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BRIDGES

BRIDGES is a recurring feature of J-NABS intended to provide a forum for the interchange of ideas and information between basic and applied researchers in benthic science. Articles in this series will focus on topical research areas and linkages between basic and applied aspects of research, monitoring, policy, and education. Readers with ideas for topics should contact Associate Editors Nick Aumen and Ashley Moerke.

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Enhanced source-water monitoring for New York City: summary and perspective

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Abstract. Distributing 4.5 billion liters of clean fresh water every day to >9 million New York City (NYC) and suburban residents and countless other users is an enormous task that is made even more difficult by the aspiration to supply that water without filtration. To accomplish that task with a sense of confidence requires adequate data to: 1) gauge the quality of water in the source streams, 2) measure changes in that quality over time, and 3) assess the factors that might contribute to future degradation. The primary goal of the Stroud Water Research Center's large-scale enhanced water-quality monitoring project (the Project) described in the papers in this special series was to create a baseline of water quality and ecosystem health for the streams and reservoirs that provide drinking water to NYC and to relate current conditions to land use/cover. The results show that streams and rivers located west of Hudson River (WOH) deliver good to very good water to most of the receiving reservoirs. The project confirmed the eutrophic condition of the WOH Cannonsville reservoir and further linked that condition to nutrient inputs from the West Branch Delaware River. The project also confirmed that many streams located east of Hudson River (EOH) had fair to poor water quality and that streams in the Croton and Kensico watersheds were biologically and functionally degraded. Streams in some parts of the WOH region appear to be on a trajectory toward conditions already present in streams in the EOH region. Anthropogenic changes in land use from forested to agricultural in the WOH region have affected water chemistry, macroinvertebrate community structure, and stream function, although the impact is less than that caused by changes in land use from forested to urban in the EOH region. Understanding the processes of change in both regions should improve conservation, restoration, and best management practices by revealing the causes of problems, the extent and nature of those problems, and the type of landuse conditions that lead to water-quality degradation. The addition of novel parameters such as nutrient spiraling and whole-stream metabolism to traditional biomonitoring tools has established a new bridge between basic and applied research at the ecosystem level.

Key words: water-quality monitoring, ecosystem function, stream assessment, drinking water, New York.

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Motivation for the Project

The primary goal of the Stroud Water Research Center's large-scale enhanced water-quality monitoring project (the Project) was to provide useful, spatially explicit information about the quality of the physical, chemical, and biological characteristics of the streams and water of the New York City (NYC) water-supply system. The public and the water-supply managers who work on its behalf need to know: 1) the condition of a stream and the quality of its water at a given site, 2) the sources of any degradation, 3) whether environmental laws or regulations are being violated, and 4) how poor water quality can be improved and very good water quality preserved. A secondary goal of the Project was to apply concepts born from basic research to practical problems and real-world issues, and to test and refine research paradigms across a gradient of environmental conditions. We believed—and this project confirmed—that good monitoring grows out of basic research and that basic research can grow from good monitoring.

The Project, although stimulated by mandates associated with the 1997 Memorandum of Agreement to supply drinking water to NYC without filtration (Blaine et al. 2006), ultimately has its origins in the 1974 Safe Drinking Water Act (SDWA), which stipulated that for suppliers to avoid the enormous expense of filtration they must: 1) implement a watershed management program that actively protects water quality, and 2) demonstrate that source waters have low levels of turbidity and fecal coliforms, adequate pathogen control to deactivate *Cryptosporidium* and *Giardia*, and low concentrations of disinfection by-products.

There are many reasons to protect the NYC source watersheds even if the entire supply were to undergo filtration. Regardless of whether a water supply is filtered, strong relationships exist among intensity of human use, water-quality degradation, and the cost of delivering safe drinking water to the public. For example, in a survey of 12 water-treatment plants in Texas, Dearmont et al. (1998) found that utilities processing raw water with organic (primarily pesticides) and inorganic (As, Ba, Pb, Hg, and NO_3^-) contamination paid 28.5% more for treatment than utilities using water without those contaminants, and every 1% increase in raw water turbidity increased treatment costs by 0.25%. In a recent study of the source area of 3 water suppliers, Ernst et al. (2004) determined that each 10% increase in forest cover led to a corresponding ~20% decrease in treatment and chemical costs. Thus, water-quality monitoring may soon be driven as much by economics as by legislation, particularly in light of the growing recognition by utilities that watersheds provide the first stage of drinking-water treatment.

The Project was neither conceived nor constructed to be the ultimate model program for monitoring source drinking waters. Rather, it was designed to complement a large on-going program involving municipal, county, state, and federal regulatory agencies (National Research Council 2000). The Project sought to broaden and deepen the traditional monitoring horizon by: 1) expanding the spatial and temporal scale of analysis of standard variables such as macroinvertebrates, 2) adding new molecules such as cholesterols, fragrance materials, and caffeine to the array of standard chemicals used in monitoring, 3) refining the detection levels of polycyclic aromatic hydrocarbons and other variables, and 4) including ecosystem metabolism and nutrient spiraling in streams and primary productivity in reservoirs as measures of functional integrity.

The Project's team approach was novel in that it allowed extensive and inclusive analyses of a broad range of variables at each site and linked structural and functional measures in its water-quality monitoring program. The project stressed consistency in what was measured, when and where it was measured, who was doing the measuring, and how the measuring was being done. The chemical variables, for example, were measured on simultaneous collections at each site, which allowed us to examine relationships between variables (e.g., dissolved organic C [DOC] vs fecal steroids; Kaplan et al. 2006). Perhaps most important, by linking the physical, chemical, and biological responses of stream water quality and stream ecosystem integrity to land uses in 2 areas with vastly different geologies and anthropogenic impacts, the Project sought to assess the impact of human activities on streams and reservoirs that ranged from pristine to heavily impaired. The result of these efforts is a baseline of environmental data that describes current water quality in representative streams throughout the source-water watersheds and provides a solid foundation for measuring future changes. To avoid duplication, certain elements commonly found in monitoring programs, such as metal and pesticide measurements, are intentionally absent from the Project. The study greatly increased our understanding of the spatial and temporal variations in water quality across the NYC source watersheds, and the papers in this series provide detailed analyses of natural and anthropogenic factors that influence the structural and functional properties of the stream ecosystems in those watersheds.

Primary Results of the Project

The papers in this series describe different aspects of a project designed and executed with the above philosophical approach. Arscott et al. (2006a) set the stage by describing the landscape template for the project and explaining how similarities and differences in land use/cover (hereafter land use) were quantified at the watershed, riparian network, and local reach scales. Their discussion of the differences in the physical setting and human land uses between the WOH and EOH regions established the environmental framework of the project. Dow et al. (2006) built on this framework to address fundamental questions about the relationships among land use, scale, and basic water chemistry. Of particular significance was their ability to tease apart the direct and indirect effects that the complex interaction between geology and human land use has on ion and nutrient chemistry. Kaplan et al. (2006) expanded on this work by examining the impact of both natural and anthropogenic factors on DOC and particulate C concentrations. The key to understanding spatial variation in C concentrations is to overlay point and nonpoint sources of these substances from both human activities and natural sources (especially wetlands). Moreover, the broad spatial coverage and the authors' exploration of interannual variability enabled them to identify background organic C concentrations from sites with low levels of human impacts, which in turn provide regionally specific targets for best management practices.

In the last component of the chemical assessment of water quality, Aufdenkampe et al. (2006) identified potential sources of contaminants by analyzing molecular tracers of PAHs, fecal steroids, fragrance materials, and caffeine across all 60 sampling sites. Their work indicates that traditional analytical methods are insufficiently sensitive to quantify trace organics at concentrations relevant to water-quality degradation, or even to establish criteria for adequately doing so. Their improved method yielded the important observation that absolute concentrations of all the molecular tracers correlated well with most human activity on the landscape. Moreover, their analysis confirmed that even watersheds with minimal human activity at the local scale contain tracers of PAH in significant concentrations, at times in amounts that are considered toxic or near toxic, because of atmospheric deposition.

The chemical aspects of water-quality assessment were integrated with detailed biological studies, including macroinvertebrates at the population and community levels and nutrient spiraling and stream metabolism at the ecosystem level. Based on the abundance and taxonomic composition of the macroinvertebrates provided by Kratzer et al. (2006), we estimate that the average stream in the region had lost ~⅓ of its maximum water-quality score to date, with substantially higher losses in the EOH than the WOH watersheds (41.5% vs 23%). This biological degradation is related to watershed characteristics such as land use, point sources, stream size, and stream type. In addition, Kratzer et al. (2006) tested the strength of community relationships with land use, which they quantified at the reach, riparian, and watershed scales described in Arscott et al. (2006a), and found generally better relationships at the watershed scale. Their ability to remove or partition macroinvertebrate spatial variance attributable to geology enabled Kratzer et al. (2006) to account for systematic differences among watersheds within regions (e.g., Neversink River and Roundout Creek vs West Branch Delaware River). Arscott et al. (2006b) supported the interpretations of macroinvertebrate response to both subtle and strong environmental gradients by documenting the degree to which taxonomic resolution and inclusion of rare taxa added sensitivity to multivariate community analyses.

The structural aspects of biological communities such as macroinvertebrates are commonly used to assess stream health and water quality (Barbour et al. 1999), but whole ecosystem-level measures have not been used, perhaps because doing so is logistically difficult, labor intensive, and expensive. The failure to use ecosystem measures in biomonitoring is surprising because the structure and function of stream ecosystems have been a major focus of basic research since publication of the River Continuum Concept 26 y ago (Vannote et al. 1980), and recent comparisons of terrestrial ecosystems emphasize the importance of the interactions of biodiversity changes, ecosystem function, and abiotic factors (Loreau et al. 2001). Thus, stream ecosystem services (sensu Daily and Ellison 2001) have been linked to stream function, but the relationship among stream ecosystem structure, function, and services remains a little-explored aspect of water-quality monitoring, with the exception of a few recent attempts outside North America (Young et al. 2004, Albal et al. 2005). The Project may be the largest and most extensive attempt reported to date to bring stream ecosystem function into the water-quality-monitoring arena.

Newbold et al. (2006) and Bott et al. (2006b) respectively describe and quantify ecosystem function based on nutrient spiraling and stream metabolism experiments. The experiments were conducted at 10 sites representing a gradient of water-quality conditions and at which all variables included in the Project were measured for 3 y. Both studies effectively linked ecosystem function to land use, macroinvertebrate communities, water chemistry, molecular tracers of contamination, and other variables. Newbold et al. (2006) concluded that stream spiraling was sensitive to human impacts, most clearly through responses to nutrient loadings associated with humans. The authors used a conceptual path analysis to clarify their findings because relationships to land use are complex. Bott et al. (2006b) highlighted the sensitivity of stream primary production to riparian conditions by connecting site differences in stream metabolism to land use and human-generated toxic substances. Bott et al. (2006a) used measures of primary production and standing stock of chlorophyll *a* to make the connection between a reservoir's function and the metabolism of its influent stream, describe reservoir conditions in detail, and relate conditions ranging from oligotrophic to eutrophic to land use in 8 reservoirs. The functional elements of the Project show that unimpacted stream reaches deliver more ecosystem services (i.e., process more dissolved nutrients) than do reaches that have been altered by human activities. This result is consistent with recent research indicating that forested riparian buffers significantly increase the ability of a stream to deliver ecosystem services (Sweeney et al. 2004).

Linking Human Impact, Ecosystem Function, and Stream Ecosystem Services

The connection among human impact, ecosystem function, and the delivery of stream ecosystem services seems obvious, but to date this connection has been a little-tested assumption with regard to stream watershed management, conservation, and restoration. That this connection would be definitively tested in an applied, rather than a basic, research context is an interesting outcome that stems from our decision to apply ecosystem dynamics to water-quality monitoring. We had proposed from the outset that functional measures would add a new and significant perspective to data obtained from chemical transport studies and routine surveys of biological populations and communities. These new measures alert watershed managers that impairment of small headwater streams can quickly impact larger downstream tributaries and reservoirs (Meyer et al. 2003) because a river system is a continuum of connected conditions from the headwaters to the mouth or reservoir inlet (Vannote et al. 1980). Thus, mitigating drinking-water issues such as taste and odor problems, bacterial regrowth in water distribution systems, and costs of filtration must be a watershed-wide effort that extends from protecting the smallest headwater streams to improving wastewater treatment plants on large rivers.

As the papers in this series show, there is no single prescription for a water-quality monitoring program. Its scope must vary with its goals and objectives as well as with the size and nature of the watersheds. However, certain key issues will arise in every program: 1) the consideration of spatial scale and hierarchical frameworks (sensu Frissell et al. 1986), 2) the complication of coupled natural and anthropogenic variation (sensu Allan 2004), 3) the value of measuring seemingly redundant variables, and 4) the importance of using methods that are sensitive enough to detect concentrations of contaminants well below established criteria. In addition to those issues, the series emphasizes that monitoring projects should be designed to evaluate current conditions and simultaneously to create a baseline for measuring future change. Thus, the ongoing NYC enhanced monitoring effort represents a significant long-term investment in the city's drinking-water supply system by both New York State Department of Environmental Conservation and the US Environmental Protection Agency. The papers in this series describe an initial return on the investment. It is an investment that will continue to grow as Project elements are re-investigated in the future to determine how the quality of streams, rivers, and their fresh water have responded to the execution of the watershed management plan (NYC DEP 2004).

One of the most innovative and important results of the Project has been the infusion of basic research into the arena of traditional monitoring. The addition of novel variables such as nutrient spiraling and whole-stream metabolism has established a new bridge between basic and applied research, and it has done so at a new level—the ecosystem. Likewise, expanding the use of molecular tracers and pushing their detection limits to the femtogram level have brought a significant tool to the effort to protect the quality of fresh water. Global population is projected to reach 8.5 billion by 2025. Thus, the issues discussed in this series resonate well beyond the NYC source watersheds, for the protection and restoration of the world's increasingly vulnerable sources of fresh water require the continued application of basic research findings to watershed monitoring programs.

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