[a]	MNC	Hunter Brk nr Mohansic State Park	41.278899	–73.835252	T	15.6	21.3	158.3
	52[a,b]	TCS	Cross R in Ward Pound Ridge Reservoir	41.260288	–73.601986	I WB	44.5	163.7	679.7
	53	TCS	Stone Hill R nr Bedford Hills	41.245949	–73.669116	T	34.6	40.8	367.5
	54	MNC	Unnamed Trib to Croton R	41.248582	–73.821063	T	3.6	6.7	27.1
	55[a,b]	KSC	Kisco R nr Stanwood	41.228980	–73.743563	I WB S	45.5	187.6	883.6
	56	KSC	Gedney Brk nr Kitchawan	41.226161	–73.794589	T	3.1	4.3	27.5
	57[a]	KSC	Kisco R at Mount Kisco	41.208288	–73.740647	T	38.9	66.8	334.8
	58	MNC	Trib to Croton R nr Lake Purdy	41.326199	–73.693261	T WB	5.4	6.8	56.9
	59[a]	KSC	Trib to Kensico Reservoir nr Hawthorn	41.095218	–73.772152	T	0.2	0.3	2.2
	60[a]	KSC	Trib to Kensico Reservoir nr West Chester Airport	41.069169	–73.717890	T WB	0.4	0.6	4.3

[a] Site co-located at a NYC Department of Environmental Protection (DEP) sampling site (2 co-located NYC DEP sites were ~1.2 km downstream of the corresponding SWRC site with one known tributary between them)

[b] Site co-located at a US Geological Survey (USGS) gauging station (exact USGS station can be found in chapter 2, table 2.3 of SWRC 2003)

parisons of yield among watersheds. Streamflow was summarized across months and years (October-to-September water year) for the 2000 to 2002 study period and for time periods before our study. Data were available from 1964 to 1999 for WOH sites, but none of the EOH sites had monitoring periods >8 y. Spatial summaries were computed on a watershed level (defined by 5 reservoir watersheds) for the WOH sites, but all EOH sites were summarized as a single region.

Analysis of variance (ANOVA) was used to test for significant differences ($p \leq 0.05$) in annual discharge among the EOH region and the 5 WOH watersheds. The relationships between mean annual discharge and other landscape variables (e.g., soils, surficial geology, land use) were assessed with Pearson correlations. Discharge data also were used to determine site- and sampling-date-specific flow conditions when sampling for other elements of the Project (Appendix).

Land use.—Rasterized landuse data (obtained from NYC DEP) were derived from 2001 Landsat Enhanced Thematic Mapper Plus (ETM+) satellite imagery (5 April, 8 June, 10 July, and 12 September 2001). A classification scheme based on Anderson Level 4 (Anderson et al. 1976) was developed by NYC DEP to classify ETM+ images after overlaying them with National Wetland Inventory polygon data (mid 1980s), NY State Office of Real Property Services Tax Parcel data, US Department of Agriculture Farm Security Agency and Watershed Agriculture programs, and other ancillary data sources (NYC DEP 2004). The spatial resolution of this composite landuse data layer was 10-m grid-cell size.

Preliminary assessment of the success of classification indicated that the Anderson Level 2 classification was the most complete level. Nevertheless, many grid cells, particularly urban ones, were classified only at Anderson Level 1. Therefore, a computer routine was developed to classify several urban grid cells remaining at Anderson Level 1 to the appropriate Anderson Level 2 category (Anderson et al. 1976). The reclassification scheme identified the majority value of all Anderson Level 2-categorized cells in a neighborhood surrounding the grid cell requiring reclassification and assigned that classification to the cell in question. This scheme was run iteratively, with the neighborhood of grid cells increasing by 1 grid-cell width in each run, until <5% of all cells requiring reclassification in the input raster remained unclassified. Some agriculture and brushland grid cells also were classified only to an Anderson Level 1 category, but those grid cells were either too few within a watershed or too isolated from other similarly categorized grid cells to achieve reclassification. The result was that 13 of 60 watersheds had >1% of cells classified to Anderson Level 1 urban, agriculture, or brushland categories, and only 2 of those 13 watersheds had >5% of cells classified to Anderson Level 1 urban, agriculture, or brushland categories. Following this reclassification scheme, land use at Anderson Level 2 classification was summarized as % cover for watershed-, riparian-, and reach-scale areas.

Percent landuse values at the riparian and reach scales were compared to % landuse values at the watershed scale using regression analyses. Significance of regressions and regression slopes (H_o: $\beta_1 = 1$) and intercepts (H_o: $\beta_0 = 0$) were used to assess these relationships. A slope not significantly different from 1 with an intercept not significantly different from 0 indicates that % landuse values at the finer scale were similar to % landuse values at the watershed scale, i.e., that proportional land use did not change with scale. Principal Components Analysis (PCA) was used to illustrate primary landuse variable(s) (after arcsin $\sqrt{[x]}$ transformations) within each study region that best defined landuse gradients among sites. EOH and WOH results were compared to identify major regional differences in landuse gradients.

Population and road density.—Population density was compiled from the 2000 census data using census blocks, the smallest population units available, within each county in the study area (Census 2000; http://www.census.gov/geo/www/census2k.html). Census data were retrieved as Census 2000 TIGER/Line data from Environmental Systems Research Institute (http://www.esri.com/data/download/census2000_tigerline/index.html). Watershed-, riparian-, and reach-scale boundaries were used to determine the portion of each census block that fell within a given study watershed. The fraction of the census-block area falling within a given watershed, riparian, or reach delineation was multiplied by the total population count for that census block, summed for all census blocks within a delineated area, and then divided by that area to estimate scale-specific population densities. Census blocks were large relative to buffer delineations and, therefore, riparian and reach values were more likely than watershed values to have measurement error associated with cell size (i.e., buffers never contained an entire census block, whereas watersheds often did).

Road densities in EOH watersheds were quantified from digitized 1996 New York Department of Transportation (NY DOT) Planimetric Images provided by NYC DEP. WOH roads were digitized in 1993 from USGS digital line graphs. Road data layers were intersected with watershed-, riparian-, and reach-scale delineations for all 60 study sites, and the lengths of roads in each area were summed and divided by watershed-, riparian-, or reach-scale area to derive road densities.

Watershed-scale population and road densities were included in a PCA of landscape variables after $\log_{10}(x)$ transformations (see *Land use* above). As with landuse data at different scales, regression analysis was used to assess the similarity of population and road densities at riparian and reach scales vs at the watershed scale.

Point-source discharges.—Point-source discharges were quantified only once and were supplied as monthly mean daily discharge over the study period by the NYC DEP for all State Pollutant Discharge Elimination System (SPDE) monitored sites ($n = 131$). Most of these sites were wastewater treatment facilities. A corresponding GIS point coverage of SPDE locations was used to determine the number of point sources in each study watershed. Each monthly mean daily discharge was multiplied by the number of days in the month, summed for all months and for all sites within a study watershed, and divided by watershed area to derive an estimate of annual SPDE outflow across watersheds for each year. Point-source discharges were not quantified at the reach or riparian scales because all SPDE facilities release to a water body or waterway and selection of SPDE facilities within the buffer around the entire stream network would have provided a result identical to the watershed-scale result. Only 2 SPDE sites were within 1 km of our study sites (sites 51 and 55), and no statistical weighting was applied to account for sample site distances to point sources.

Results

Precipitation

Average annual precipitation over the study period was remarkably similar between the 2 regions (EOH: 115 cm, WOH: 114 cm). However, these values

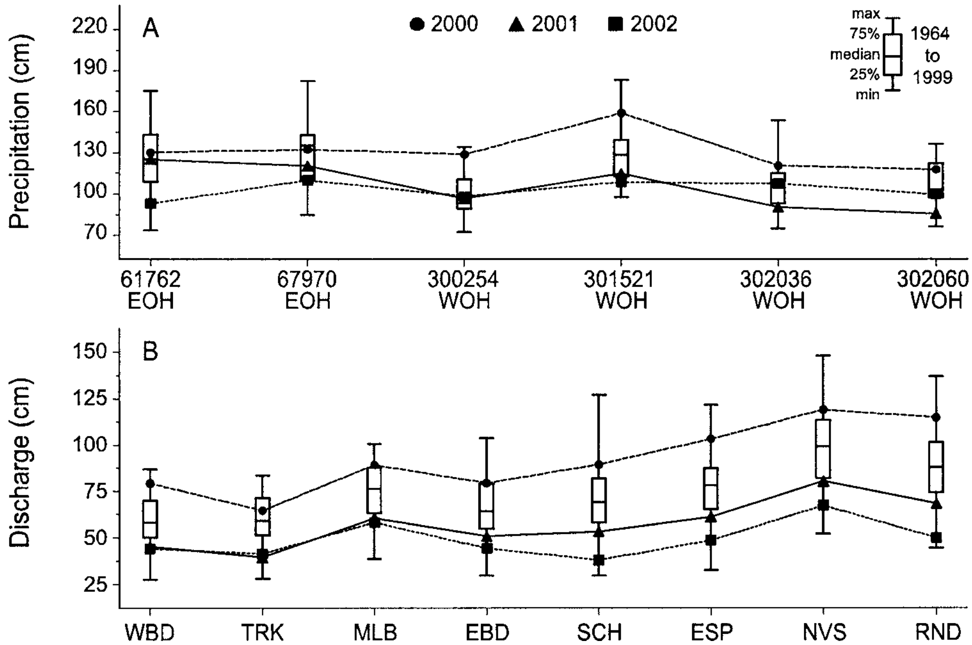

FIG. 3. Box plots of total annual precipitation at long-term precipitation monitoring sites (1964–1999) in the east of Hudson River (EOH) or west of Hudson River (WOH) regions (numbers are National Oceanic and Atmospheric Administration [NOAA] site identifiers) (A), and watershed-area-normalized total annual discharge from 1964 to 1999 for stream gauging sites unaffected by water withdrawals or reservoir operations where historic data existed (only WOH sites: B). In both panels, years 2000 to 2002 are identified individually. NOAA watershed identifiers: WBD = West Branch of the Delaware River, EBD = East Branch Delaware River, TRK = Tremper Kill (in the EBD watershed), MLB = Mill Brook (in the EBD watershed), SCH = Schoharie Creek, ESP = Esopus Creek, NVS = Neversink River, RND = Rondout Creek.

probably did not reflect the spatial distribution of precipitation across the study regions. Given uniform meteorological conditions, precipitation tends to increase with elevation (Dunne and Leopold 1978). Annual precipitation volume at WOH sites was significantly and positively related to elevation ($R^2 = 0.39$, slope $= 0.042$ cm/m) based on regression analysis using average annual precipitation volumes adjusted for a relationship with latitude (no relationship was found with longitude). No significant relationship between annual precipitation volume and elevation was found for EOH sites. The WOH precipitation–elevation relationship and the fact that only 3 of the 14 WOH NOAA sites were at elevations greater than the hypsometric mean elevation of 592 m (EOH hypsometric mean elevation = 162 m), suggested that the WOH average annual precipitation value was an underestimate of the actual mean value for this region.

Six of the 21 NOAA sites had records sufficient for an historical evaluation of climatic conditions. Annual (October–September water year) precipitation totals for each of the 3 y (2000, 2001, and 2002) were assessed relative to the distribution of precipitation totals over the 1964 to 1999 period (Fig. 3A). Year 2000 was the wettest year in the 3-y study period, and it was a wet year relative to the historical record of 1964 to 1999. Depending on the specific station used in the comparison, either 2001 or 2002 were among the driest years across the 1964 to 1999 period.

The wettest months of the year during our study were March through June (Fig. 4A, B), with the notable exception of April 2001, which had the lowest (WOH) or nearly the lowest (EOH) average monthly total. The dry conditions noted for 2001 and 2002 began with low winter precipitation totals during 2001, especially at WOH sites (Fig. 4A). Low winter precipitation in early 2002 contributed to dry conditions in 2002.

Hydrology

Interannual patterns in flow (Fig. 3B) reflected historic precipitation patterns (Fig. 3A). Total annual discharge for 2000 was above the 75th percentile of total annual discharge for the defined historical period for all but 1 of the USGS sites. Total annual discharge for 2001 and 2002 were below the 25th percentile for the historical period across all 8 USGS sites. Patterns of monthly discharge during the 3-y study period averaged across USGS sites for WOH and EOH were seasonal. In general, discharge was high in late winter/spring and low in late summer/autumn (Fig.

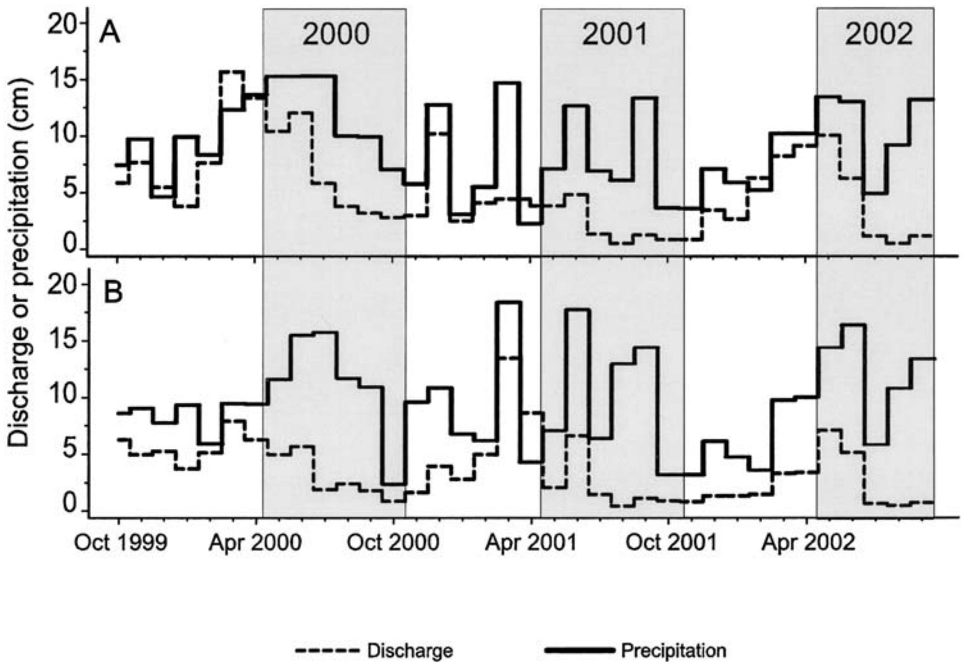

FIG. 4. Mean monthly precipitation and area-specific discharge in the west of Hudson River (WOH; A) and east of Hudson River (EOH; B) regions over the 3-y study period. The spring through summer (May–October) sampling windows are indicated by shaded areas. EOH discharge sites: $n = 8$, precipitation sites: $n = 5$ or 6 depending on month; WOH discharge sites: $n = 42$, precipitation sites: $n = 11$ to 14 depending on month.

4A, B). A rain-on-snow event in April 2001 led to high discharge in WOH streams (Fig. 4A). Average annual discharge over the 3-y study period was significantly lower for EOH streams than for streams in the 5 WOH watersheds (ANOVA, $F = 22.3$, $p < 0.0001$; Fig. 5). Average annual discharge was significantly higher in Neversink and Rondout (NVR) streams than in all other streams except Esopus (ESP).

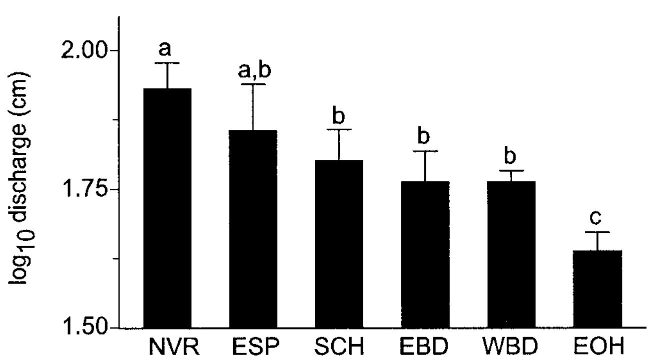

FIG. 5. Mean (+95% CI) annual discharge (2000–2002) for 5 watersheds in the west of Hudson River region and for the entire east of Hudson River (EOH) region. Bars with different letters are significantly different (ANOVA, $p \leq 0.05$). See Fig. 3 for abbreviations. NVR = Neversink River and Rondout Creek: $n = 10$, ESP: $n = 5$, SCH: $n = 12$, EBD: $n = 6$, WBD: $n = 10$, EOH: $n = 8$.

Area-specific discharge was significantly and positively correlated ($r = 0.85$) with % surficial bedrock in the EOH region and the 5 WOH watersheds (summarized from surficial geology maps; Isachsen et al. 2000) and significantly and negatively correlated ($r = -0.82$) with area-weighted % soil organic matter content (obtained from the Soil Survey Geographic database, NRCS 1994). Area-specific discharge was significantly and positively correlated with % forest in the watersheds ($r = 0.90$) and negatively correlated with % urban in the watersheds ($r = -0.85$). These patterns were unexpected in the context of impervious surface influences on discharge (see Discussion).

Land use, population and road density, and point sources

Watershed scale.—Landscape characteristics differed considerably between WOH and EOH regions (Figs 6A–D, 7A–D). Agricultural landuse categories included cropland, orchard, farmstead, and grassland. WOH 2000 real property tax parcel information indicated that ~80% of the actively farmed agricultural tax parcels were livestock operations, primarily dairy farms, and ~15% were row-crop operations. A head count of livestock has been estimated at 35,000 in the EBD and WBD subregions (National Research Council

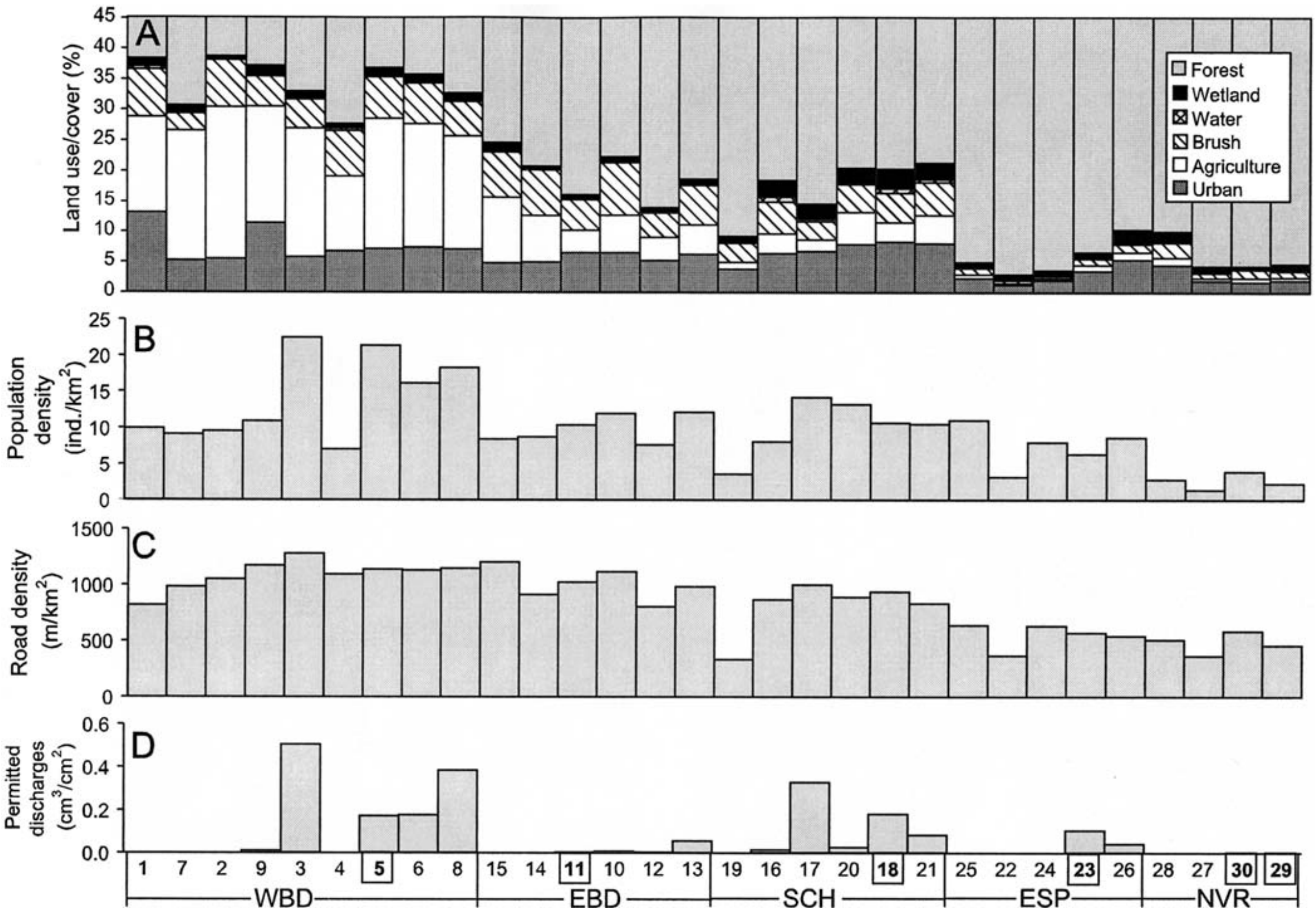

FIG. 6. Land use (A), population density (B), road density (C), and mean annual (2000–2002) State Pollutant Discharge Elimination System (SPDE) discharge (D) for watersheds associated with the 30 west of Hudson River (WOH) stream-monitoring sites. Sites are arranged according to watershed and are sorted from smallest to largest within each watershed (bold font and boxes around site numbers indicate integrative sites; see text for explanation). See Fig. 3 for watershed abbreviations and Table 1 for Stroud Water Research Center site names.

2000). This count approaches the number of humans in these watersheds.

The proximity of EOH watersheds to NYC has caused clear influences from metropolitan infrastructure. EOH watersheds had higher % urban land uses (residential, commercial, and industrial) and % wetland and water than WOH watersheds (Figs 6A, 7A). Percent water was high in EOH watersheds because several sites were downstream of reservoirs/controlled lakes, and lake density was high in the EOH region. Percent forest was >90% in 9 of the 30 WOH watersheds, whereas only 1 EOH site (48 [Crook Brook]) approached that value (87%). In the remaining 21 WOH watersheds, agriculture, urban, and mixed brush/grassland land uses replaced forest. Mean watershed-scale population density (±1 SD) in the EOH (210 ± 178.2 ind./km^2) was significantly greater (ANOVA, F = 37.85, $p < 0.05$) than in WOH watersheds (9.7 ± 5.2 ind./km^2) (Figs 6B, 7B). Average, minimum, and maximum road density was significantly greater (Tukey's Honestly Significant Difference [HSD] test, $p < 0.001$) in EOH watersheds (mean = 3.5 ± 1.37 km/km^2, minimum = 1.5 km/km^2, maximum = 6.1 km/km^2) than for sites in WOH watersheds (mean = 0.8 ± 0.28 km/km^2, min = 0.3 km/km^2, max = 1.3 km/km^2) (Figs 6C, 7C). Fourteen of 30 WOH and 13 of 30 EOH sites had known point-source discharges in their watersheds (Figs 6D, 7D). Point sources at 3 of the EOH sites were high (Fig. 7D) and helped define locations of expected biological and chemical impacts from point-source contributions (Dow et al. 2006, Aufdenkampe et al. 2006, Kaplan et al. 2006, Kratzer et al. 2006).

Watershed-scale variations in land use within each region were explored using PCA. The first 2 factors (F1, F2) accounted for 68% of the among-site variance

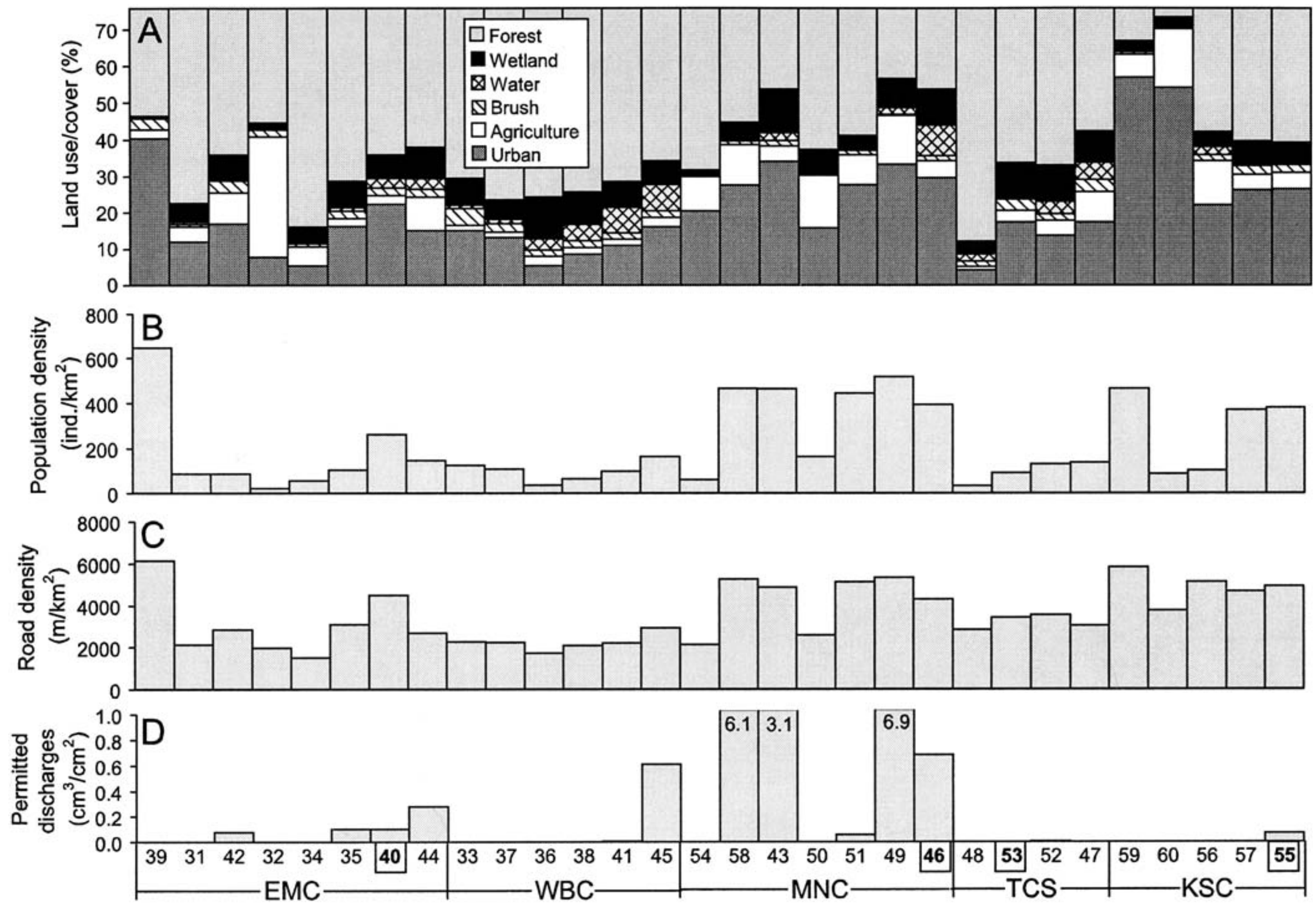

Fig. 7. Land use (A), population density (B), road density (C), and mean annual (2000–2002) State Pollutant Discharge Elimination System (SPDE) discharge (D) for watersheds associated with the 30 east of Hudson River (EOH) stream-monitoring sites. Sites are arranged according to watershed and are sorted from smallest to largest within each watershed (bold font and boxes around site numbers indicate integrative sites; see text for explanation). Watershed identifiers: EMC = East and Middle Branch Croton River, WBC = West Branch Croton River, MNC = Muscoot River and other sites north of Croton Reservoir, TCS = Titicus, Cross, and Stone Hill rivers, KSC = Kensico Reservoir and other sites south of Croton Reservoir. See Table 1 for Stroud Water Research Center site names.

in WOH watershed characteristics, with most of the variance represented on the 1st axis (F1 = 51%; Fig. 8A). Road density (9% absolute contribution) and % grassland (9%) contributed most to the definition of F1, followed closely by % other urban (8%), % cropland (8%), population density (8%), % farmstead (7%), and % deciduous forest (7%). F2 was defined primarily by % coniferous forest (23%), % mixed forest (21%), % wetland (14%), and % commercial (11%). This multivariate, 2-dimensional space distinguished sites (Fig. 8B) with highest % forest (Esopus [ESP] and Neversink [NVR] sites) from sites with more % commercial and % wetland (several Schoharie [SCH] sites) and from sites with predominantly agricultural and some urban uses (East [EBD] and West Branch Delaware [WBD]).

F1 and F2 accounted for 46% of the among-site variance in EOH watershed characteristics, with the % variance represented roughly equal between F1 and F2 (Fig. 9A). Percent transportation (12%), % shrubland (11%), and % grassland (11%) contributed most to the definition of F1 (Fig. 9A), but % cropland (10%), % wetland (7%), % water (7%), and % deciduous forest (7%) also were important along this dimension. F2 was defined mostly by population density (19%), % residential (17%), road density (16%), and % commercial (12%). Sites within the same watershed did not always cluster close together in this 2-dimensional space (Fig. 9B). Sites 59 and 60 had the greatest % transportation but differed in % agricultural (cropland and grassland) and % residential land uses and in population and road densities. The Westchester Coun-

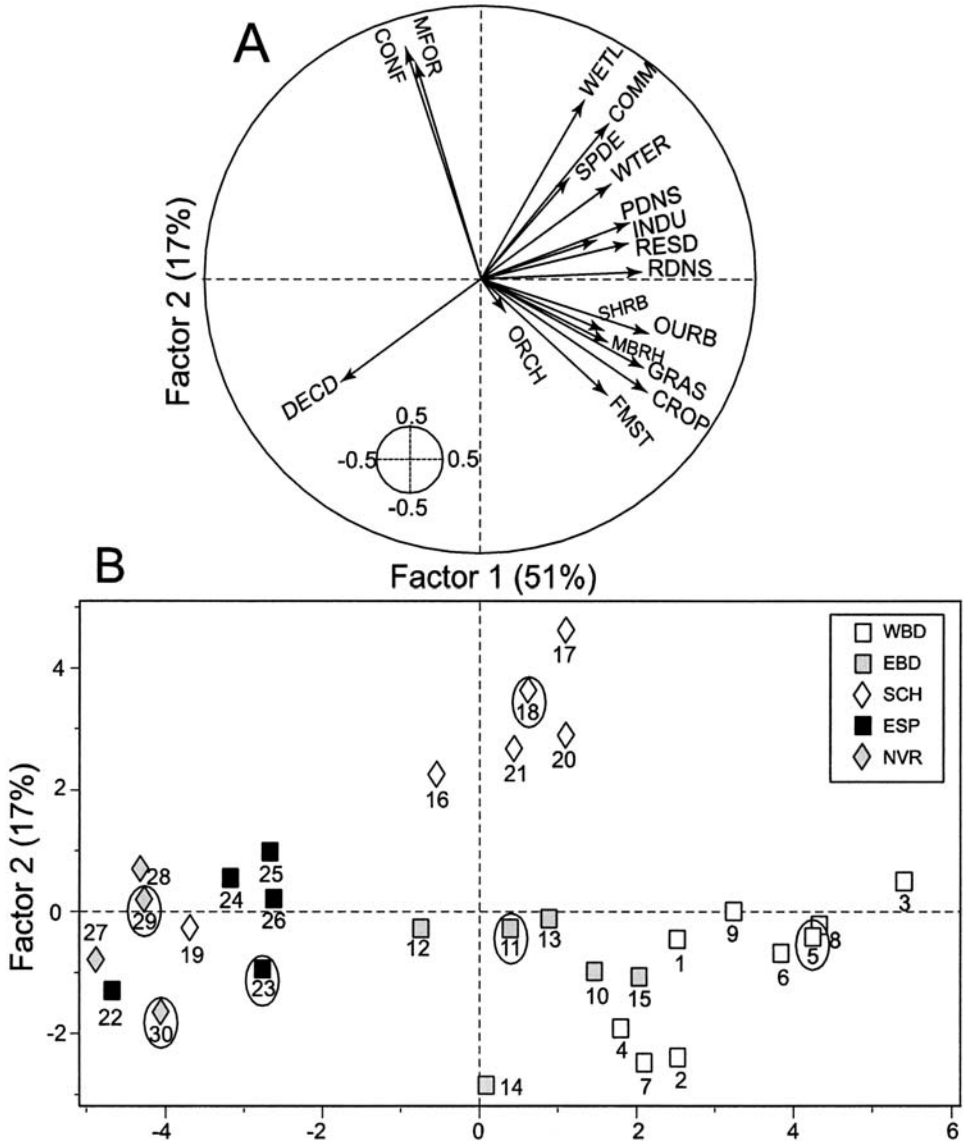

FIG. 8. Principal Components Analysis of land use, population and road density, and State Pollutant Discharge Elimination System (SPDE) permitted discharges (from Fig. 6) occurring in watersheds associated with the 30 west of Hudson River (WOH) stream-monitoring sites. A.—Factor loadings (F1 and F2) for each landscape variable (see Table 2 for landscape variable abbreviations; WTER = % water). B.—Plot of F1 and F2 scores for each site. See Fig. 3 for watershed abbreviations. Circled sites are integrative sites (see text for explanation).

ty Airport is in the southeastern corner of the watershed of site 60. Sites 43, 46, 55, and 57 had the highest % commercial and % residential land uses and some of the highest watershed population densities in the EOH (Fig. 9B).

These results illustrated clear differences in gradients of land use and other watershed variables between WOH and EOH. EOH sites were less forested, more urbanized, and had greater flow contributions from point-source discharges than WOH sites. EOH sites also had greater wetland and lake/reservoir area upstream from study sites than WOH sites. WOH sites were either more forested or had more agricultural land use in their watersheds and always had lower population and road densities than EOH sites.

Comparison of scales.—Landuse values quantified at the watershed scale were strongly related to landuse values quantified at riparian scales across all tested variables in both regions (Table 2). Watershed-scale vs riparian-scale regression slopes were significantly different from 1 for 12 of the 16 variables tested in the WOH region (9 slopes $>$ 1, 3 slopes $<$ 1) and 12 of

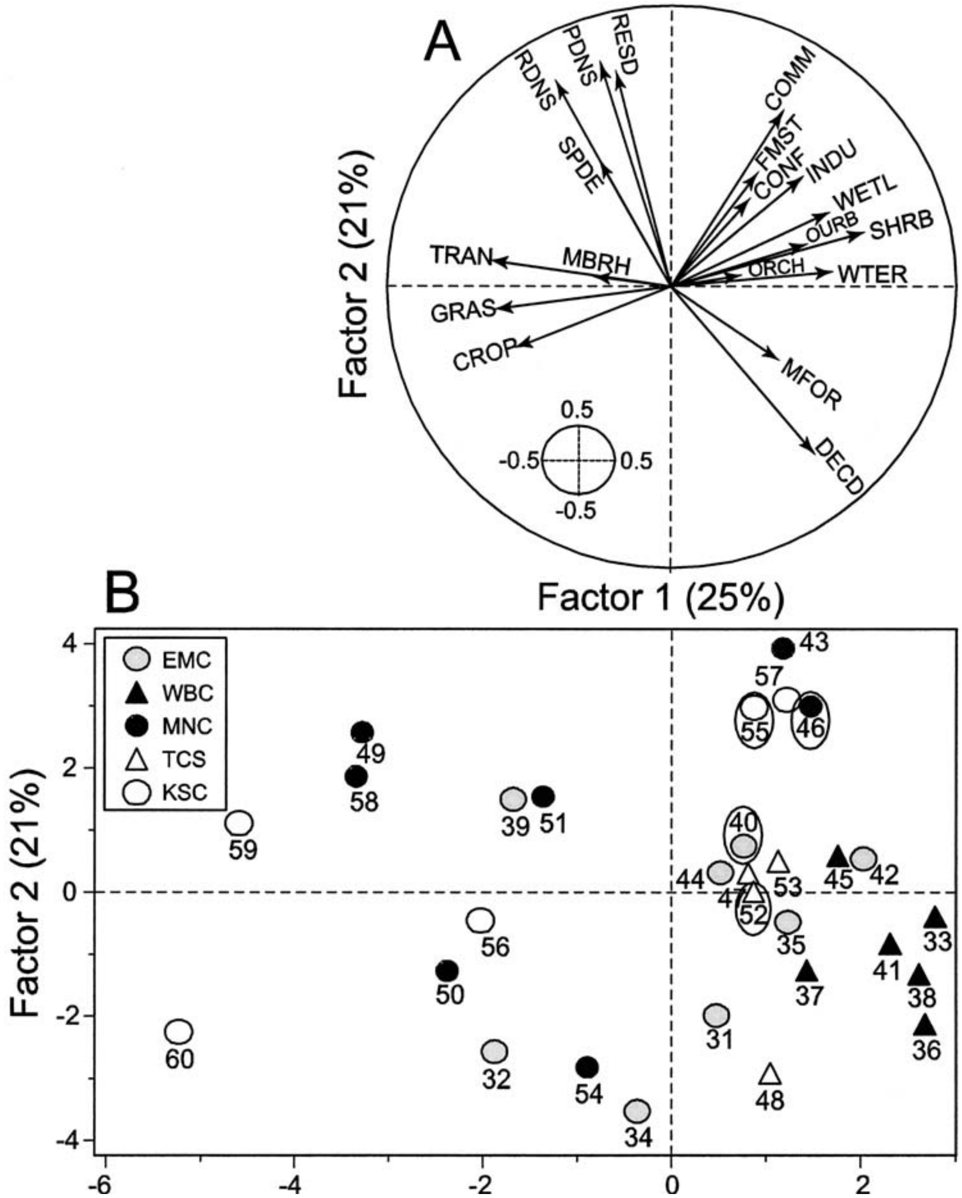

FIG. 9. Principal Components Analysis of land use, population and road density, and State Pollutant Discharge Elimination System (SPDE) permitted discharges (from Fig. 7) occurring in watersheds associated with the 30 east of Hudson River (EOH) stream-monitoring sites. A.—Factor loadings (F1 and F2) for each landscape variable (see Table 2 for landscape variable abbreviations; WTER = % water). B.—Plot of F1 and F2 scores for each site. See Fig. 7 for watershed abbreviations. Circled sites are integrative sites (see text for explanation).

the 17 variables tested in the EOH region (11 slopes < 1, 1 slope > 1). Regression intercepts were significantly different from 0 in 8 of the 16 WOH models (6 intercepts > 0, 2 intercepts < 0). Regression intercepts were significantly different from 0 in 4 of the 17 EOH models (4 intercepts > 0). These results indicated that many human-associated variables were more concentrated along the riparian corridor than in the watershed as a whole in the WOH region (i.e., most slopes > 1 and most intercepts > 0), whereas the inverse was true in the EOH region (i.e., most slopes < 1 and most intercepts at or near 0). Notable exceptions to this generalization included other urban, orchard, and grassland land uses in the WOH region. Of the natural landuse categories, wetlands were concentrated in the riparian corridors in both regions. Deciduous forest always was less concentrated in WOH riparian corridors than in the watershed despite the fact that

TABLE 2. Regression results for relationship between the riparian- or reach-scale landscape variables (dependent variables) and watershed-scale landscape variables (independent variables). Results are separated by region (east of Hudson River [EOH] and west of Hudson River [WOH]). Landscape variable abbreviations: PDNS = population density, RDNS = road density, RESD = % residential, COMM = % commercial, INDU = % industry, TRAN = % transportation, OURB = % other urban, CROP = % cropland, ORCH = % orchard, FMST = % farmstead, GRAS = % grassland, SHRB = % shrubland, MBRH = % mixed brush-grassland, DECD = % deciduous forest, CONF = % coniferous forest, MFOR = % mixed forest, WETL = % wetland. * indicates significant ($p \leq 0.05$) regression intercepts (β_0) or slopes (β_1), – in β_0 column indicates a nonsignificant y-intercept, – in R^2 column indicates a nonsignificant regression, NA = regressions that could not be done because of missing values.

	WOH						EOH					
	Watershed vs riparian			Watershed vs reach			Watershed vs riparian			Watershed vs reach		
Landscape variable	R^2	β_0	β_1	R^2	β_0	β_1	R^2	β_0	β_1	R^2	β_0	β_1
PDNS	0.80*	–	1.46*	–	–	–	0.91*	–	0.86*	0.19*	–	0.98
RDNS	0.32*	848*	1.1	0.15*	6739*	−4.24*	0.69*	–	0.79*	–	2603*	–
RESD	0.81*	0.49*	1.46*	–	–	–	0.50*	–	0.81	0.27*	–	0.45*
COMM	0.90*	–	1.62*	–	–	–	0.74*	–	0.63*	0.42*	–	5.47*
INDU	0.56*	–	3.87*	NA	NA	NA	0.74*	–	0.33*	–	–	–
TRAN	NA	NA	NA	NA	NA	NA	0.86*	–	0.86	0.77*	–	0.97
OURB	0.78*	0.73*	0.91	–	3.1*	–	0.13*	1.7*	0.19*	–	–	–
CROP	0.97*	–	1.24*	0.47*	–	2.13*	0.91*	–	0.64*	0.17*	–	0.24*
ORCH	1.00*	–	0.94*	NA	NA	NA	0.92*	–	0.44*	–	–	–
FMST	0.95*	–	1.90*	–	–	–	0.74*	–	0.34*	0.56*	–	0.39*
GRAS	0.85*	–	0.84*	0.30*	–	0.81	0.68*	–	0.71*	–	2.6*	–
SHRB	0.92*	−0.54*	1.17*	0.19*	–	0.61	0.77*	–	0.66*	0.15*	–	0.92
MBRH	0.95*	–	1.14*	–	–	–	0.36*	–	0.86	–	–	–
DECD	0.78*	−29*	1.21	–	–	–	0.60*	–	0.77	0.15*	–	0.72
CONF	0.74*	9.3*	0.80*	–	30*	–	0.70*	4.1*	0.81	0.21*	–	1.86
MFOR	0.73*	1.3*	0.97	–	7.9*	–	0.45*	0.81*	0.57*	0.17*	–	0.59
WETL	0.61*	1.5*	3.79*	–	–	–	0.80*	3.8*	2.40*	0.20*	–	2.05

the regression had a slope >1 (i.e., y-intercept was very low at 29%). Deciduous forest was similar at both scales in the EOH, whereas coniferous forest was slightly more concentrated in the riparian corridor.

Landuse values at watershed and reach scales were related for only 4 of 16 variables in the WOH region and 11 of 17 variables in the EOH region (Table 2). R^2 was <0.50 for all regressions for WOH models, indicating little similarity between watershed and reach scales. R^2 was >0.55 only for transportation and farmstead land uses in the EOH region. Road density was much greater at the reach scale than at the watershed or riparian scales in the EOH region, but reach-scale road density was not significantly related to watershed- or to riparian-scale road densities. Overall, these results suggest that variables summarized at the reach-scale described different conditions than variables summarized at the watershed or riparian scales.

These scale comparisons revealed that: 1) summaries of landuse variables at the watershed and riparian scales were significantly correlated within both regions, 2) summaries of landuse variables at the reach scale were not correlated with summaries at the other 2 scales, and 3) human land uses (particularly roads) were more concentrated in riparian areas than in WOH watersheds as a whole and less concentrated in riparian areas than in EOH watersheds as a whole.

Discussion

Precipitation and hydrology

Precipitation across the Hudson and Delaware River watersheds is typically lowest in January and February, highest in July and August, and fairly evenly distributed over the remaining months of the year (quantified from 1961–1990 at a station near Troy, New York; Jackson et al. 2005). During the 3-y study period, seasonal wet/dry periods were somewhat different from historical trends, with the wettest period occurring from March to June and the driest period from January to February. The range in total annual precipitation during the study period demonstrated the importance of a multiyear monitoring program to capture interannual variability in environmental conditions.

Area-specific discharge of WOH streams was greater than area-specific discharge of EOH streams, but average annual precipitation in the EOH region was similar to average annual precipitation in the WOH region. The underestimation of WOH precipitation may partly explain the disparity in area-specific discharge, but the underestimation alone does not account for differences in area-specific discharges between these regions. Lull and Sopper (1966) found that precipitation, % forest, elevation, latitude, mean summer temperature (July), and % wetland were the variables that most influenced annual and seasonal discharges in northeastern US watersheds. They observed that % forest was positively correlated with runoff because of greater precipitation, lower temperature, steeper slopes, and shallower soils in northeastern US forested areas than in minimally forested areas. Our observations of broad-scale hydrologic differences also showed that % forest was positively correlated with area-specific discharge because the Neversink/Rondout watersheds were the most forested and EOH watersheds were the least forested. Conversely, % urban was negatively correlated with area-specific discharge, a result that contradicts the well-established effects of impervious surface cover on watershed hydrology (Booth and Jackson 1997). One plausible explanation for our results (in addition to the underestimates of precipitation at higher elevations, particularly in the Neversink and Esopus watersheds) is regional differences in hydrologic retention capacity among watersheds. In particular, EOH watersheds had more wetlands, deeper soils, less bedrock, and more lakes and reservoirs than WOH watersheds.

Land use

Many studies have noted that GIS-generated landuse data are very useful for predicting or explaining water-chemistry variables and biological characteristics at sites on streams and rivers (e.g., Johnson and Gage 1997, Gergel et al. 1999, 2002, Mehaffey et al. 2001, Sponseller et al. 2001, Meador and Goldstein 2003). In many cases, watershed-scale GIS variables had more explanatory power than reach-scale GIS variables (but see Sponseller et al. 2001). For example, Gergel et al. (1999) found that watershed-scale % wetland cover always explained a greater proportion of variance of dissolved organic C concentrations than near-shore/riparian-zone-scale % wetland cover in Wisconsin lakes and rivers. However, different response variables (e.g., chemical variables vs invertebrate communities) probably have different relationships with landuse variables, and predictive or explanatory power of specific landuse variables may depend on the scale at which they are quantified and on local stream conditions (Allan 2004).

Habitat variables (e.g., canopy fragmentation, bank stability, erosion, substrate character) measured in the field to assess riparian and other physical and geomorphic conditions also can account for a substantial amount of the variability in biological response variables. For example, Lammert and Allan (1999) found that fish and macroinvertebrate variability were predicted better by GIS-derived riparian-scale land use than watershed-scale land use, but local habitat variables measured at the sites were better predictors than GIS-generated variables. England and Rosemond (2004) reported that canopy cover measured in the field using a densitometer explained changes in allochthonously and autochthonously derived energy flow through a simple food web better than GIS-generated measures of reach-scale % forest 100 and 1000 m upstream from sites. These results suggest that habitat variables measured in the field describe statistically different aspects of the local environment than GIS-generated variables captured at fine scales. Which approach (field measurement of local conditions vs GIS-generated variables) will best explain which response variable is unclear and will probably depend on the response variable measured and the geographic domain of interest (Gergel et al. 2002, Allan 2004, Dow et al. 2006).

Differences between studies in results obtained when using GIS-derived variables to explain stream-response variables probably are linked to issues of spatial resolution of the data, the age of the digital data, the scale and extent used when summarizing GIS variables, and the intricacies of field-sampling protocols used in measuring stream-response variables. Stewart et al. (2001) suggested that differences may arise, in part, from whether riparian land use is summarized separately or as part of watershed land use. Our watershed-scale land-cover data included information on the riparian buffers, but a post hoc assessment of the effect of removing the riparian information from our data set indicated that the removal did not significantly change watershed-scale landuse values. Regression analyses comparing landuse values obtained with and without the riparian information had R^2 values > 0.96 and slopes ≈ 1, probably because the areas of the watersheds typically were large relative to the areas of the riparian buffers.

Implications of these results for the Project

Human land uses differed greatly between EOH and WOH regions and defined different anthropogenic gradients. Population and road densities, residential and commercial land uses, and point-source discharges were higher and forest and agriculture land uses were lower in the EOH region than in the WOH region. In the EOH region, land uses ranged from forested to urban among watersheds. In the WOH, where several watersheds were primarily forested, conditions ranged from forested to agricultural, and several watersheds were influenced less by agriculture and more by urbanization (roads, commercial use, and point sources) and wetlands. However, these influences were of considerably lower magnitudes in WOH watersheds than in EOH watersheds.

Allan (2004) stated that environmental variables in streams could be expected to vary in their responsiveness to large- vs local-scale environmental factors. In several articles in this special series (Aufdenkampe et al. 2006, Dow et al. 2006, Kratzer et al. 2006), the predictive or explanatory power of watershed-, riparian-, and reach-scale landuse variables will be compared and contrasted. An understanding of how landuse variables differ among scales is central to interpreting the results of other elements of the Project. The primary results obtained in our study were that: 1) landuse values quantified at the watershed scale were strongly related to landuse values quantified at riparian scales across all tested variables in both regions, 2) landuse values quantified at the reach scale were not related to landuse values quantified at the watershed or riparian scales for many variables in both regions, and 3) human land uses (particularly road densities) were more concentrated in riparian areas than in watersheds overall in WOH watersheds and less concentrated in riparian areas than in watersheds overall in EOH watersheds. Mehaffey et al. (2001) also quantified land use in WOH watersheds at multiple spatial scales and found that human land use was more concentrated along riparian corridors than in whole watersheds, a result that is typical for mountainous terrains where the only land suitable for human infrastructure is in valley bottoms.

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Appendix. Determination of site- and date-specific discharge and baseflow conditions on sampling dates.

Analysis

Discharge, as mean daily flow, was estimated or extracted from existing US Geological Survey (USGS) records for each study site ($n = 60$) on the dates of baseflow-specific sample collections. For sites without co-located USGS gauging stations ($n = 36$; Table 1), discharge was estimated from discharge–watershed-area regression equations developed independently for the east of Hudson River (EOH) region and each of the 5 west of Hudson River (WOH) watersheds (Table 1) on each sampling date using data from the 50 USGS stations. Regression intercepts were not significantly different from 0 in only 3 of the 150 initial equations. Therefore, a 2nd regression iteration was run for each date and study site with the intercept term set equal to 0. Outliers were determined visually from bivariate and residual plots of discharge vs watershed area and were removed prior to a 3rd regression iteration.

Standard criteria were developed to ensure that a consistent definition of baseflow condition was met at the time of all summer baseflow sampling for water chemistry (Dow et al. 2006). Hydrologic conditions at anticipated sampling sites were checked online via the USGS real-time hydrological network (http://waterdata.usgs.gov/nwis/rt). A visual assessment was made of relevant hydrographs compared to the baseflow criterion that streamflow changed <10% over the 24 h preceding sampling (using provisional, 15-min discharge data available online). Hydrograph data were difficult to monitor during longer field excursions. Therefore, if a stream appeared unusually turbid or if the wetted perimeter displayed signs of high flow when samples were collected, the site was (re)sampled at a later date. The difference between mean daily discharge on the sampling date and the date prior to sampling was used as a postsampling assessment of whether the baseflow criterion had been met for each sampling date. Both actual mean daily discharge values from co-located USGS sites and estimated discharge values for sites not co-located with USGS sites were used in this assessment. Over 50% of all samples were within the 10% change-in-discharge criterion and >75% of samples had changes in discharge of <20% from one day to the next.

For those dates exceeding the 10% criterion, provisional 15-min instantaneous discharge hydrographs were examined. This evaluation permitted a more precise determination of baseflow than could be made from daily mean discharges, especially given the potential for short-duration summer storms common in this region. For inorganic chemistry (Dow et al. 2006), dissolved organic C and organic particles (Bott et al. 2006a, Kaplan et al. 2006), 5 samples (out of 180 total project samples) from 1 date (in 2000) were collected during the rising limb of a minor storm. For molecular tracers (Aufdenkampe et al. 2006), 14 samples (out of 180) collected from 3 different dates (1 date in 2000 and 2 in 2002) were collected during changing stage conditions. These events were minor at these 4th- to 6th-order stream sites (44–172 km^2 watersheds) because flow increased only 13 to 101% of pre-event discharge and time-to-peak discharge was between 6 and 25 h. In addition, field technicians did not notice any increased turbidity at the time of sampling.

Results

Site-specific mean daily discharge during sampling periods did not necessarily match observed monthly and annual hydrologic patterns. Water chemistry (Aufdenkampe et al. 2006, Dow et al. 2006, Kaplan et al. 2006) and benthic macroinvertebrate (Arscott et al. 2006, Kratzer et al. 2006) samples were collected during baseflow, but not all sites were visited on the same day. Site-specific, between-year differences in baseflow discharge were not consistent throughout the WOH. WOH baseflow discharges during water-chemistry sampling (summer baseflow) were greater in 2002 than in 2000 or 2001 at all sites in the West and East Branch Delaware and the Esopus watersheds and at 2 of 4 sites in the Neversink/Rondout watershed (Fig. A, panel A). Interannual differences in baseflow discharge were not consistent among sites during macroinvertebrate sampling in the WOH (Fig. A, panel C). Baseflow discharges during water-chemistry sampling at most sites were greater in 2001 than in 2000 (except for 2 East Branch Delaware sites). EOH baseflow discharges during water-chemistry and macroinvertebrate sampling (spring baseflow) were greatest during the 2000 field season at most sites (Fig. A, panels B and D), but peak discharge within the 30 d prior to macroinvertebrate sampling was greatest in 2001 for all WOH and EOH sites (Fig. A, panels E and F).

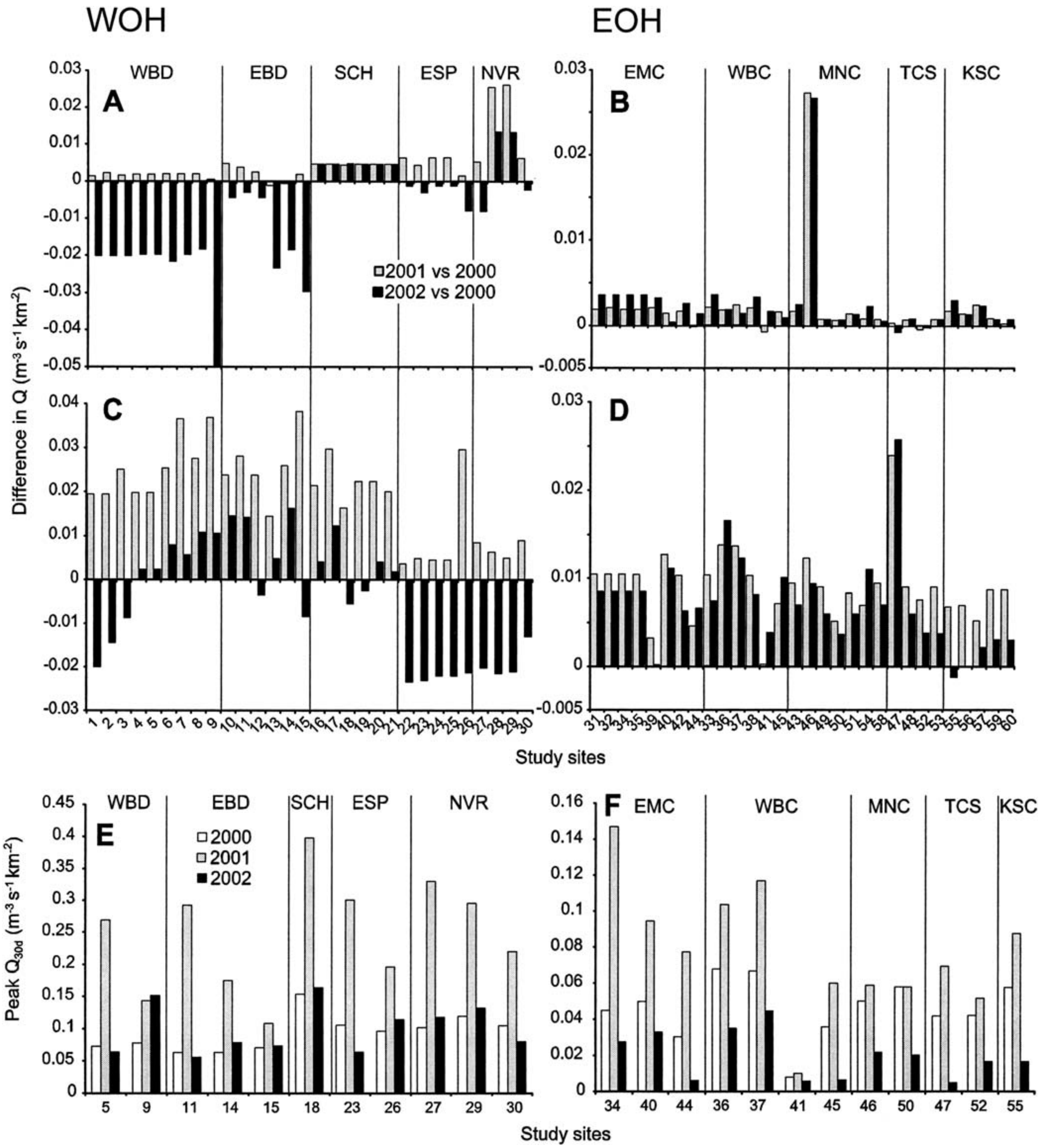

FIG. A. Interannual differences in mean daily baseflow discharge (Q) compared to Q during water-chemistry (A and B) or benthic macroinvertebrate (C and D) sampling in 2000 at sites in the west of Hudson River (WOH) and east of Hudson River (EOH) regions, and peak stormflow during 30 d prior to macroinvertebrate sampling in the WOH (E) and EOH (F) regions. Only data for sites co-located with US Geological Survey (USGS) gauging stages are presented in panels E and F. Mean daily Q at sites not co-located with a USGS gauging station was predicted based on that basin's Q-watershed-area relationship (SWRC 2003). See Table 1 for site names and watershed abbreviations.