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QUANTIFYING URBAN INTENSITY IN DRAINAGE BASINS FOR ASSESSING STREAM ECOLOGICAL CONDITIONS[1]

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ABSTRACT: Three investigations are underway, as part of the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program, to study the relation between varying levels of urban intensity in drainage basins and in-stream water quality, measured by physical, chemical, and biological factors. These studies are being conducted in the vicinities of Boston (Massachusetts), Salt Lake City (Utah), and Birmingham (Alabama), areas where rapid urbanization is occurring. For each study, water quality will be sampled in approximately 30 drainage basins that represent a gradient of urban intensity. This paper focuses on the methods used to characterize and select the basins used in the studies. It presents a methodology for limiting the variability of natural landscape characteristics in the potential study drainage basins and for ranking the magnitude of human influence, or urbanization, based on land cover, infrastructure, and socioeconomic data in potential study basins. Basin characterization efforts associated with the Boston study are described for illustrative purposes.
(KEY TERMS: urban intensity; gradient; environmental framework; water quality; ecology)

INTRODUCTION

The deleterious effects of urbanization on water-quality are evident across the United States. In locations as geographically diverse as Washington state (Nelson, 1999), Portland, Oregon (Abrams and Prescott, 1999), the Edwards Aquifer region of Texas (Kennedy, 1999), and south Florida (Williams, 1999), urbanization is reported to adversely affect the physical (e.g., sedimentation), chemical (e.g., eutrophication), and biological (e.g. endangered salmonid species) characteristics of water quality. Concern about the effects of urbanization has motivated efforts to understand and manage urban development on the part of governmental organizations at the national (the Smart Growth Program of the U.S. Environmental Protection Agency (2000)), regional (Smart Growth Networks, 2000), and local (Pelley, 1999; American Planning Association, 2000) levels, as well as by research efforts such as the Baltimore Ecosystem Study, funded by the National Science Foundation (Foresman *et al.*, 1999) and the Urban Dynamics Research Program (U.S. Geological Survey, 2000a).

As part of the National Water Quality Assessment (NAWQA) Program (U.S. Geological Survey, 2000b) an investigation is underway to determine the relation between varying intensities of drainage basin urbanization and water quality in three contrasting environmental settings: (1) the humid Northeast (Boston, Massachusetts, metropolitan area), (2) the humid Southeast (Birmingham, Alabama, metropolitan area), and (3) the arid West (Salt Lake City, Utah, metropolitan area. For budgetary reasons, each study has approximately 30 study drainage basins, with the basins in each study area having similar natural (e.g., climate, elevation, soils) characteristics and a gradient of urban development intensity.

This paper describes activities that occur during the planning phase of these studies. The major objectives of the planning phase are to: identify a population of potential study basins and divide this population of potential basins into groupings with similar natural characteristics; rank the population of potential study basins based on their urban intensity; and choose a set of study basins with similar natural characteristics that represent a gradient of urban intensity. An environmental framework, developed by analysis of features such as ecoregions and geologic and soil drainage characteristics, is used to identify

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the population of potential study basins and group these basins in clusters that are relatively homogeneous in terms of natural landscape features that might affect water quality. The urban intensity of each basin is measured using an index that integrates information about the multiple dimensions of human influence on the urban landscape at the drainage basin scale. The index, which includes information about land cover, infrastructure, population, and socioeconomic characteristics, provides an a priori ranking of potential study sites that is used to ensure that sites chosen for the investigation represent a cross-section of urban intensity. Some of the variables used in the index may also be important factors for explaining variations in water quality; this cannot be determined, however, until water quality data are collected and analyzed.

These methods were applied at three locations across the country. In order to maximize the possibility for comparing and contrasting the eventual study findings, characterization of the drainage basins used in each of the three investigations were accomplished using land cover, infrastructure, population, and socioeconomic data sets developed using similar protocols (Table 1). Typically these were national data sets available in all NAWQA study areas. Superior data (e.g., more recent or better resolution) may have been available for some variables in each of the study locations but were not used at the planning stage. Basin characterization and site-selection efforts associated with the Boston study are described here for illustrative purposes.

AN EVOLVING PERSPECTIVE ON WATER-QUALITY

The gradient design used in the NAWQA Program to investigate the effects of urbanization is premised on two perspectives about water-quality. First, in-stream water-quality is an ecological construct. Water-quality is a composite of physical, chemical, and biological characteristics that vary in space and

TABLE 1. Potential Sources of Digital Mapped Information for Use in Characterizing Natural and Urban Landscape Patterns in Drainage Basins.

Landscape Theme	Available Maps	Scale
	Natural Landscape Characteristics	
Ecological Regions	U.S. Environmental Protection Agency (USEPA) Level III Ecoregions	7,000,000
	USEPA Level IV Ecoregions	250,000
	U.S. Forest Service Subsections (level IV resolution)	250,000
Soil Drainage Characteristics	U.S. Department of Agriculture State Soil Data Base (STATSGO) Soil Hydrologic Groups	250,000
Watershed Boundaries	Developed From Digital Elevation Models (U.S. Geological Survey, 2000c)	varies
Lithochemical Zones	Bedrock Litho-Chemical Zones (Robinson, 1997)	Approx. 250,000
	Anthropogenic Landscape Characteristics	
Land Cover Data	Multi-Resolution Land Characteristics (MRLC) (Loveland and Shaw, 1996)	100,000
Derived From Land Cover	Impervious Surface	
	Urban Sprawl	
	Riparian Land Cover	
Infrastructure	Roads	100,000
	Point Source Dischargers	Point
	USEPA Toxic Release Inventory	Point
	Dams	Point
Census Block Group Derived (examples)	Population	100,000
	Housing Unit Density	100,000
	Per Capita Income	100,000
	Socioeconomic Indices	100,000

time and are influenced by natural factors and by the human activities and values (Karr, 1991; Fairweather, 1999; Figure 1). Traditional measures of water-quality have relied on physical and chemical characteristics as surrogate indicators for potential achievement of biological integrity – a goal of the Clean Water Act (Yoder, 1995). Because biological communities are subject to an array of physical, chemical, and biological influences, the condition of these communities reflect the integration of these influences as they occur over time and space (Yoder, 1995). Advancements in the understanding and measurement of in-stream biological communities over the past 15 years makes it possible and practical to consider water-quality, and the factors that influence it, from an ecological perspective (Davis, 1995).

Second, landscape and stream characteristics within a watershed reflect not only the physical and geographic context of a watershed but the choices associated with human values and priorities. These choices are reflected in the mix of land uses in a watershed and in the diverse activities associated with even the same land uses. The character of the urban residential landscape, for example, can vary dramatically as socioeconomic factors – income, age of housing stock, levels of education – change among neighborhoods. Variations in both natural and built characteristics in a watershed affect stream flow

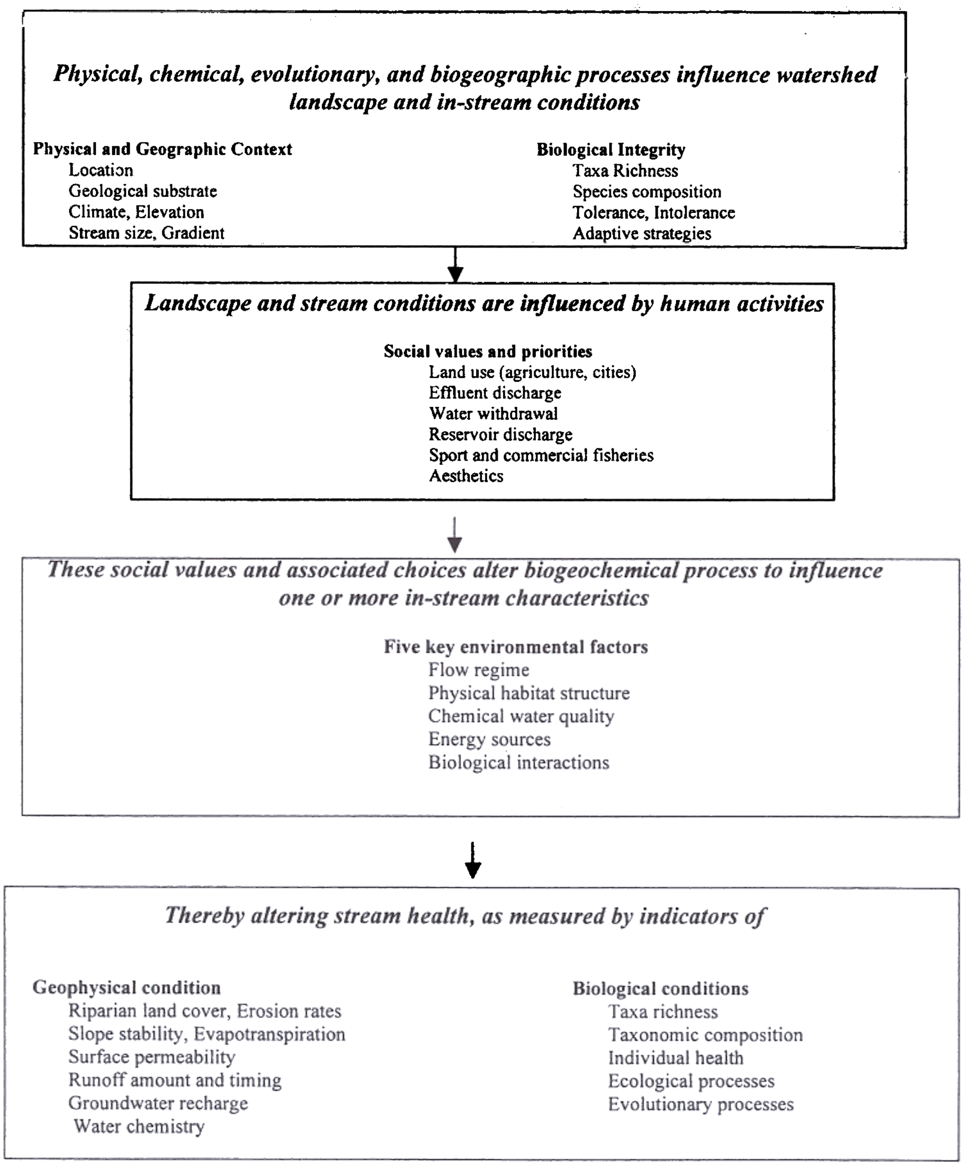

Figure 1. Conceptual Framework of an Ecological Construct for Instream Water Quality (after Karr and Chu, 1997).

variability (Hammer, 1972; Bevin, 1986; Poff *et al.*, 1997; U.S. Environmental Protection Agency, 1997b), eutrophication (Mueller and Helsel, 1996; U.S. Geological Survey, 1999), the distribution of fish (Steedman, 1988; Whittier *et al.*, 1988; Poff and Ward, 1989; Taylor *et al.*, 1993; Poff and Allan, 1995; Angermeier and Winston, 1998), invertebrates (Corkum and Ciborowski, 1988; Corkum, 1989, 1990, 1992; Quinn and Hickey, 1990; Tate and Heiny, 1995), as well as combined measures of biological, chemical, and physical water-quality measures (Cuffney *et al.*, 2000). There also is a spatio-temporal scale to these relationships – that is, water-quality responses are influenced by both regional and local factors, and they vary across space and time (Angermeier and Winston, 1998).

This conceptual framework has shaped the tasks associated with the study planning effort in two important ways. First, a drainage basin-oriented investigation of the effects of urbanization on water quality must control for the effects of natural factors, while allowing the degree of urbanization to vary in known ways between study basins. Large variations in the natural characteristics of study drainage basins such as drainage basin size, climate, elevation, soils, and geology will obscure the nature of any relation between urbanization and water quality. An *a priori* knowledge of the degree of urbanization in each candidate study basin allows the choice of a set of basins that together reflect a gradient of urbanization representative of conditions across a population of potential sites. Second, the degree of urbanization cannot adequately be described using only land cover data, such as the amount of developed land within a drainage basin. In this study, spatial patterns in infrastructure and socioeconomic characteristics are also used to determine the degree of urbanization. Although not discussed in this paper, the response data collected at streams in each study will include nutrients, pesticides, and ions in stream water, trace elements in bed sediments, geomorphic and habitat characteristics, hydrologic stage, water temperature, alkalinity, pH, dissolved oxygen, specific conductance, chlorophyll a, benthic algae and invertebrate communities, and fish communities

CHARACTERIZING THE NATURAL LANDSCAPE

The urban gradient study design relies on a hierarchical environmental framework to identify a population of potential study basins and limit the variability of natural landscape factors that might confound an understanding of the water-quality response. For each of the three studies, a top-level framework is used to identify a broad region, with biotic and abiotic characteristics distinct from adjoining regions, within which the water-quality effects of urbanization will be studied. All watersheds of a particular size range are then identified within this broad region. A geographic information system is used to overlay the drainage basin boundaries and thematic maps of natural (e.g., soils) and anthropogenic (e.g., low density residential land use) factors and develop a table of basin characteristics. The factors describing natural basin characteristics data are used to group the potential study basins into clusters that are relatively homogeneous in terms of these characteristics. These groupings, in conjunction with information about watershed urbanization, allow a final choice of study watersheds that have limited variation in natural characteristics and a desired variation in the degree of urbanization.

The top-level of the framework is defined by a single U.S. Environmental Protection Agency (USEPA) level III ecoregion (Omernik, 1995); for the Boston-area study this was Level III Region 59, the Northeastern Coastal Zone. This national-scale framework, which delimits areas that are relatively homogeneous in terms of both biotic and abiotic characteristics, has been widely used to investigate water-quality patterns (Hughes *et al.*, 1994). Level III ecoregions are compiled by using relatively small-scale spatial information (e.g., 1:2,000,000 and smaller) about the general patterns in climate, physiography, potential natural vegetation, soil, geology, and land cover. These ecoregions are homogeneous relative to adjoining ecoregions in terms of these factors. By narrowing the focus of each study to a single ecoregion, the investigation situates each study within a widely used regional framework that also enforces a measure of control over variability in natural factors that influence water-quality.

The area defined by a single level III ecoregion also serves as a boundary for defining the population of potential study watersheds, with drainage areas in the approximate range of 50 to 250 km^2. Basins in this size range are comparable to the size of basins generally used in the NAWQA program to assess the impacts of a particular land use (Gilliom *et al.*, 1995); in addition, the lower end of this size range will generally be adequate to ensure perennial stream flow, while the upper end is still small enough to limit the mix of land uses. The population of basin boundaries in this size range was delineated by using 30-meter digital elevation model (DEM) data in conjunction with geographic information system (GIS) programs (U. S. Geological Survey, 2000c). After comparing the results with basin boundaries developed using topographic maps, these digitally derived basins were judged to be adequate for identifying potential study drainage basins. The population of drainage basins ranged from 200 (New England study) to 1,700 (Birmingham study) drainage basins.

Given the overarching environmental framework – the population of 50 to 250-km^2 drainage basins in a single Level III ecoregion – additional data on natural characteristics, based on higher resolution and larger scale spatial data, were developed for each of the candidate study basins. A geographic information system was used to overlay the drainage basin boundaries for all candidate basins with the higher resolution data on natural characteristics. One factor used in this additional characterization were subregions of the Level III ecoregion. In the New England study, U.S. Forest Service ecological region boundaries were used to define nine subregions within USEPA region 59. The Forest Service subregions were compiled by using larger scale data than the level-III boundaries and indicate distinct patterns associated primarily with large-scale vegetation, geology, and soil data (Keys *et al.,* 1995). In addition, explicit data about soil drainage characteristics, based on soil hydrologic groups (U.S. Department of Agriculture, 1994), and bedrock geology characteristics (Robinson, 1997) were generated for each candidate basin.

K-means clustering (SPSS, Inc., 1999), using basin-level data on subregion (nine variables), geological (nine variables) and soil drainage (two variables) characteristics, was used to identify groupings of basins that were relatively homogeneous in terms of these higher resolution natural landscape characteristics (Table 2). This clustering method divides candidate basins into groups by maximizing the between-cluster variation and minimizing the within-cluster variation. Groupings of basins consisting of two to 15 clusters were evaluated to determine which one provided the most practical and common sense environmental framework. This is a commonly used approach for finding the optimal number of clusters in a cluster analysis (Kachigan, 1986). The disproportionately large F-ratios observed for the Forest Service subregions (Table 3) indicate that these are the primary environmental setting variables that discriminate among clusters. This was consistent regardless of the number of clusters considered in the development of the environmental framework. An environmental setting based on nine clusters was chosen for use in the site-selection process because it maximized the number Forest Service subregions that were statistically significant in discriminating among clusters.

At the conclusion of this stage in the basin characterization and selection effort, several steps were accomplished. A Level III ecoregion was chosen to serve as the overall boundary for the study and for determining the population of study basins. A population of study drainage basins was identified and a number of characteristics were developed for each of these basins, including: the percent of basin area in each of nine ecological subregions, nine different geological zones, and two soil drainage classes. These variables were used in a cluster analysis, which resulted in a grouping of candidate basins into clusters that share similar natural characteristics. Each candidate basin was assigned a cluster affiliation.

CHARACTERIZING THE ANTHROPOGENIC LANDSCAPE

Efforts to understand the functioning of urban ecosystems have emphasized the linkages in the spatial patterns and processes of both sociocultural and biophysical resources (Grove and Burch, 1997). These investigations suggest that it is impossible to understand the differentiation that occurs in the spatial pattern and processes associated with natural ecological systems without an understanding of the spatial pattern and processes of human ecological systems, including socioeconomic factors. Anthropogenic landscape characteristics used in this study to describe the population of potential gradient study basins include: (1) biophysical measures of the urban landscape, such as land cover and impervious surface (Wang *et al.,* 1997); (2) measures of the infrastructure that supports urban development patterns (Center for Watershed Protection, 1998); and (3) socioeconomic measures describing factors such as population, housing, and income (Anson, 1991; Grove and Burch, 1997). A GIS was used to overlay thematic maps of these characteristics with drainage basin boundaries. These data were compiled in a basin characteristics spreadsheet, with a single row for each potential basin and multiple columns for the land cover, infrastructure, and socioeconomic variables, and used to develop the urban intensity index.

The primary source of land cover/land use information was data developed as part of the Multi-Resolution Land Characteristics (MRLC) consortium, a Federal interagency project to develop mapped land-cover data for the contiguous United States based on Landsat Thematic Mapper satellite images (Loveland and Shaw, 1996). These hierarchically organized data provide both general land cover information (e.g., developed versus forest) and more specific land use-type information. For instance, land classified as developed in the general land cover classification also has a land use designation as either low or high intensity residential or commercial/industrial/transportation. MRLC data used in this study were collected in the early 1990s and processing of the data for the conterminous United States was nearly completed

TABLE 2. Variables Used in the Analysis of New England Urban Watershed Gradient.
(Variables in bold type were correlated at a level > = 0.50 with 1997 population density and were used in the construction of the urban intensity index. Bold italics indicates significant negative correlation. Variables marked with an asterisk are redundant with other variables listed in parentheses and were not used in index development.)

Environmental Framework Characteristics	
SHED_MI2	Watershed area (square miles)
WELLPCT	Proportion of watershed with well-drained soils
POORPCT	Proportion of watershed with poor-drained soils
LITHO_1	Major litho-chemical group 1: carbonate rich (square miles)
LITHO_2	Major litho-chemical group 2: carbonate poor, clastic sedimentary, depositional basins (square miles)
LITHO_3	Major litho-chemical group 3: mafic igneous and metamorphic equivalents (square miles)
LITHO_4	Major litho-chemical group 4: ultramafic (square miles)
LITHO_5	Major litho-chemical group 5: metamorphosed, clastic sedimentary (square miles)
LITHO_6	Major litho-chemical group 6: felsic igneous and plutonic (square miles)
LITHO_7	Major litho-chemical group 7: calcareous metamorphosed clastic sedimentary (square miles)
LITHO_8	Major litho-chemical group 8: sulfidic clastic sedimentary rocks (square miles)
LITHO_9	Major litho-chemical group 9: unconsolidated glacial deposits (square miles)
EC_221Aa	Subregion 221Aa - Boston basin (square miles)
EC_221Ac	Subregion 221Ac - Narragansett/Bristol lowlands (square miles)
EC_221Ad	Subregion 221Ad - S. New England Coastal lowlands (square miles)
EC_221Ae	Subregion 221Ae - Hudson highlands (square miles)
EC_221Af	Subregion 221Af - Lower Connecticut River valley (square miles)
EC_221Ag	Subregion 221Ag - SE New England Coastal hills and Plains (square miles)
EC_221Ah	Subregion 221Ah - Worcester/Monadnock plateau (square miles)
EC_221Ai	Subregion 221Ai - Gulf of Maine Coastal Plain (square miles)
EC_221Ak	Subregion 221Ak - Gulf of Main Coastal lowlands (square miles)
Landuse Characteristics	
LU21_AB	Proportion of watershed with low intensity residential land on well-drained soils
LU21_CD	Proportion of watershed with low intensity residential land on poor-drained soils
LU22_AB	Proportion of watershed with high intensity residential land on well-drained soils
LU22_CD	Proportion of watershed with high intensity residential land on poor-drained soils
LU23_AB	Proportion of watershed with commercial/Industrial/Transportation on well-drained soils
LU23_CD	Proportion of watershed with commercial/Industrial/Transportation on poor-drained soils
IMPERV	Proportion of watershed with impervious land surface (not used in index calculation)
URBAN_MI	Total urban land area in watershed (square miles)
COMRESIN	Commercial/residential urban land index (ratio of commercial to residential land cover)
FOR_MI	Total forested land area in watershed (square miles)
WET_MI	Total wetland area in watershed (square miles)
MRLC_11	Watershed area in open water (square miles)
MRLC_12	Watershed area in Perennial Ice/Snow (square miles)
MRLC_21	Watershed area in Low Intensity Residential (square miles)
MRLC_22	Watershed area in High Intensity Residential (square miles)
MRLC_23	Watershed area in Commercial/Industrial/Transportation (square miles)
MRLC_31	Watershed area in Bare Rock/Sand/Clay (square miles)
MRLC_32	Watershed area in Quarries/Strip Mines/Gravel Pits (square miles)
MRLC_33	Watershed area in Transitional cover (square miles)
MRLC_41	Watershed area in Deciduous Forest (square miles)
MRLC_42	Watershed area in Evergreen Forest (square miles)
MRLC_43	Watershed area in Mixed Forest (square miles)
MRLC_51	Watershed area in Deciduous Shrubland (square miles)
MRLC_52	Watershed area in Evergreen Shrubland (square miles)
MRLC_53	Watershed area in Mixed Shrubland (square miles)
MRLC_61	Watershed area in Orchards/Vineyards/Other (square miles)
MRLC_71	Watershed area in Grasslands/Herbaceous (square miles)
MRLC_81	Watershed area in Pasture/Hay (square miles)
MRLC_82	Watershed area in Row Crops (square miles)
MRLC_83	Watershed area in Small Grains (square miles)
MRLC_84	Watershed area in Fallow (square miles)
MRLC_85	Watershed area in Urban/Recreational Grasses (square miles)
MRLC_91	Watershed area in Woody Wetlands (square miles)
MRLC_92	Watershed area in Emergent Herbaceous Wetlands (square miles)

TABLE 2. Variables Used in the Analysis of New England Urban Watershed Gradient (cont'd.).
(Variables in bold type were correlated at a level > = 0.50 with 1997 population density and were used in the construction of the urban intensity index. Bold italics indicates significant negative correlation. Variables marked with an asterisk are redundant with other variables listed in parentheses and were not used in index development.)

Landuse Characteristics (cont'd.)	
BUF_AREA	Total area (square miles) within 240 meter wide buffer (120 m. on each side of stream) in watershed
BUF_11	Total area (square miles) of MRLC 11 within buffer
BUF_21	Total area (square miles) of MRLC 21 within buffer
BUF_22	Total area (square miles) of MRLC 22 within buffer
BUF_23	Total area (square miles) of MRLC 23 within buffer
BUF_31	Total area (square miles) of MRLC 31 within buffer
BUF_32	Total area (square miles) of MRLC 32 within buffer
BUF_33	Total area (square miles) of MRLC 33 within buffer
BUF_41	Total area (square miles) of MRLC 41 within buffer
BUF_42	Total area (square miles) of MRLC 42 within buffer
BUF_43	Total area (square miles) of MRLC 43 within buffer
BUF_51	Total area (square miles) of MRLC 51 within buffer
BUF_61	Total area (square miles) of MRLC 61 within buffer
BUF_81	Total area (square miles) of MRLC 81 within buffer
BUF_82	Total area (square miles) of MRLC 82 within buffer
BUF_85	Total area (square miles) of MRLC 85 within buffer
BUF_91	Total area (square miles) of MRLC 91 within buffer
BUF_92	Total area (square miles) of MRLC 92 within buffer
URB_BUF	Percent of watershed buffer area in urban land cover
FOR_BUF	Percent of watershed buffer area in forested land cover
WET_BUF	Percent of watershed buffer area in wetland land cover
Infrastructure Characteristics	
ROAD_KM*	Road length in watershed (kilometers) (ROAD_DEN)
ROAD_DEN	Road density in watershed [road length (km)/watershed area (km2)]
PSCOUNT	Number of points source dischargers in watershed (EPA database)
DAMCOUNT	Number of dams in watershed
TRICOUNT	Number of Toxics Release Inventory sites in watershed
Population Characteristics	
AGESTR97	Age structure of population (population under 18/population over 18)
POP90*	1990 population (P97DENM)
POP97*	1997 population (P97DENMI)
P90DENMI*	1990 population density (people/square mile of watershed area) (P97DEN)
P97DENMI	1997 population density (people/square mile of watershed area)
POP9097*	Population change 1990-1997 (proportion) (P97DEN)
URBSPRWL	Urban sprawl index [(urban land area/1997 population)*10,000]
Socioeconomic Characteristics	
PCINC97	1997 per capital income (dollars)
HOUSEAGE	Age of residential housing stock (years)
AVGBEDRM	Average number of bedrooms in residences
SEI-1	Socioeconomic index 1: high levels of income and owner occupied housing; low population density
SEI-2	Socioeconomic index 2: high levels of population, housing units, households, and rental units
SEI-3	Socioeconomic index 3: high levels of income, population density, per capita income, rental units
SEI-4	Socioeconomic index 1: high levels of length of tenure in house and occupancy rates, low per capita income, and 90-97 pop change
SEI-5	Socioeconomic index 5: high levels of children, persons below poverty level, housing units on septic systems

by the summer of 2000. Accuracy assessments have been completed for the areas within the Boston and Birmingham studies (written communication, Limin Yang, U.S. Geological Survey, July 2000.). Classification errors for the developed land classes in these areas ranged between 15 and 50 percent, with better accuracies in the New England classification. Residential land areas were generally classified more accurately than commercial/industrial/transportation areas.

TABLE 3. Summary Statistics for K-Means Clustering of Environmental Variables Into Nine Groups of Relatively Homogeneous Environmental Settings.

(Variables are defined in Table 2. F-ratios indicates the extent to which the individual variables help separate the clusters. Thus, F-ratios in the 100's are more important in defining the clusters than F-ratios in the teens.)

Variable	F-Ratio
SHED_MI2	3.52
WELLPCT	19.1
POORPCT	19.26
LITHO_1	3.58
LITHO_2	60.61
LITHO_3	21.45
LITHO_4	6.72
LITHO_5	13.52
LITHO_6	10.99
LITHO_7	38.02
Subecoregions	
EC_221Aa	1.64
EC_221Ac	290.24
EC_221Ad	3.08
EC_221Ae	23.87
EC_221Af	108.43
EC_221Ag	176.07
EC_221Ah	10.04
EC_221Ai	196.08
EC_221Ak	229.76

The MRLC land-cover data were also used to derive estimates of another important characteristic of urban intensity – impervious surface area. Several steps were followed to estimate impervious surface. A range of impervious-surface percentages associated with the detailed land-cover classes used in the MRLC classification were compiled from existing literature (Stankowski, 1972; Bedient and Huber, 1988; Arnold and Gibbons, 1996; Booth and Jackson, 1997; Center for Watershed Protection, 1998). Simple distributions (e.g., uniform, triangular) were developed from these literature values and were used with each MRLC land cover type in the basin characteristics spreadsheet as multipliers in a formula that estimated impervious-surface area for all land-cover types. These individual estimates were summed into a single impervious surface estimate for each potential basin. For each watershed, the spreadsheet was calculated repeatedly, using 1,000 iterations in this simulation. The software kept track of the outcomes of each iteration, created a distribution of all possible output values, and reported the mean impervious value for each watershed.

Several infrastructure measures associated with anthropogenic activities were used to characterize urban intensity. These included road density, the number of point-source dischargers (U.S. Environmental Protection Agency, 1999), the number of dams (U.S. Army Corps of Engineers, 1996), and the number of Toxic Release Inventory sites (U.S. Environmental Protection Agency, 1997a; Price and Clawges, 1999).

Socioeconomic conditions shape perceptions of both the degree (e.g., amount of density) and character (e.g., affluence) of development within a drainage basin; they may also exert an important effect on factors that can influence water quality (Grove and Burch, 1997; Ryznar, 1998). For example, population and housing density provide a direct measure of development intensity and are likely to be correlated with impervious surface (Stankowski, 1972). Residential use of fertilizers and pesticides may vary according to the income levels of neighborhoods within a watershed, although the very limited data on the use of these chemicals in urban areas makes assessment of this intuitively appealing claim difficult. Census counts (1990 data), estimates (1997), and projections (2002) for population, labor, income, and housing characteristics, based on census block group areas, were used to characterize the socioeconomic aspects of the urban landscape (Table 2; Geolytics, 1998). Socioeconomic indices (SEI) also were derived for each basin by using ordination of population, labor, income, and housing census variables (Anson, 1991; Table 4). For the Boston study, the indices were based on 80 census variables computed over the 11,500 census block groups within the New England states. The indices contrast areas with differing combinations of social, income, housing, and labor characteristics. For example, high scores for SEI-1 (which explains 23 percent of the variation between block groups in the 80 dimensional space) are associated with areas with a high number of high school graduates, relatively high household incomes, and a high level of owner occupied housing. Scores for SEI-3 are positively associated with households with very high income, small numbers of children, high percentages of college graduates, and high proportion of rental housing.

DEVELOPING AN INDEX OF URBAN INTENSITY

The planning phase of an urban gradient study uses an *a priori* measure of the intensity, or degree to which a basin is urbanized, in order to rank potential study basins. This ranking, along with information

TABLE 4. New England Census Block Group Socioeconomic Indices (SEI) and Primary Associated Variables. [Indices were derived from principal components analysis of 80 social, income, and housing characteristics associated with 1990 (counts), 1997 (estimates), and 2002 (projections) census block group data (Geolytics, 1998). Variables in these socioeconomic classes with relative high (+) and low (-) loadings on these indices are listed. HS - high school; pop - population; yo - years old; fam - families; chil - children; HH - households; K - thousands; own occ - owner occupied; HU - housing unit.]

	Social	Income	Housing
SEI-1	+ high school grad + 2 and 3+ vehicle households - population density 90 and 97	+ household and family income - % poverty, fam in poverty, chil < 18 + 97 household income - % HH income less than 15K	+ own occ housing units + OOHU with mortgage + average number of bedrooms + % own occ housing units - % rental occupied housing units
	+ 1990 population + 1 vehicle households + 97 and 02 population + persons 16+	+ number of households + number of families	+ number of housing units + number of occupied housing units + number of rental and % rental units + 97 hu - total and occupied + 02 hu - total and occupied - average number of bedrooms
SEI-3	+ % Bachelors degree or higher - children/1,000 women 25-34 yo + pop density 90 and 97 - 90-97 & 90-02 pop change - proportion pop under 18 + % using public transportation	+ 90, 97, 02 per capita income + % household income > $100,000	+ housing unit density + age of housing unit + % housing units on public sewer - % housing units on septic + % housing units on utility gas + proportion hu occupied, 90, 97 & 02 + % rental occupied housing units
SEI-4	- % Bachelors degree of higher + % born in state of residence + proportion pop under 18 - 90-97 & 90-02 pop change	90 per capita income	+ % housing units using fuel oil + length of tenure in house + proportion hu occupied, 90, 97 & 02 - % condo housing units
	+ children/1,000 women 25-44 yo - % born in state of residence + proportion pop under 18 + % females > 16 unemployed	+ household income + % persons below poverty + % poverty, fam in poverty, chil < 18 + % household income > $100,000 + % female headed household + proportion population under 18	- 90-97 & 90-02 population change + average number of bedrooms - % housing units on public sewer + % housing units on septic - 90-97 & 90-02 change in # of hu

about each basin's natural characteristics, is necessary to choose a final set of study basins that have similar natural characteristics and a desired distribution of urban intensity.

Neighborhoods within a city or communities within a single metropolitan area have distinct urban intensities that are a function of not only the amount of developed land, but also of differences in infrastructure, population, social, income, and housing characteristics. A multi-metric approach was used in the planning phase of the gradient studies to characterize the relative urban intensity of each potential study basin. Multi-metric indices are used to describe the overall condition of complex systems (Ward, 1996; Karr and Chu, 1997). Used in disciplinary settings as distinct as Wall Street (e.g., index of leading economic indicators; Mitchell and Burns, 1938) and stream ecology (e.g., index of biological integrity; Yoder and Rankin, 1995), indices combine a number of generally accepted individual condition measures of the system being assessed (e.g., net business formation and new manufacturing orders for assessing economic health; amount of developed land and population density for assessing the intensity of urban development) that may be correlated but which provide distinct information about different dimensions of often complex systems. This approach allows the integration of multiple, commonly used sources of information about the urban landscape, such as urban land area, amount of impervious surface, road density, population density, and socioeconomic indices into a single measure of urban intensity (Cuffney *et al.,* 2000; Karr and Chu, 1997).

In the Boston area study, a basin attribute table with 73 landuse, infrastructure, population, and socioeconomic variables was developed for each of the 208 potential study basins within the Level III ecoregion. Principal component analysis of the variance structure of the 73 variables across the 208 candidate basins indicated that the 1997 population density was the most important characteristic in explaining the variation among the basins. The urban index was developed based on 43 landscape and socioeconomic characteristics that had an absolute Pearson correlation value of greater than or equal to 0.50 with 1997 population density (Table 2).

The urban index was calculated by using a five-step procedure, with the resulting index values ranging from 0 to 100 over the set of candidate basins. An example of the calculation of the urban intensity index for one watershed using representative variables is given in Table 5 and a graphical representation of the index results for the candidate New England study basins is presented in Figure 2. Calculation of the index proceeds as follows.

1. Adjust raw data for basin size and measurement units (see variables in Table 2):

Proportions into percentages
Areas into percent of basin area
Toxic Release Inventory, point-source dischargers, and dam counts into densities (count per unit area)
SEI= SEI - minimum(SEI) to maintain absolute differences and make all values positive
Negative correlation with population = 100% - percentage

2. Transform original data so value of variables range from 0-100 for candidate sites:

$$Y = (X - X_{min}) \div (X_{max} - X_{min})$$

where X is the value of variable X for the site, Y is the transformed value of variable X for the site, X_{min} is the minimum value of variable X over all sites, and X_{max} is the maximum value of variable X over all sites.

3. Variables that were negatively correlated with population density are adjusted so that all variables increase as population density increases:

$$Y = 100 - Y_{neg\ corr.}$$

4. Urban intensity is calculated as the average value of the transformed variables:

$$URBI = \left(\sum_{1}^{n} Y_i \right) / n$$

where Y_i is the adjusted value of variable i, and n is the number of variables in the index.

5. Transform index URBI so the range of intensity is 0-100 for candidate sites:

$$X_{adj} = (X - X_{min}) \div (X_{max} - X_{min})*100$$

where X is the value of the URBI index for the site, X_{adj} is the transformed value of the URBI index for the site, X_{min} is the minimum value of the URBI index over all sites, and X_{max} is the maximum value of the URBI index over all sites.

SELECTING DRAINAGE BASINS FOR THE GRADIENT STUDIES

The objectives of the site-selection process were to choose sites that: (1) represented the range of urban-intensity in the population of potential study basins; and (2) were relatively homogeneous in terms of the natural factors that might cause variability in the physical, chemical, or biological water-quality response. In addition, site-selection considered the availability of adequate access for sampling, the ability to complete all required sampling at each site, the comparability of local habitat conditions (e.g., substrate, flow, landscape features) at potential sites, and whether actual land use and other urban characteristics matched the GIS-derived basin description. Site selection was iterative, with project personnel considering computer generated site information and information developed from site reconnaissance. In some cases, site reconnaissance suggested the need to relocate a potential sampling location up- or downstream, in which case the basin characteristics table and index values were updated.

To meet the first site-selection objective, the relation between impervious area (which was not used in the index) and the urban intensity index was analyzed to identify the location along a gradient of urban intensity potential water-quality change thresholds (Klein, 1979; Schueler, 1995; Booth and Jackson, 1997; Figure 3). The literature suggests that an increased rate of adverse effects on biological communities can be expected when total impervious area in the basin reaches approximately 12 percent, and very adverse effects can be anticipated at and above 30 percent. The relation between impervious surface and the urban intensity index shown in Figure 3 indicates that these potential threshold levels correspond to urban intensity index values in New England of 28 and 66. Because an important study objective is to describe the existence and nature of any relationship between urbanization and water quality, the most important areas of the gradient in which to distribute

TABLE 5. Example Calculation of the Urban Intensity Index for One Watershed Using Representative Variable Types.

WSHED	Units	Adjustment	Maximum	Minimum	Adjusted
imperv[1]	0.03	3.12	45.85	1.66	3.30
LU21_CD[1]	0.01	0.63	48.38	0.00	1.31
LU22_CD[1]	0.00	0.00	11.47	0.00	0.00
LU23_CD[1]	0.00	0.08	12.76	0.00	0.66
urban_mi[2]	1.02	2.99	70.36	0.25	3.91
for_mi[2]	24.92	72.99	88.18	17.65	21.54
MRLC_21[2]	0.90	2.64	53.99	0.16	4.60
MRLC_22[2]	0.00	0.00	11.56	0.00	0.01
MRLC_23[2]	0.12	0.35	15.02	0.08	1.77
MRLC_43[2]	8.62	25.25	48.11	4.61	52.54
BUF_21[2]	0.12	0.36	11.37	0.00	3.15
BUF_22[2]	0.00	0.00	2.57	0.00	0.00
BUF_23[2]	0.01	0.03	3.99	0.00	0.79
URB_BUF	2.71	2.71	69.15	0.00	3.91
FOR_BUF	66.57	66.57	93.83	13.99	34.14
TRICOUNT[3]	1.00	2.93	179.39	0.00	1.63
SEI_3[4]	-3.84	0.74	8.88	-4.69	8.36
AGESTR97[1]	0.42	41.52	48.57	22.83	27.39
ROAD-DEN	1.68	1.68	9.56	1.14	6.45
			Average value of all metrics:		9.24
			Maximum average for all sites:		80.54
			Minimum average for all sites:		4.04
			Index adjusted to 0-100 range:		6.80

[1]Proportion of basin area converted to percentage of basin area.
[2]Area converted to percentage of basin area.
[3]Total counts converted to counts per 100 mi^2 of basin area.
[4]SEI adjusted = SEI - minimum SEI.

sites are the pre-effect (urban intensity index < 28) and effect zones (urban intensity index of 28-66); sites in this intensity range should indicate the existence and shape of any relation between urbanization and water quality. Eighteen sites were chosen in the pre-effect range of the urban index and 11 sites were chosen in the effect zone. Sites with high levels of urban intensity are less important because these sites play less of a role in defining impairment thresholds and rates of impairment. Three sites were chosen with an urban index greater than 66.

To meet the second site-selection objective, the reconnaissance effort concentrated on identifying basins in the Gulf of Maine subecoregion (EC_221Ai, Table 2). This region has experienced substantial urban growth, and its location west and northwest of Boston suggests that this growth will continue. Twenty-five of the 32 sites in the New England study were in Cluster 2 or Cluster 5, both strongly associated with the Gulf of Maine region. The primary reasons for selecting sites that were not in these clusters were the lack of sites in the Gulf of Maine clusters with acceptable sampling conditions or with high-level urban intensity. The remaining sites were in adjoining subecoregions or were part of existing sampling networks that were included in this study.

CONCLUSIONS

Planning activities conducted as part of the NAWQA urban gradient studies have suggested several lessons regarding basin characterization and study site selection. Several are related to the scale of the project. Each of the three studies was limited to 30 sites for budgetary reasons. One of the questions going into the study design process was "What spatial area could be adequately represented by 30 sampling sites with a size range of 50 - 250 km^2?" Basin characterization efforts in the three studies suggest that a project of this scale can represent a gradient of urbanization while controlling for the effects of natural characteristics at the scale of a USEPA Level IV subregion. Understanding the water quality effects of urbanization at the scale of an entire Level III ecoregion would require many more sites or a focus on a

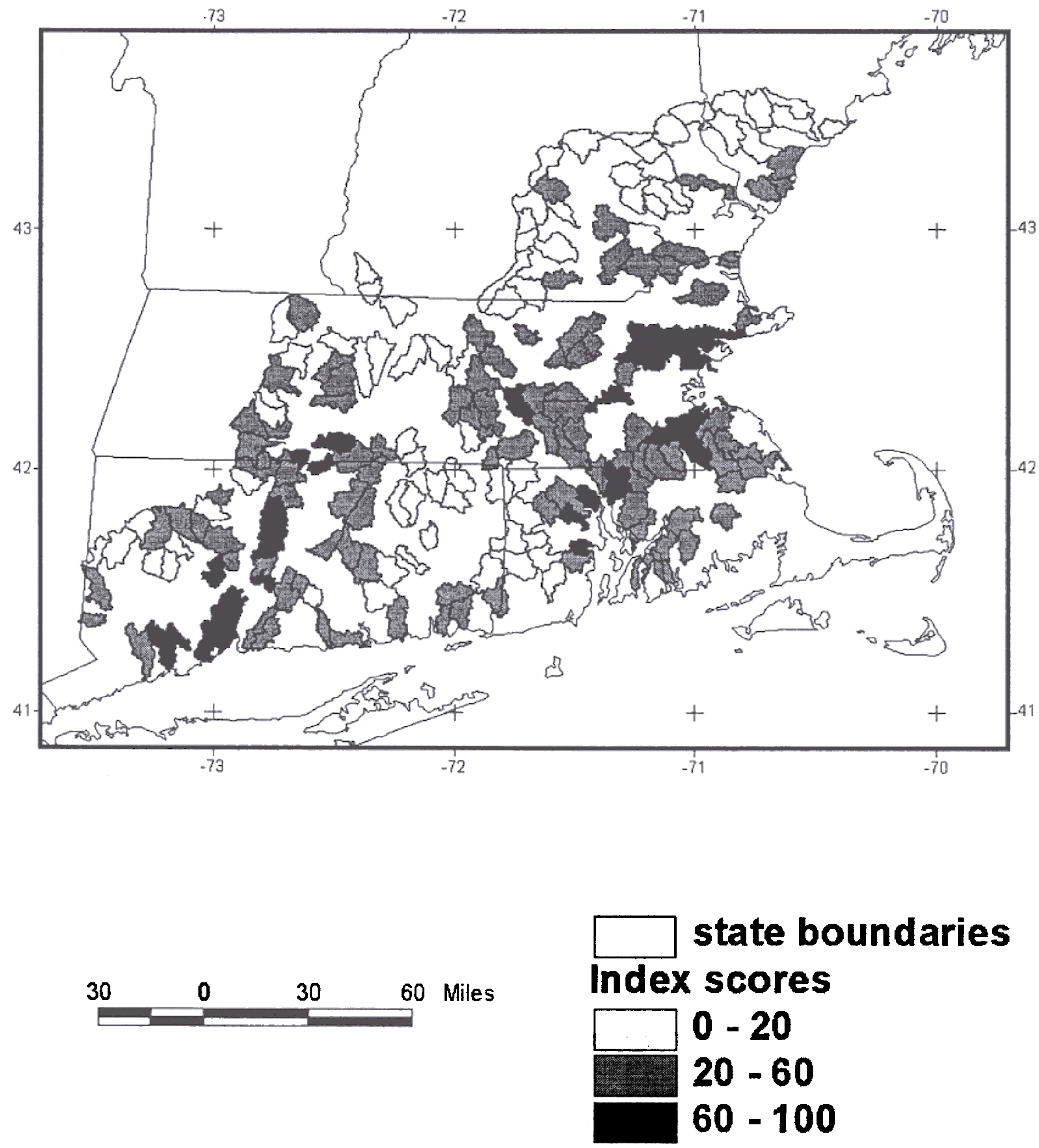

Figure 2. Urban Intensity Index Scores for New England Land Use Gradient Study.

small range of the gradient of urbanization across the region.

Another scale related lesson is that the basins that have been selected provide a regional-scale answer to the question of what water quality impacts are caused by urbanization. Study basins used in the three investigations do not allow issues of interest to local land use managers to be addressed, such as the effects on water quality of different configuration of urban development (e.g., cluster zoning of new residential of office development) or urban best management practices. To do this would require a different design that limits the variability of both natural conditions and the level of urbanization, while allowing either the configuration of urban development or the use of urban best management practices to vary.

The most important lesson from implementing the methods described in this paper is that it is possible to identify and analyze the natural and anthropogenic characteristics of a population of potential study drainage basins for a large spatial area in a relatively short period of time using straightforward GIS techniques and nationally available data sets. These techniques are scaleable, in the sense that they can be easily implemented in larger or smaller areas.

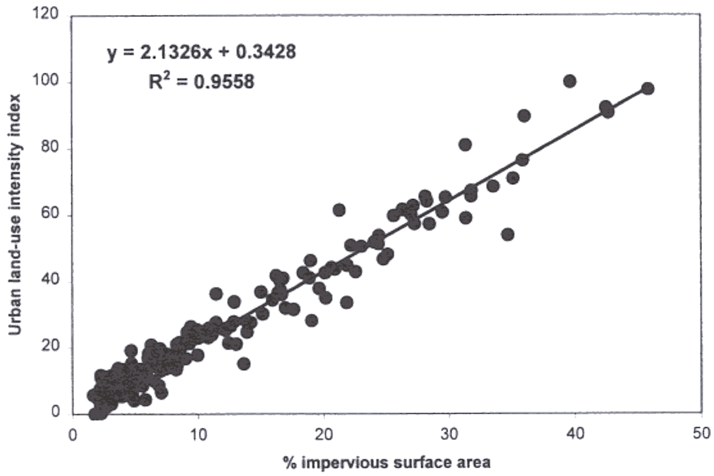

Figure 3. The Relation Between Impervious Area and the Urban Intensity Index in the Boston Study.

Another lesson related to the methodology of identifying and selecting basin for an urban gradient study relates to the importance of field reconnaissance. Basin reconnaissance was judged by project staff to be a centrally important in selecting study basin that not only made sense based on the GIS analysis but also from a standpoint of large scale factors that cannot be considered by the GIS, especially related to suitability of the site for sampling activities and the local habitat features. Reconnaissance is costly in terms of staff time. The Boston study staff visited approximately 150 potential drainage basins. Approximately three weeks for one staff person were spent preparing for the reconnaissance effort. Three staff people took four weeks to complete these visits, and another week of one person's time was spent compiling the information into a useable format. Ideally, the timing of reconnaissance should correspond to a low flow period; seasonally unusual wet weather conditions hampered the ability of Boston staff to visit and assess sites.

The value of the index is potentially constrained by several factors. The first is the age of the land cover data. Sampling activities in the Birmingham study during the summer of 2000 suggest that large changes in land cover have occurred since the MRLC data were collected eight years earlier. This is likely to be the case in any rapidly urbanizing area of the country. A significant challenge in developing an *a priori* urban intensity index lies in gaining access to contemporary land cover data. This challenge is amplified if there is a need to implement these studies simultaneously in many areas across the country. The ability to compare and contrast results from multiple studies relies to a great extent on the availability of explanatory and response data collected using common protocols. The need for regularly updated land cover information in urbanizing areas, based on comparable data and classification protocols, far exceeds the availability of such data.

The urban intensity index did not include any measure or estimate of impervious surface; the impervious surface estimate for each basin was used instead to assist in site selection. Imperviousness is a particularly important indicator of urban intensity because it can be readily measured at a variety of scales (i.e., from the parcel level to the watershed) and because it has been consistently shown to affect stream hydrology and water quality (Schueler, 1995). The measurement of impervious surface for large spatial areas, whether from interpretation of large-scale aerial photography or through classification of remotely sensed data, was not practical for this project. As is the case with land cover data, the need for impervious surface data far exceeds the resources typically available to generate the data, particularly to support investigations with a large spatial extent. Research is needed on techniques to measure or model impervious surface data at the scale needed to support regional investigations of the impacts of urbanization.

The value of the urban intensity index in explaining water quality response will be uncertain until water quality data have been collected and analyzed. The index was intended primarily to be used to provide an a priori basis for ranking the relative intensity of urban development. The conceptual understanding of factors that are associated with urban intensity was purposefully inclusive and included factors not usually considered in explaining variations in water quality. An important result of the analysis stage of the urban gradient studies will be to shed light on the explanatory value of the individual variables that comprise the index.

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