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Enhanced source-water monitoring for New York City: historical framework, political context, and project design

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Abstract. An enhanced water-quality monitoring project was established in 2000 for streams providing drinking water to New York City (NYC). The project's design considered the history of the NYC source watersheds, and some of the broader issues facing freshwater supply systems in general. NYC's relationship with its watershed has historically been acrimonious and filled with mistrust, a situation that became critical in 1989 when the US Environmental Protection Agency (EPA) issued the Surface Water Treatment Rule (SWTR), which required all unfiltered public water-supply systems either to provide filtration or to comply with a stringent set of water-quality, operational, and watershed-control standards. Plans to implement this rule caused further mistrust and lawsuits, which led in 1997 to the NYC Watershed Memorandum of Agreement (MOA), a compromise that was accepted by all the stakeholders. The MOA addressed fundamental issues about: 1) the protection, allocation, and ownership of water resources, 2) the identification and valuation of ecosystem services, 3) the compatibility of environmental protection and economic development, and 4) strategies for bringing together diverse stakeholders in the watershed. One of the provisions of the MOA was to enhance the existing city, state, and federal monitoring programs for NYC's source watersheds. The monitoring project described in this series, which is part of that enhancement, recognizes philosophically that source watersheds and their ecosystems are: 1) the ultimate source of the water, 2) the major source of anthropogenic contaminants in the water, and 3) the primary natural processors of water-borne contaminants. Protecting NYC's source-water areas requires an integrated approach that ties historical and contemporary land use into the design of a large-scale, enhanced, water-quality monitoring project (the Project). The Project set forth 4 primary objectives: 1) to create a quantitative baseline of selected physical, chemical, and biological characteristics of source-water streams and reservoirs for use in assessing future changes in the quality of NYC's drinking water and the integrity of the associated aquatic ecosystems, 2) to include in the baseline factors that are sensitive to temporal variability, are reproducible, and lend themselves to unconfounded analyses among sampling sites and times, 3) to integrate temporal and spatial change in both the level of selected contaminants and the structure and function of biological communities and ecosystems to assess whether impairment impacts the ability of the streams to provide ecosystem services related to water quality, and 4) to provide additional direction and perspective to the overall watershed management plan for the NYC source-water area. All papers in this series cover Phase I of the monitoring project, which involved physical, chemical, and biological measurements made during 2000 to 2002 at 60 stream sites distributed across a 5066-km^2 study area.

Key words: water-quality monitoring, Memorandum of Agreement, Safe Drinking Water Act.

Management of water resources is one of the most significant issues humans face (Fitzhugh and Richter 2004). Nearly a billion people in the developing world lack safe drinking water, and another 3 billion lack access to sanitation systems adequate to reduce exposure to water-borne diseases (Gleick 1999). In the face of such challenges, a new *water paradigm* has emerged. This paradigm involves the search for new sources to meet escalating demands, the incorporation of ecological theory and values into water policy, and the decoupling of the link between economic development and increased water consumption (Gleick 2000). The new paradigm, in turn, has prompted a call for new approaches to preserve and restore river systems and for recognition that humans must balance their needs with the sustainability needs of the world's rivers (Postel and Richter 2003). It is now clear that freshwater biodiversity is in crisis and that each

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species or ecosystem lost to degradation results in a concomitant loss of ecosystem services that are critical to the long-term sustainability of humanity.

Nowhere is the need to rethink water-resource management more critical than in urban areas. The percentage of the world's population living in cities is projected to grow from 48% in 2003 to 60% (4.9 billion) by 2030 (United Nations 2004). In the US, where urban water supply is already an issue, the population is expected to increase from 275 million in 2000 to 351 million by 2030 (US Census Bureau 2000). One of the most extensive and complex urban water-supply systems in the US is that associated with New York City (NYC). It is the largest single source of unfiltered water in the world, supplying >9 million people with >4.5 billion liters of water per day. The NYC source watersheds cover an area of 5066 km^2 that stretches 200 km from the city across 9 counties (Fig. 1). Ninety percent of the water comes from streams and rivers of the upper Delaware River watershed (50%) and the Catskills region (40%), and >9% comes from headwater streams of the Croton/Kensico watersheds. Less than 1% of NYC's total supply comes from groundwater (NYC DEP 2004b). The system, which includes 19 reservoirs and 3 controlled lakes, has a total capacity of 2195 billion liters. The water is transported through 3 aqueducts (including the 135-km Delaware Aqueduct, at one time the longest continuous tunnel in the world) and 7 other tunnels (with an 8^{th} tunnel under construction) to a network of water mains >11,000 km in length. In addition, waste water is removed through a system that consists of 10,400 km of sewer mains (Galusha 1999, NYC DEP 2004b).

We describe the historical framework, political context, and design for a recent large-scale enhanced water-quality monitoring project (the Project) in the streams, rivers, and reservoirs of the NYC drinking-water system. Project results for the first 3 y (2000–2002) are described in detail in the following 10 papers in this special series.

Perspective

The drinking-water industry in the US and abroad now recognizes that protecting sources of fresh water is a critical component of any long-term plan for a drinking-water system (e.g., US Safe Drinking Water Act Amendments of 1996). With this recognition has come a new understanding of the central role that watersheds and their aquatic ecosystems play in the filtration/treatment process necessary to provide clean, safe, and cost-effective drinking water to the public. Protecting those sources of fresh water requires a management plan that is based on a solid understanding of the streams and the watersheds they drain.

In designing the monitoring project discussed in this series, we viewed the watersheds and their ecosystems as having 3 critical functions. They were: 1) the ultimate source of water, 2) the principal entry point for naturally occurring and anthropogenic constituents (physical, chemical, and biological) in the water, and 3) the primary natural processors of water-borne constituents (nutrients, parasites, pollutants, etc.). Because landuse activities in source-water areas affect each of these functions, successful source-water protection requires an integrated watershed approach to assess sources, impacts, and processes relevant to the streams and reservoirs of the source area. To be effective, the approach must: 1) focus on constituents of natural and anthropogenic origin (hereafter contaminants) that can, at certain concentrations, contaminate water and render it unsuitable for human consumption or unable to support wildlife, and 2) recognize that contaminant dynamics in the NYC source area involve 4 basic elements—source, transport, ecosystem impairment, and symptom. Most monitoring programs, including the historic one for NYC, adequately characterize contaminant transport (levels of contaminants in the source water and distribution system, which consist of streams, rivers, reservoirs, and distribution pipes), and contaminant symptoms (turbidity, O_2 deficits, taste and odor, disinfection-byproduct-formation potential, etc.). Monitoring of these characteristics is driven by local, state, and federal regulations and by operational needs such as understanding the ambient quality of water for treatment purposes.

The monitoring project described here focuses largely on the remaining 2 elements: contaminant source and ecosystem impairment. The project was designed to enhance existing city, state, and federal efforts by introducing both new study variables and different spatial or temporal scales for monitoring variability in selected study variables. Understanding the spatial and temporal variation in key variables of tributaries that drain the principal watersheds and subwatersheds of the system is critical to developing a database on which to build long-term plans for remediation, restoration, and protection of the NYC water system. Providing an adequate baseline requires an intensive and coordinated spatial and temporal sampling project, and sophisticated analytical techniques that can distinguish among and quantify various possible sources of contaminants within each of the source watersheds. A good baseline, however, must go beyond measurements of constituents and contaminants per se. It also must recognize that impairment from contaminants can cause changes in

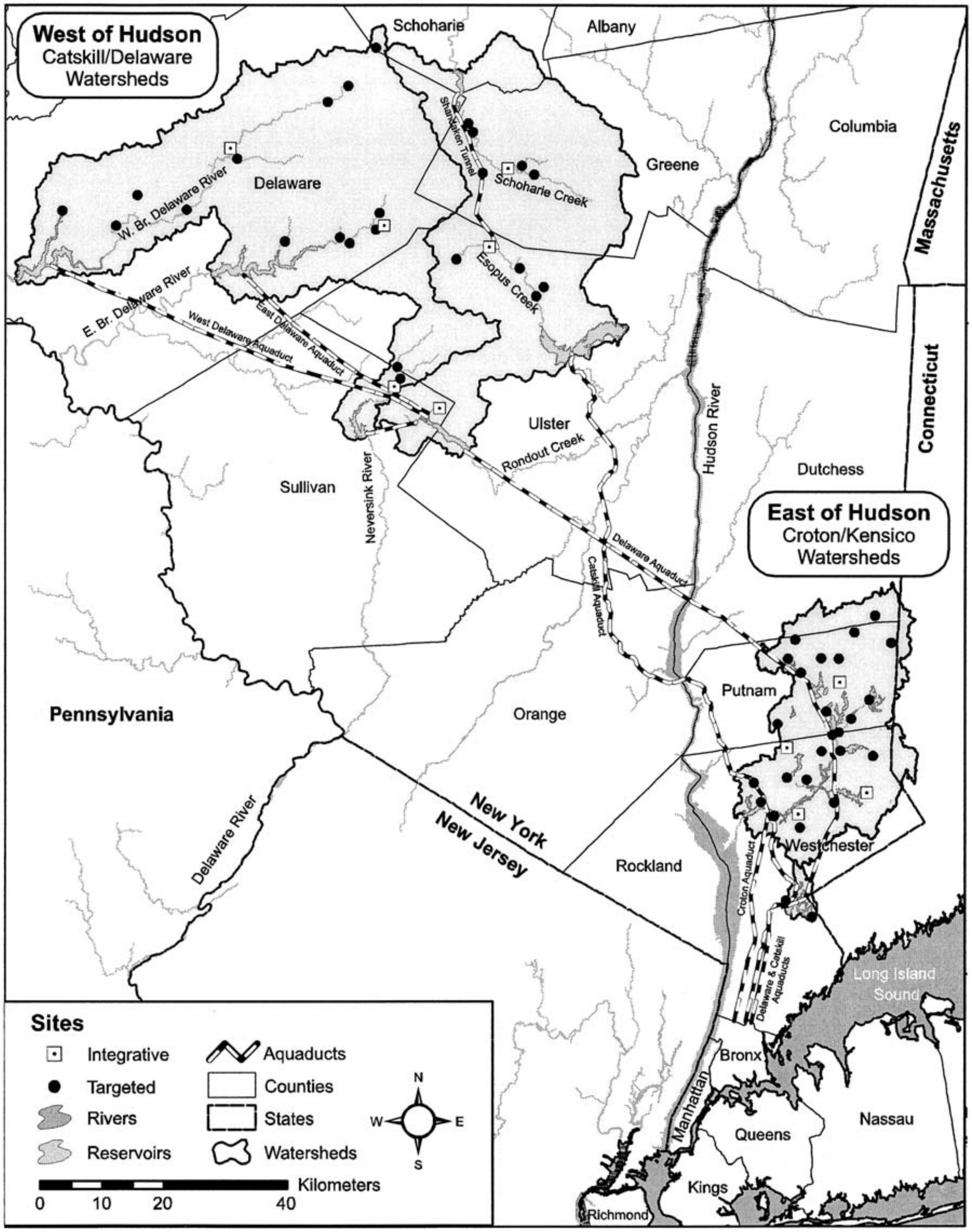

FIG. 1. Southeastern New York State and parts of Massachusetts, Connecticut, New Jersey, and Pennsylvania showing source-water areas (shaded areas near West of Hudson and East of Hudson panels) for New York City's drinking-water supply and 60 study sites.

the structural or functional properties of the ecosystem, and that these changes will decrease the ecosystem's ability to incorporate, process, metabolize, or otherwise sequester natural and anthropogenic materials effectively or efficiently in the watershed.

Historical Background

Considerable tension has existed for years between NYC and the residents of the source watershed area. Much of that tension has had to do with disagreements over water because NYC rose to unprecedented wealth and power despite an astonishing shortage of onsite natural resources. Complaints about the quantity and quality of fresh water began to surface almost as soon as the first Dutch settlers had taken up residence on Manhattan Island in the 1620s. In fact, one of the determining factors in the English capture of New Amsterdam (and renaming it New York) in 1664 was Governor Peter Stuyvesant's failure to provide an adequate supply of water for the garrison's defenders (Yeats-Thomas 2001).

By the early 19th century, NYC's population was growing exponentially—it increased 24× between the first US census in 1790 and the outbreak of the Civil War—and it was clear that the city would have to import water. In 1837, NYC began a series of engineering projects that would deliver water from the Croton River in Westchester and Putnam counties, which lie north of the city on the east side of the Hudson River.

The east-of-Hudson (EOH) system consisted of 12 reservoirs and 3 controlled lakes that drained an area of 971 km^2 by the time it was completed in 1911. From the beginning, the project reflected both the remarkable feats of engineering and the substantial economic and human costs that would continue to mark the development of the NYC water system. The system required the flooding of at least 15 communities and the displacement of thousands of people from their homes in addition to the costs of construction and the dangers faced by the large and mostly immigrant and African American labor force (Galusha 1999).

Even before construction was completed, the EOH water system's supply proved inadequate to meet NYC's escalating demand. Therefore, in 1905, the city decided to cross the Hudson River and bring water from the Catskill Mountains to NYC. The first part of the Catskill system, which included the huge Ashokan Reservoir a few kilometers west of the Hudson, was completed in 1915, and the final components, the Schoharie Reservoir and Shandaken Tunnel, were finished in 1928.

By then, the city was again in search of new water supplies, and it devised a plan to develop the New York State tributaries of the Delaware River. The Delaware, however, was also a source of water for New Jersey and Pennsylvania, and New Jersey filed a lawsuit to prevent NYC's appropriation of the river's water. In 1931, the US Supreme Court, declaring in the words of Justice Oliver Wendell Holmes that "a river is more than an amenity, it is a treasure [that] offers a necessity of life that must be rationed among those who have power over it," ruled that NYC remove no more than an average of 1665 million liters of water a day from the Delaware system (a figure that was increased in 1954 to 3028 million liters). In return, NYC was required to maintain sufficient stream flow for the 2 downstream states and to ensure that the water delivered to them was clean (State of New Jersey v. State of New York, 283 U.S. 336 [1931]).

Construction of the Delaware system began in 1937 and, after an interruption during World War II, it was completed in 1964 with the opening of the Cannonsville Reservoir >190 km northwest of NYC. Located on the west branch of the Delaware River, the Cannonsville is 1 of 6 large west-of-Hudson (WOH) reservoirs that collectively drain almost 4100 km^2 of land in the Catskill and Delaware watersheds. As in the EOH region, the cost of developing the 6 WOH reservoirs, associated tunnels, and 2 primary aqueducts was high. Billions of dollars were spent, ~2 dozen communities were flooded, almost 6000 people lost their homes, and hundreds of workers lost their lives (Galusha 1999).

Impetus for Change and the Forging of a Partnership

In 1989, the EPA issued the Surface Water Treatment Rule (SWTR; 40 CFR Part 141.70. Title 40 – Protection of environment. Chapter 1 – Environmental Projection Agency, Part 141 – National primary drinking water regulations. [Available from: http://www.access.gpo.gov/nara/cfr/waisidx_02/40cfr141_02.html]), which required all unfiltered public water-supply systems either to provide filtration or to comply with a stringent set of water-quality, operational, and watershed-control standards. The new rule placed NYC in a difficult position. On the one hand, its sprawling supply system, which daily provides >4.5 billion liters of what many believe to be the best drinking water of any large city in the world, was difficult to regulate and control. On the other hand, initial estimates of the cost of building a filtration plant ranged as high as $6 billion, with annual operating costs estimated to be >$300 million, costs that would put enormous pressure on the city's budget (NRC 2000).

In September 1993, the city submitted an application for a waiver from filtration, which the EPA conditionally accepted 3 mo later, but only after adding >150 conditions, most of which involved watershed protection and monitoring programs. Among its most important provisions were the requirements that the city acquire 32,375 ha of land for source-water protection in the Delaware and Catskill watersheds by the end of the century and that it issue revised regulations for protecting the watershed by 30 September 1994.

Both NYC, now through its Department of Environmental Protection (NYC DEP), and New York State, through its Department of Environmental Conservation (NYS DEC), had been involved in oversight of NYC's watersheds for many years, but regulatory enforcement of the system historically had been erratic. In fact, the city had not updated its watershed directives between 1953 and 1989 (Yeats-Thomas 2001). In response to the SWTR and subsequent EPA directives, NYC DEP issued a more stringent set of rules for farmers, homeowners, and businesses. However, the new rules, which seemed to the city to be reasonable, long overdue, and even minimal protections of its water supply, sparked enormous resentment in the watershed communities. Without warning and without consultation, said one watershed resident, the city set out to "lock down the watershed." In particular, to many residents of the WOH watersheds that provide NYC with 90% of its drinking water, the city's action seemed one more example of what they perceived as its dismissive attitude toward the region. Local officials insisted that the new regulations would destroy the character of their communities and further erode the region's vulnerable economy by imposing severe restrictions on residential, agricultural, and industrial land use (Platt et al. 2000). These officials condemned the irony that NYC, perhaps the most urban and developed place on Earth, was seeking to impose a vision of rural preservation on a region that was desperate for economic development.

In 1994, the Coalition of Watershed Towns, an organization representing 34 towns, 9 villages, and 5 counties in the WOH watershed, filed a lawsuit to prevent the city from implementing its plans. The opposition to the set of rules was so determined and so vocal that NYC was unable to move ahead with its efforts to comply with the EPA directive.

The EPA and others were faced with the impasse created by the reaction of the watershed communities to NYC's proposed regulations, and they pressed New York Governor George Pataki to intervene. In April 1995, he brought together representatives of the federal, state, and city governments, the watershed municipalities, and interested environmental organizations and directed them to hammer out a resolution that would move the process forward. On 21 January 1997, they produced the NYC Watershed Memorandum of Agreement (MOA), a 134-page document (plus hundreds of pages of appendices) that reflects both the complexities of the negotiations and the philosophical differences among the signatories. Implementation of the MOA has had its difficulties, but the agreement has fundamentally changed stakeholder relationships in the NYC watershed.

The sheer size of the NYC water system and huge physical and demographic differences among its various parts have inhibited the development of any sense of a unified watershed community over the years. The MOA negotiations brought together all the stakeholders in the water system and asked them to create a single vision for the whole watershed despite that daunting challenge. The ensuing discussions sought to overcome the history of NYC's perceived coercion and exploitation of the outlying areas by recognizing all the parties as voluntary partners in a joint venture. The process did not ignore stakeholder differences. Instead, it tried to forge a consensus based on mutual self-interest and on the long-term needs of all parties.

The pivotal concept in the effort to bring together the city and the watershed communities is the MOA's assertion that "the goals of drinking water protection and economic vitality within the Watershed communities are not inconsistent and it is the intention of the Parties to enter into a new era of partnership to cooperate in the development and implementation of a Watershed protection program that maintains and enhances the quality of the NYC drinking water supply system and the economic vitality and social character of the Watershed communities" (DeBuono and Fox 1997).

For its part, the city committed to spend >$1.2 billion in the watersheds, primarily in the WOH region. The sum is considerably less than the cost of building, maintaining, and operating a filtration plant, but it represents an enormous investment in the upstate communities. It has been, and continues to be, used to acquire land, to make the infrastructure improvements needed to meet water-quality standards, and to spur environmentally sensitive economic development. Of particular note is the ban on the city's use of the power of eminent domain, which had been used in the past to condemn and clear land for reservoir basins. The threat of its use in the future caused the Coalition to refuse further negotiation without the assurance that eminent domain was off the table. Instead, the purchase of both fee title and easements would be on a "willing buyer/willing

TABLE 1. Comparison of the New York City drinking-water-supply system with other cities using surface-water resources for drinking water. Unless otherwise indicated, sources are rivers. F = forest, A = agriculture, R = residential, U = urban, M = mining, I = industry, WW = water and wetlands, L = livestock, SS = septic systems, WWTP = wastewater treatment plant.

City	Population serviced (ind. × 10^6)	Water delivered (L × 10^6/d)	% from surface sources	Major surface sources	Public ownership
Atlanta, Georgia	4	2465	99	Chattahoochee, Etowah, Flint, Oconee, Ocmulgee	Little to none
Boston, Massachusetts	2.5	869	100	Quabbin/Ware, Wachusett/Sudbury	~60%
Chicago, Illinois	5.1	3780	100	Lake Michigan	Little to none
Dallas, Texas	1.9	1898	100	Trinity, Sabine	Little to none
Greenville, South Carolina	0.3	231	100	North Saluda, Table Rock Reservoir, Lake Keowee	100% of Table Rock Reservoir and North Saluda
Los Angeles, California	3.9	2328	86	Sacramento, San Joaquin Delta, Eastern Sierra Nevada, Colorado	Little to none
New York City	8.5	4574	>99	Catskills/Delaware/ Croton river systems	~27%
Philadelphia, Pennsylvania	1.6	1021	100	Schuylkill, Delaware	Little to none
Phoenix, Arizona	1.4	771	96	Salt, Verde, Colorado, Agua Fria	Little to none
Portland, Oregon	0.8	401	90–100	Bull Run	100%
Seattle, Washington	1.3	571	90–100	Cedar, Tolt	100%

[a] Olson 2003
[b] USEPA 2004

seller" basis, and NYC would pay full taxes on the land and easements it acquired. In addition, it would not seek to buy land in hamlets that WOH municipalities had designated off limits.

For their part, the representatives of the watershed communities agreed with the other signatories on the need "to assure the continued adequate supply of exceptional quality drinking water" for 9 million people in and around NYC. They also agreed that "the NYC water supply is an extremely valuable natural resource that must be protected in a comprehensive manner" (DeBuono and Fox 1997).

Developing a Watershed Management Program

The NYC DEP is responsible for delivering water to end users in the NYC metropolitan area, for the quantity and quality of the water it delivers, and for monitoring and managing the source areas and distribution system. State and City authorities, however, own or have under their protection only ~27% of the source-water area (primarily areas around major reservoirs as well as the Catskills Park and Forest Preserve). The remaining lands are under private ownership (NRC 2000). There are few cases in the US where the surface water-source watersheds of a larger municipality are completely under city, state, or federal control (Table 1). Most urban suppliers take water from systems in which only a small percentage of the land is legally protected, and the source-water areas for many large cities extend across several states, which further complicates protection efforts.

The NYC DEP relies on the ecological integrity of the source areas, the natural settling process in its reservoirs (to remove particles), and chlorine disinfection at intake points (to inactivate pathogens), to provide high-quality drinking water to NYC consumers. It is critical that these factors be understood and plans be developed to minimize future degradation because human activities in the source-water areas have the potential to degrade water quality. Most large municipal water suppliers in the US have comprehensive watershed-management plans and monitoring activities (e.g., MDC 2000, CH2MHILL 2003, WRBU 2004) but, to our knowledge, none conducts studies that integrate data on stream function (e.g., stream metabolism and nutrient uptake), aquatic community structure (macroinvertebrates), and ion, nutrient, and molecular tracer chemistry of tributaries to reservoirs/intakes. This integration, and the inclusion of ecosystem-level variables along with direct and indirect (tracer) measures of potential contaminants, distinguishes the Project from all other watershed management and monitoring programs.

Surface-water quality and drinking-water quality historically have been regulated under different frameworks. The 1972 Federal Water Pollution Control Act (amended in 1977, when it also became known as

TABLE 1. Extended.

Land use or potential source of contaminants[a,b]	Filtration	Chlorine disinfection	Other disinfection	Reference
43% F, 16% A, 16% R	Yes	Yes	Yes	Jordan, Jones, and Goulding 2003 CH2MHILL 2003
~78% F and WW, 7% A, 8% R	No	No	Yes	MWRA 2004
WWTP, A	Yes	Yes	No	DWM 2004
A	Yes	No	Yes	DWU 2003
F; limited access	Yes	No	Yes	GWS 2003
Source-dependent; U, SS, WWTP, L, M	Yes	Yes	Yes	LADWP 2003
See within	No	Yes	No	NYC DEP 2004a, b
70% F, 17% A, 10% WWTP, M, R, and U	Yes	Yes	No	PWD 2003
A, U, R, I	Yes	Yes	No	PWSD 2003
F; limited access	No	Yes	No	BWW 2003
F; limited access	Partial	Yes	Yes	SPU 2003

the Clean Water Act [CWA]) has been the primary regulatory mechanism for "…restoration and maintenance of chemical, physical, and biological integrity of the Nation's waters" to insure the protection of fish, shellfish, wildlife, and recreation. The NYS DEC conducts statewide water assessments and research to satisfy provisions of the CWA. The state impaired waters list (EPA's 303d list required by the 1972 CWA) currently includes 9 lakes/reservoirs and 3 streams in the NYC source-water areas; impairments include Hg, PCBs, P, or silt/sediment-related issues (Table 2).

The EPA regulates drinking-water standards under the 1974 Safe Drinking Water Act (SDWA), which requires assessment, control, and prevention measures against biological and chemical contamination of drinking water. A 1996 amendment to the SDWA additionally requires states to develop and implement source-water-assessment programs. At present, the SWTR mandates filtration unless a supplier can demonstrate that: 1) its source-water quality is exceptional, 2) fecal coliform concentrations and turbidity are below certain thresholds, 3) disinfection achieves 99.9% deactivation of *Giardia* and viruses and does not create disinfection byproducts in excess of certain levels, and 4) the supplier has an active watershed-management program.

To comply with these rules, NYC DEP has developed a comprehensive watershed-management program that includes water-quality monitoring, best management practices (BMPs) for stormwater treatment, septic system and municipal waste treatment plant upgrades, land acquisition, and agricultural management programs. As a result, NYC DEP has been able to avoid filtration for the Catskills/Delaware (WOH) portion of the water supply (NYC DEP 2004a). However, it was unable to avoid filtration of waters taken from the Croton/Kensico (EOH) system (NRC 2000), and NYC DEP is currently building a water-treatment plant that is scheduled for completion in 2011 (NYC DEP 2004b). Furthermore, in response to a possible rule change in 2005 (EPA's Long Term 2 Enhanced Surface Water Treatment Rule), NYC DEP has designed an ultraviolet treatment plant for the Catskills/Delaware system to improve control of microbial pathogens.

Objectives and Design of the Project

The Project had 4 primary objectives: 1) to create a quantitative baseline of selected physical, chemical, and biological characteristics of source-water streams and reservoirs for use in assessing future changes in the quality of NYC drinking water and the integrity of the associated aquatic ecosystems, 2) to include in the baseline factors that are sensitive to human impact, are reproducible, and lend themselves to unconfounded analyses among sampling sites and times, 3) to integrate temporal and spatial change in both the level of selected contaminants and the structure and function of biological communities and ecosystems to assess whether impairment impacts the ability of the

Table 2. Water bodies in the New York City drinking-water source areas on the New York State 2004 Section 303(d) List (28 January 2004). Streams included in our study are in bold. All reservoirs except Cross River and Boyd Corners were included in our study (Bott et al. 2006). PCB = polychlorinated biphenyls, TMDL = total maximum daily load, STP = sewage treatment plant, WTS = water treatment system.

Waterbody	County	Type	Cause/pollutant	Source	Year of listing
Part 1: Individual waterbody segments with impairments requiring TMDL development					
Schoharie Reservoir	Greene	Reservoir	Silt/sediment	Erosion, construction	1998
Ashokan Reservoir	Ulster	Reservoir	Silt/sediment	Streambank erosion	2002
Upper Esopus Creek	**Ulster**	**River**	**Silt/sediment**	Streambank erosion	1998
Part 2b: Multiple segment/categorical (fish consumption) waterbodies requiring TMDL development					
Schoharie Reservoir	Schoharie	Reservoir	Hg	Atmospheric deposition	1998
Boyd Corners Reservoir	Putnam	Reservoir	Hg	Atmospheric deposition	1998
Cross River Reservoir	Westchester	Reservoir	Hg	Atmospheric deposition	1998
Rondout Reservoir	Ulster	Reservoir	Hg	Atmospheric deposition	1998
Ashokan Reservoir	Ulster	Reservoir	Hg	Atmospheric deposition	1998
Neversink Reservoir	Sullivan	Reservoir	Hg	Atmospheric deposition	2002
Pepacton Reservoir	Delaware	Reservoir	Hg	Atmospheric deposition	2002
Cannonsville Reservoir	Delaware	Reservoir	Hg	Atmospheric deposition	2002
Upper Trout Creek and tributaries	**Delaware**	**River**	**PCBs**	Contaminated sediment from landfill disposal	2002
Part 3a: Waterbodies requiring verification of impairment based on new methods					
Lower Hallocks Mill Brook	**Westchester**	**River**	**P**	Municipal STP	2002
Lake Carmel	Putnam	Lake	P	Onsite WTS	2002
Delisted waters that were previously listed					
Pepacton Reservoir	Delaware	Reservoir	Pathogens	Onsite WTS	1998
Upper West Branch Delaware and tributaries	**Delaware**	**River**	**P**	Agricultural runoff	1998

streams to provide ecosystem services related to water quality, and 4) to provide additional direction and perspective to the overall watershed-management plan for the NYC source-water area. Thus, data collected from the Project would provide the basis to assess: 1) the current status of water quality and aquatic ecosystem structure and function in response to ongoing and historical land use, BMP implementation, and other factors, and 2) the response of ecosystems and water quality to future changes in watershed activities and conditions.

The Project was designed as a broad synoptic survey, to be repeated annually, that focuses on among-stream variability. All major source-water watersheds were included in the Project. This broad synoptic approach avoids 2 serious problems associated with a spatially focused/seasonal approach: 1) pseudoreplication, where multiple samples taken throughout the year from a given stream represent only one stream and one watershed; and 2) serial autocorrelation, where repeated measures of the same variable (e.g., baseline chemistry, macroinvertebrates) during the year tend to be correlated with one another through time and, therefore, are not independent.

The Project was implemented as a 6-y project composed of 2 distinct 3-y phases. In Phase I (reported here), 60 sampling stations were established on streams distributed among major subwatersheds of the principal source watersheds (Fig. 1). The 60 sampling stations were designated as either *targeted* ($n = 50$) or *integrative* ($n = 10$), depending on their location in the watershed, the type of variables being measured, and the monitoring frequency. Targeted stations were situated throughout the watersheds on streams of varying size. Integrative stations were situated sufficiently downstream to integrate effects of land use and other factors on a given project element or task under study over a large portion of the watershed although, in some instances, downstream distance was constrained by stream size. Sampling stations also were established on 8 reservoirs. Integrative stations were paired with reservoirs to permit statistical evaluation of linkages between a reservoir's influent stream and reservoir state (i.e., productivity).

Site-selection criteria deliberately incorporated the range of land uses/covers across the geologic and soil characteristics of all NYC source watersheds. Study watersheds ranged from completely forested with low human population densities to completely urban with high human population densities (Arscott et al. 2006a). Secondary site-selection criteria included presence of US Geological Survey stream gauging stations, site access, and feasibility of conducting certain study components (particularly stream solute injections). The scientific strengths of the project were the number of elements measured, the spatial scope of the study (60 stream and 8 reservoir sites), and its replication over 3 y. The papers in this series report the results of Phase I. The Stroud Center's full report to NYS DEC covering this time period can be accessed online at www.stroudcenter.org/research/nyproject/.

Elements of the Project

The Project includes 8 major elements. Results from any one element build upon results from others because a high degree of integration exists among several groups of these elements. Some elements involve targeted measures (i.e., snapshots in time and space), whereas others are integrated across space and time. We designed the Project elements to provide a holistic view of stream and reservoir water quality and the potential watershed factors governing or affecting water quality at the sites. The sampling time was optimized for each element (e.g., spring for macroinvertebrates, summer/autumn for nutrient spiraling, etc.) to maximize the utility of the element as an independent assessor of water quality and as a covariate in the integrative analysis. Additional covariates measured outside the Project (e.g., detailed account of climate, hydrology, and geology for the study region) were incorporated into the overall analysis for a comprehensive analysis of land use/cover variability among the study sites (Arscott et al. 2006a).

Project elements and rationale

Nutrients and major ions in transport.—Concentrations of nutrients and major ions transported in streams can be useful indicators of ecosystem health or impairment within the context of geochemical conditions, particularly when monitored over time and across complex landscapes. In addition, major ions and nutrients can be used to quantify and predict changes in water quality in response to changes in land use. Major ions and nutrients were monitored in study streams under baseflow (Dow et al. 2006) and stormflow conditions. Major ions included cations (Na^+, Mg^{2+}, Ca^{2+}, and K^+), anions (SO_4^{2-}, Cl^-), nutrients (various forms of N and P), as well as alkalinity, pH, and conductivity. Nutrients and major ions associated with storm flows were sampled at 3 stream sites, each of which was selected to represent one of the 3 major land uses/cover types found in the study region: agriculture, urban/suburban, and forest. Results of the stormflow element are not reported in this issue because it was designed as a 6-y study.

Organic particle dynamics.—Organic particle (suspended solids) dynamics indicate the ability of a stream ecosystem to process organic matter, provide a link between the upstream generation of organic energy and its transfer downstream, and yield an estimate of C loading to downstream reservoirs. The concentration, size, distribution, and transport of organic particles under baseflow conditions were studied at all 60 stream sites and during stormflow conditions at the 3 stormflow sampling sites (Kaplan et al. 2006).

DOC and BDOC dynamics.—Dissolved organic C (DOC) is an indicator of organic loadings to streams and of terrestrial processing (e.g., in the soil, forests, and wetlands) of organic matter. In the absence of extensive wetlands, bogs, or swamps, baseflow concentrations of DOC in undisturbed watersheds generally range from ~1 to 3 mg C/L (Allan 1995). Higher concentrations suggest sources of organic pollution, such as point sources from sewage treatment plant discharges or nonpoint-source runoff from urban or rural landscapes. The biodegradable DOC fraction (BDOC) consists of organic molecules that heterotrophic bacteria can use as a source of energy and C. Within the context of drinking-water quality, some subset of DOC constitutes the precursor of disinfection byproducts, and BDOC constitutes the nutritional resources that can contribute to biological regrowth within water-distribution systems. DOC and BDOC were monitored during baseflow conditions at all 60 stream sites (Kaplan et al. 2006), during stormflow conditions (DOC only) at the 3 stormflow sampling sites, and in the 8 reservoirs.

Molecular tracer analysis.—Molecular tracers are a broad group of organic compounds in the aquatic environment that are unique to various contaminant sources. The use of such tracers is an emerging technology that qualitatively links the presence of a particular contaminant in a stream or river to a specific source (including atmospheric deposition) in the upstream watershed. Tracers used in the project included: fragrances (found in household products such as detergents) and caffeine, which are used to indicate the presence of wastewater treatment plant (WWTP) or septic effluent; fecal steroids, which track animal (farm or wildlife) and human contamination; and polycyclic aromatic hydrocarbons (PAH), which target urban/suburban and atmospheric sources of contamination (Aufdenkampe et al. 2006). Sampling for tracers occurred primarily during summer baseflow conditions, although a subset of stream sites (28 of the 60) also was monitored in winter. Storm flow was sampled for tracers during spring, summer, and autumn at the 3 stormflow sampling sites.

Macroinvertebrate community structure and function.—Benthic macroinvertebrates provide important reach-specific information but, unlike samples of molecular tracers, major ions, and nutrients, they also provide information on ecosystem services and an extended temporal perspective regarding ecosystem health and water quality because the organisms: 1) have limited mobility and relatively long life spans (e.g., a few months to a year or more for some species), 2) respond to a wide variety of environmental changes and stresses, and 3) are an important link in the aquatic food web (Barbour et al. 1999). Thus, the presence or conspicuous absence of certain macroinvertebrate species at a site is a meaningful record of environmental conditions during the recent past, including ephemeral events that might be missed by assessment programs that rely only on periodic sampling of water chemistry. Macroinvertebrates were studied at all 60 stream sites and were sampled during the first few weeks of May (Arscott et al. 2006b, Kratzer et al. 2006). Therefore, the taxa collected were near the end of their 6- to 9-mo growth cycles, so their presence and abundance reflect conditions extending back several months before their collection date.

N, P, and DOC spiraling.—N, P, and carbohydrates tend to be taken up and recycled several times as they move downstream in a river system. This cycling and the simultaneous downstream transport are sometimes referred to as nutrient spiraling. Spiraling length represents the distance the average nutrient atom travels as it completes one cycle of use (i.e., passing from a dissolved available form, through one or more metabolic transformations, and returning to a dissolved available form). Spiraling reflects the degree of metabolic activity in the stream ecosystem, the ability of the system to retain nutrients, and the relative use rates (hence degree of nutrient limitation) among different nutrients. Spiraling represents a fundamental measure of stream ecosystem function because spiraling length also describes the scale at which upstream processes are linked to downstream processes. Newbold et al. (2006) hypothesized that ecosystem impairment is likely to increase spiraling length (reduce the cycling intensity) through reduced uptake, excessive loading, or decreased retentive ability of the ecosystem, and tested this hypothesis by measuring spiraling lengths of N, P, and C (DOC as glucose and arabinose) in the 10 integrative stream sites during baseflow conditions.

Net stream metabolism.—Stream metabolism was assessed concurrently with nutrient spiraling at the 10 integrative stream sites (Bott et al. 2006b). Stream metabolism measurements provide data on 2 fundamental ecosystem functions: primary productivity and community respiration. Gross primary productivity (GPP), which is measured and reported as g O_2 m^{-2} d^{-1}, represents a measure of the rate of synthesis of plant (primarily algal) biomass by the stream. Respiration (g O_2 m^{-2} d^{-1}) is an index of the breakdown of reduced chemical energy, including the metabolic costs of photosynthesis. These functional attributes are expected to relate principally to biomass of algae, heterotrophic microorganisms and, to a lesser extent, macroinvertebrates. Actual rates also are influenced by environmental variables including light, temperature, and dissolved and particulate nutrients. Changes in activity or in the balance of activity over time would be an important indicator that watershed activities are affecting ecosystem function in a stream entering a reservoir (Bunn et al. 1999), and they would consequently indicate a need for follow-up monitoring work on upstream tributaries.

Reservoir primary productivity.—Primary productivity was measured in 8 reservoirs (Bott et al. 2006a) to provide an upstream–downstream link between the reservoir proper and primary influent streams (where primary productivity also was measured) feeding the reservoir. If a major tributary contributes a significant amount of nutrients to its reservoir, then reservoirs would rank in the same relative order as their tributaries based on metabolic activity. If they do not rank similarly, and the pattern has been sustained over a period of years, we would infer that nutrients from other sources (or reservoir morphology or other physical characteristics) were more important regulators of metabolic activity than nutrients from the primary tributary. As with the influent streams, a change in activity over time would suggest that watershed changes are affecting processes in the system. Algal productivity and community respiration in the reservoirs were quantified by measuring changes in dissolved O_2 in the light and dark in each reservoir (g O_2 m^{-2} d^{-1}). Measurements were done during the summer to facilitate comparisons between streams and reservoirs.

To aid the reader, Appendix 1 lists the following papers in the series and the data sets used in each paper, and Appendix 2 lists frequently used acronyms in the series.

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APPENDIX 1. Papers in the series (in order of appearance) and the data sets associated with them. The 10th paper (Sweeney et al. 2006) is a summary and has no associated data sets.

Authors	Title	Primary data sets presented	Secondary data sets analyzed or referenced
Arscott et al. 2006a	Landscape template of New York City's drinking-water-supply watersheds	Characteristics of 60 stream study sites (Figs 1 and 2, Table 1) Land use/cover (Figs 6–9, Table 2) Precipitation (Figs 3 and 4) Discharge (Figs 3 and 4, Table 1, Appendix Fig. A) Watershed characteristics (geology, population density, road density, stream network density, lake density, and point-source discharges) (Figs 6–9)	None
Dow et al. 2006	Relating major ions and nutrients to watershed conditions across a mixed-use, water-supply watershed	Summer baseflow water-column ion and nutrient chemistry (Figs 1 and 2, Table 3)	Land use, watershed characteristics (Arscott et al. 2006a)
Kaplan et al. 2006	Organic matter transport in New York City drinking-water-supply watersheds	Summer baseflow water-column organic matter (dissolved organic C, biodegradable dissolved organic C, total suspended solids, and particulate organic matter) (Figs 1–3, Tables 1–3)	Land use (Arscott et al. 2006a) Benthic chlorophyll *a* (Kratzer et al. 2006) Fecal steroids (Aufdenkampe et al. 2006)
Aufdenkampe et al. 2006	Molecular tracers of soot and sewage contamination in streams supplying New York City drinking water	Summer baseflow water-column molecular tracers (polycyclic aromatic hydrocarbons, fecal steroids, caffeine, and fragrance materials) (Figs 1–5)	Land use, watershed characteristics (Arscott et al. 2006a)
Kratzer et al. 2006	Macroinvertebrate distribution in relation to land use and water chemistry in New York City drinking-water-supply watersheds	Spring baseflow benthic macroinvertebrates (Figs 2, 4, and 6) Benthic chlorophyll *a*, benthic organic matter	Land use, watershed characteristics (Arscott et al. 2006a) Ion and nutrient chemistry (Dow et al. 2006)
Arscott et al. 2006b	Role of rarity and taxonomic resolution in a regional and spatial analysis of stream macroinvertebrates	None	Benthic macroinvertebrates (Kratzer et al. 2006) Land use, watershed characteristics (Arscott et al. 2006a) Ion and nutrient chemistry (Dow et al. 2006)
Newbold et al. 2006	Uptake of nutrients and organic C in streams in New York City drinking-water-supply watersheds	Solute injections (Tables 1–3)	Molecular tracers (Aufdenkampe et al. 2006) Land use (Arscott et al. 2006a) Benthic macroinvertebrates (Kratzer et al. 2006) Ecosystem metabolism (Bott et al. 2006a)
Bott et al. 2006b	Ecosystem metabolism in streams of the Catskill Mountains (Delaware and Hudson River watersheds) and Lower Hudson Valley	Ecosystem metabolism (Table 1)	Land use (Arscott et al. 2006a) Molecular tracers (Aufdenkampe et al. 2006) Ion and nutrient chemistry (Dow et al. 2006) Organic matter (Kaplan et al. 2006) Benthic macroinvertebrates (Kratzer et al. 2006) Solute injections (Newbold et al. 2006)
Bott et al. 2006a	Primary productivity in receiving reservoirs: links to influent streams	Reservoir primary production (Tables 1 and 2)	Ecosystem metabolism (Bott et al. 2006) Land use, watershed characteristics (Arscott et al. 2006a)

APPENDIX 2. Variable names and abbreviations used throughout this special series.

Abbreviation	Definition	Location or 1st introduced
1k	Reach-scale (30-m riparian buffer on either side of the upstream network, truncated at 1 km upstream)	All, Arscott et al. 2006a
1MP	1-methyl phenanthrene	Aufdenkampe et al. 2006
2MP	2-methyl phenanthrene	Aufdenkampe et al. 2006
aCOP	Cholestanol (5α-cholestan-3β-ol)	Aufdenkampe et al. 2006
AFDM	Ash-free dry mass	Kratzer et al. 2006
AHTN	Galaxolide	Aufdenkampe et al. 2006
ALK	Total alkalinity	Dow et al. 2006
ANT	Anthracene	Aufdenkampe et al. 2006
aONE	Cholestanone (5α-cholestan-3-one)	Aufdenkampe et al. 2006
A_s	Cross-sectional transient storage area	Newbold et al. 2006
A_s/A	Transient storage	Newbold et al. 2006
b	Riparian-scale (30-m riparian buffer on either side of the entire upstream network)	All, Arscott et al. 2006a
BAA	Benz(a)anthracene	Aufdenkampe et al. 2006
BAP	Benzo(a)pyrene	Aufdenkampe et al. 2006
BBF	Benzo(b)fluoranthene	Aufdenkampe et al. 2006
B–C	Bray−Curtis similarity	Arscott et al. 2006b
bCOP	Coprostanol (5β-cholestan-3β-ol)	Aufdenkampe et al. 2006
BDOC	Biodegradable dissolved organic C	Kaplan et al. 2006
BKF	Benzo(k)fluoranthene	Aufdenkampe et al. 2006
BOD	Biological O_2 demand	Bott et al. 2006a, b
BOM	Benthic organic matter	Bott et al. 2006b
bONE	Coprostanone (5β-cholestan-3-one)	Aufdenkampe et al. 2006
CAF	Caffeine	Aufdenkampe et al. 2006
CCA	Canonical correspondance analysis	All
Chl *a*	Chlorophyll *a*	Kaplan et al. 2006
CHOL	Cholesterol (cholest-5-en-3β-ol)	Aufdenkampe et al. 2006
CHR	Chrysene	Aufdenkampe et al. 2006
COMM	% commercial	All, Arscott et al. 2006a
COND	Specific conductance (reference temperature = 25°C)	Dow et al. 2006
CONF	% conifer forest	All, Arscott et al. 2006a
CR_{24}	Community respiration (24-h period)	Bott et al. 2006a, b
CROP	% cropland	All, Arscott et al. 2006a
DECD	% deciduous forest	All, Arscott et al. 2006a
DOC	Dissolved organic C	Kaplan et al. 2006
DOM	Dissolved organic matter	Kaplan et al. 2006
DON	Dissolved organic N	Dow et al. 2006
EBD	East Branch Delaware River	All
EMC	East and Middle Branch Croton River	All
EOH	East of Hudson River water-supply region	All
EPI	*Epi*-coprostanol (5β-cholestan-3α-ol)	Aufdenkampe et al. 2006
EPT	Ephemeroptera, Plecoptera, Trichoptera	Kratzer et al. 2006
ESP	Esopus Creek	All
FLR	Fluoranthene	Aufdenkampe et al. 2006
FLU	Fluorene	Aufdenkampe et al. 2006
FM	Fragrance materials	Aufdenkampe et al. 2006
FMST	% farmstead	All, Arscott et al. 2006a
FS	Fecal steroids	Aufdenkampe et al. 2006
GPP	Gross primary production	Bott et al. 2006a, b
GRAS	% grassland	All, Arscott et al. 2006a
HBI	Hilsenhoff Biotic Index	Kratzer et al. 2006
HHCB	Tonalide	Aufdenkampe et al. 2006
HMW	High molecular weight	Aufdenkampe et al. 2006
INDU	% industry	All, Arscott et al. 2006a
I_s	Saturation light intensity	Bott et al. 2006a, b
KSC	Kensico Reservoir and south of New Croton Reservoir	All
LCOD	Upstream lake category (see Table 2 in Dow et al. 2006)	All, Arscott et al. 2006a
LDNS	Upstream lake density (ha/km^2)	All, Arscott et al. 2006a
LMW	Low molecular weight	Aufdenkampe et al. 2006
LUPS	Area of 1st upstream lake (ha)	All, Arscott et al. 2006a

APPENDIX 2. Continued.

Abbreviation	Definition	Location or 1st introduced
MBRH	% mixed brush-grassland	All, Arscott et al. 2006a
MFOR	% mixed forest	All, Arscott et al. 2006a
MNC	Muscoot River and north of New Croton Reservoir	All
NDM	Net daily metabolism	Bott et al. 2006a, b
NVR	Neversink River and Rondout Creek	All
ORCH	% orchard	All, Arscott et al. 2006a
OURB	% other urban	All, Arscott et al. 2006a
PAH	Polycyclic aromatic hydrocarbon	Aufdenkampe et al. 2006
PAR	Photosynthetically active radiation	Bott et al. 2006a, b
PCB	Polychorinated biphenyl	Aufdenkampe et al. 2006
PDNS	Population density	All, Arscott et al. 2006a
PHE	Phenanthrene	Aufdenkampe et al. 2006
PhoticDepth	Photic depth	Bott et al. 2006a
PhoticTemp	Photic temperature	Bott et al. 2006a
PI	Photosynthesis–irradiation	Bott et al. 2006a, b
PMA	Percent Model Affinity	Kratzer et al. 2006
PN	Particulate N	Dow et al. 2006
POC	Particulate organic C	Kaplan et al. 2006
POM	Particulate organic matter	Kaplan et al. 2006
PP	Particulate P	Dow et al. 2006
PS_{max}	Photosynthetic maximum	Bott et al. 2006a, b
PYR	Pyrene	Aufdenkampe et al. 2006
RA	Relative abundances	Arscott et al. 2006b
RDNS	Road density	All, Arscott et al. 2006a
RESD	% residential	All, Arscott et al. 2006a
RPD	Relative % differences	Aufdenkampe et al. 2006
SCH	Schoharie Creek	All
SD	Standard deviation	All
SDNS	Stream network density (m/km^2)	All, Arscott et al. 2006a
SHRB	% shrubland	All, Arscott et al. 2006a
SKN	Soluble Kjeldahl N	Dow et al. 2006
SNOL	Ethyl-cholestanol (24-ethyl-5α-cholestan-3β-ol)	Aufdenkampe et al. 2006
sPAH	Sum of soot PAHs	Aufdenkampe et al. 2006
SPDE	Mean annual watershed-area-normalized State Pollution Discharge Elimination System effluent volume (cm^3/cm^2)	All, Arscott et al. 2006a
SPDE#	Total number of point-source dischargers in upstream watershed area	All, Arscott et al. 2006a
SRP	Soluble reactive P	Dow et al. 2006
S_w	Nutrient uptake length	Newbold et al. 2006
TCS	Titicus, Cross, and Stone Hill rivers	All
TDN	Total dissolved N	Dow et al. 2006
TDP	Total dissolved P	Dow et al. 2006
TEMP	Water temperature at time of chemical collection	Dow et al. 2006
TKN	Total Kjeldahl N	Dow et al. 2006
TMDL	Total maximum daily load	Aufdenkampe et al. 2006
TN	Total N	Dow et al. 2006
TOC	Total organic C	Kaplan et al. 2006
TP	Total P	Dow et al. 2006
TRAN	% transportation	All, Arscott et al. 2006a
TSS	Total suspended solids	Kaplan et al. 2006
U	Uptake flux of a nutrient or organic solute (mass per unit streambed area per unit time)	Newbold et al. 2006
U_{max}	Maximum uptake flux	Newbold et al. 2006
V_f	Uptake velocity	Newbold et al. 2006
v_{hyd}	Hydraulic exchange velocity	Newbold et al. 2006
vPAH	Sum of volatile PAHs	Aufdenkampe et al. 2006
v_w	Water velocity	Newbold et al. 2006
VSS	Volatile suspended solids	Bott et al. 2006b
W	Watershed scale	All, Arscott et al. 2006a
WBC	West Branch Croton River	All
WBD	West Branch Delaware River	All
WETL	% wetland	All, Arscott et al. 2006a

APPENDIX 2. Continued.

Abbreviation	Definition	Location or 1st introduced
WOH	West of Hudson River water-supply region	All
WOHcat	West of Hudson River in the Catskill Mountains	Dow et al. 2006
WOHdel	West of Hudson River in the Delaware River watershed	Dow et al. 2006
WQS	New York State Department of Environmental Conservation (NYS DEC) macroinvertebrate water-quality score (multimetric index described in Kratzer et al. 2006)	Kratzer et al. 2006
WTSH	Watershed area (km^2)	All, Arscott et al. 2006a