Ultra-urban baseflow and stormflow concentrations and fluxes in a watershed undergoing restoration (WS263)

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ABSTRACT

We discuss the results of sampling baseflow and stormwater runoff in Watershed 263, an ultra-urban catchment in west Baltimore City that is undergoing restoration aimed at both improving water quality as well as the quality of life in its neighborhoods. We focus on urban hydrology and describe the high baseflow and stormwater nutrient, metal, bacterial and other pollutant concentrations and loads seen in two 15 ha headwater storm drain catchments within WS263 that were sampled from 2004 to 2010.

These data revealed several potentially important implications for watershed restoration efforts. First, the underground, or "buried stream" baseflow loads can be substantial, even relative to the surface urban runoff loads in highly impervious urban catchments. Second, the large pollutant load exports from these residential catchments suggest that older, highly urban landscapes may be important hotspots, as these small headwater catchments are numerous in the urban landscape. Third, the complex nature of the pollutant export patterns at the Baltimore and Lanvale catchments, both spatially and temporally, suggest that there may be complex drivers involved. Since this complexity may involve one or more systems of urban water networks, conceptualization in terms of the Urban Watershed Continuum (Kaushal and Belt, 2012) may be a useful tool to use both in their characterization and in designing interventions. Lastly, if these small headwater catchments truly represent a larger typology in terms of being hotspots, the characterization and mapping of older ultra-urban catchments may well be worthwhile given the large numbers of potential analogues in the urban landscape and the likely increasing role of aging infrastructure in creating more and larger "unseen" pollutant loads.

KEYWORDS

Urban runoff, buried streams, stormwater management, ultra urban landscapes, leaking water and sewer pipes, micro-BMPs, urban and community forestry.

INTRODUCTION

Watershed 263 (WS263) is an ultra-urban landscape in west Baltimore city that is undergoing comprehensive, long-term watershed restoration. The name WS263 had its origin as the 263rd of 355 stormwater outfalls slated for inclusion in Baltimore City's NPDES MS4 stormwater permit application. The sampling work described here was in support of a larger WS263 restoration effort that involved many partnerships and was led by the Baltimore City DPW (Department of Public Works), and the Parks & People Foundation (see Hager et al., in-press).

This work is part of a unique collaboration between local government, federal government and a National Science Foundation funded Long-Term Ecological Research (LTER) project that brings together knowledge and experience from urban forestry, stormwater engineering and ecological research in ways that facilitate innovative solutions to stormwater management in ultra-urban watersheds that can also integrate communities and neighborhoods. Such collaborations expand the world view of all concerned, from the technical managers to planners dealing with socio-economic issues in the neighborhood realm. Better understanding of hydrological processes in the urban uplands also contributes to larger scale management concerns, because urban water quality problems are increasingly important far downstream (e.g., the Chesapeake Bay).

The results described here are part of a study of urban hydrologic processes in two small catchments within the WS263 catchment that was led jointly by the Baltimore City DPW and the USDA Forest Service Baltimore Field Station (USFS), with laboratory support from the Cary Institute of Ecosystem Studies (CIES) and the DPW contract lab. We present water quality results from two 15 ha sub-catchments of WS263, the Baltimore and Lanvale Street catchments, at which baseflow and storm runoff was sampled over the course of about 6 years.

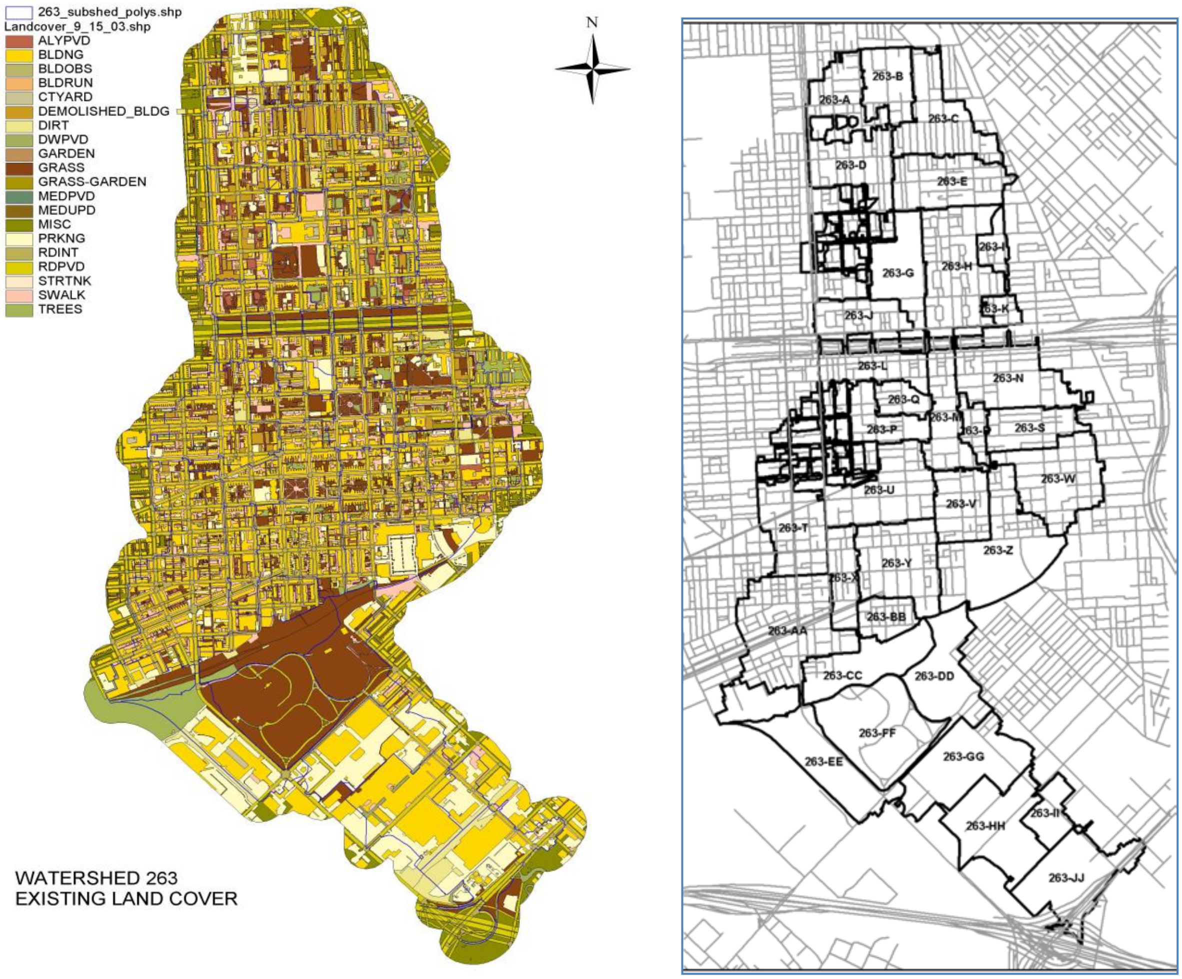

Figure 1. Land cover (left) and catchment areas (right) for the overall WS263 drainage area. The location of the Lanvale (upper) and Baltimore monitoring catchments (lower) are indicated by the higher density of catchment drainage areas on the left side of the catchment figure. Figures are from KCI Technologies, Inc. (2004).

Figure 2. The Baltimore catchment drainage area, with micro-BMP installations (red squares) (left, figure from Center for Watershed Protection, 2005). Photos of "bump-out" curbside micro-BMP and bio-infiltration micro-BMP (right) (K. Belt Photos).

Figure 3. Baseflow in the Baltimore storm drain (left, top). Neighborhood around the manhole used for access for storm and baseflow sampling (K. Belt Photos).

METHODOLOGY

Though houses and people in WS263 have been lost over time due to deterioration and economically challenging times, there is still a large resident population, with 31,000 people within the 376 ha catchment, or 82 people per ha (2000-2005 Census Data, BNIA, Hager et al., in-press). The population density in the two study catchments (U.S. Census Bureau, 2010) is slightly higher, with 93/ha (1399 total) and 65/ha (973 total) in the Baltimore and Lanvale catchments, respectively. These two catchments both have high impervious surface cover (Figure 1), 77% for Baltimore and 68% for Lanvale (CWP 2007 report for Baltimore City DPW). The installations of micro-BMPs (Best Management Practices) and other interventions were concentrated in the Baltimore catchment; the Lanvale catchment did not receive interventions, and served as a control (Figure 2).

Dry weather flow discrete samples were taken manually at bi-weekly or monthly intervals (a monthly interval was adopted ca. half way through the study) to characterize baseflows and facilitate the determination of sources (i.e., groundwater, illicit discharges, etc.). Wet weather flows were sampled with an automated sampler/flow meter, which recorded stage and average velocity continuously (Figure 3). The samplers produced flow-paced (i.e., equal flow volume subsampling intervals) storm sample composites. They were programmed such that a minimum of about 10 subsamples made up each composite to insure full coverage of the hydrograph. Continuously recorded stage and velocity data were used to compute cumulative runoff volumes in real time, which were in-turn used to trigger subsampling events. When the velocity sensor was not available due to a malfunction, the sampler was re-programmed to use Manning's equation in conjunction with the stage data and pipe geometry to continuously compute flow and to pace the sampling. The resulting composite sample therefore represented an event mean concentration (EMC), which is commonly used to characterize stormwater runoff loads. Samples were iced and were retrieved and transported to the lab within 24 hours for sample prep (e.g., filtering), storage and analysis.

A total of 2,460 lab analyses were done for nitrate nitrogen, phosphate phosphorus, sulfate, and total nitrogen and total phosphorus. Most sampling activity was clustered in the first two to four years with a lesser intensity of sampling thereafter due to reduced resources. The number of samples per year ranged from 7 to 46 for dry weather flows, and from 0 to 24 for stormflow composites. Additional parameters were analyzed, e.g., chloride, metals, bacteria, hardness, etc., but are not reported here in detail. For selected nutrient parameters, analyses were run at both the Baltimore City DPW and the CIES labs. This provided QAQC data and a check on the DPW contract lab. It also provided parallel data that could be used to compare directly to samples collected in nearby streams as part of the BES Long-term ecological research project (LTER), for which analyses were done at CIES.

Since equipment problems prevented the consistent collection of high quality flow data, annual flows were estimated from parameters derived from an intensive analysis of seven typical storms at each of the two sites, using rainfall data from nearby BES LTER tipping bucket rain gages, unit value flow data from nearby USGS small stream gages, and NOAA NWS rain gage records from the MD Science Center (Belt and Runyan, 2008). Rainfall-runoff ratios derived from an analysis of the seven storms were different for the two catchments, with Baltimore (0.61), having a much larger value than Lanvale (0.18). At the Lanvale catchment baseflow rates were small, less than 0.01 lps, but were much larger (3.5 lps), at the Baltimore catchment. In fact this rate was similar to a nearby, similarly sized forested catchment (4.2 lps, at USGS gage 01583570, Pond Branch at Oregon Ridge, MD).

RESULTS

Concentrations

Sulfate concentrations showed different temporal patterns and concentrations between the two sites (Figure 4). Baltimore generally had higher SO_4 concentrations than Lanvale for storm runoff, but not baseflow. Temporally, baseflow and stormflow concentrations at the Baltimore site showed significant reductions after 2006, as did phosphorus and nitrogen (see below). The Lanvale site also showed similar trends, although variance made this much less clear for the baseflow data.

Nitrogen concentrations showed distinct temporal patterns and differences between the two sites (Figure 5). Baltimore generally had higher NO_3 N concentrations than Lanvale for both baseflow and storm runoff, notably so for the 2004 to 2006 years. Baseflow concentrations were significantly greater than for stormwater runoff, especially at the Baltimore site. In terms of temporal patterns, the Baltimore site also showed reduced baseflow and stormflow NO_3 N concentrations after 2006, whereas at Lanvale this pattern was less clear (only 2005 and 2006 showed elevated means for baseflow and stormflow concentrations, respectively). Most of the nitrogen was in dissolved form (i.e., as nitrate N). For stormflows the two sites had somewhat similar TN concentrations, although Baltimore was generally a bit higher (except for 2006). Both sites showed a decrease in TN stormwater concentration after 2006, although for the Baltimore site the robustness of this difference hinged on only one sample in 2009. Baseflow concentrations at the Baltimore site showed a clear decrease after 2006. The Lanvale TN concentrations were quite variable initially but seemed to reach equilibrium from 2006 to 2009, with some hint of a decrease in the last year (2010).

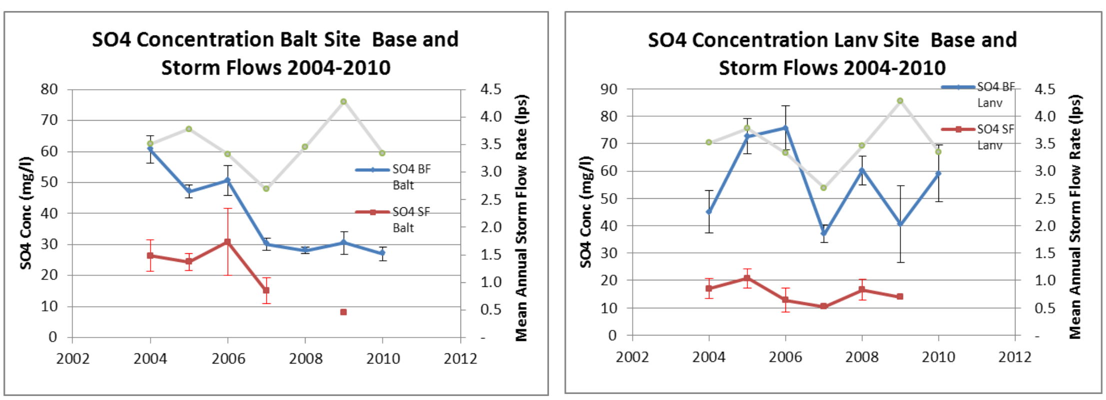

Figure 4. Sulfate concentrations for the Baltimore (left) and Lanvale (right) catchments for baseflow (BF) and stormflow (SF), from 2004 to 2010. Error bars are +/- standard error of the mean. Annual estimates of storm runoff are shown by the gray line.

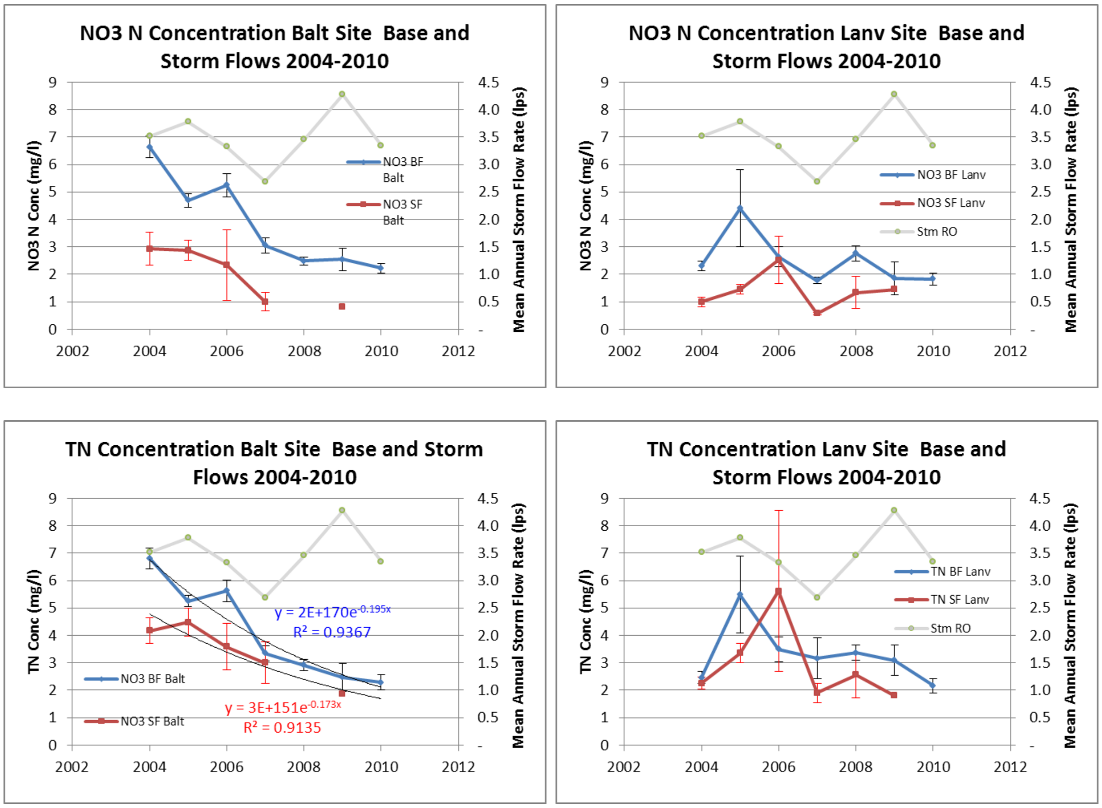

Figure 5. Nitrate N (top) and total nitrogen (bottom) concentrations for the Baltimore (left) and Lanvale (right) catchments for baseflow (BF) and stormflow (SF), from 2004 to 2010. Error bars are +/- standard error of the mean. Annual estimates of storm runoff are shown by the gray line.

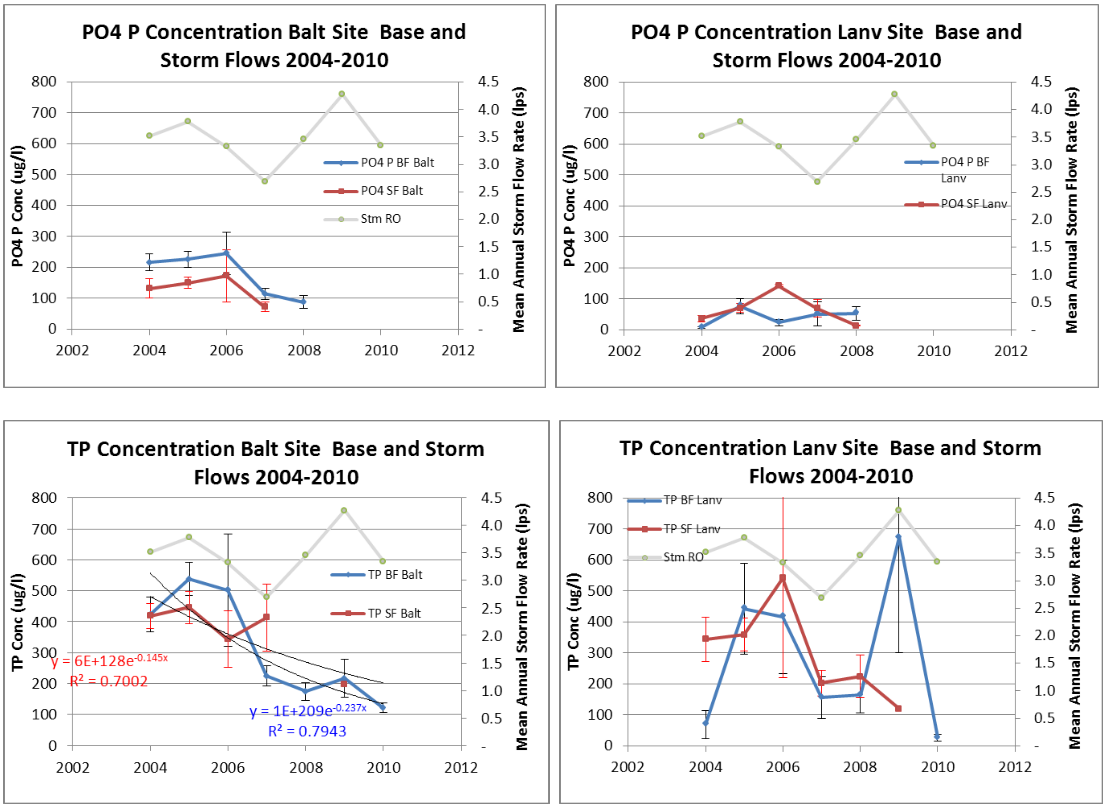

Figure 6. Phosphate P (top) and total phosphorus (bottom) concentrations for the Baltimore (left) and Lanvale (right) catchments for baseflow (BF) and stormflow (SF), from 2004 to 2010. Error bars are +/- standard error of the mean. Annual estimates of storm runoff are shown by the gray line.

Phosphorus concentrations showed interesting temporal patterns and differences between the two sites (Figure 6). Baltimore had higher PO_4 P concentrations than Lanvale for both baseflow and for storm runoff, with baseflow concentrations that were significantly greater than for stormwater runoff. The Baltimore site also showed reduced PO_4 P concentrations after 2006 whereas Lanvale did not. Most of the phosphorus was in particulate form. For stormflows the two sites had similar TP concentrations, although Baltimore was generally a bit higher (except for 2006). Both sites showed a decrease in TP stormwater concentration after 2006, although for the Baltimore site this hinges on only one sample in 2009. Baseflow concentrations at the Baltimore site showed a clear decrease after 2006. Lanvale TP concentrations showed a lot of variability but tracked the trends seen for stormwater in 4 out of the 6 years. The high variance may have arisen from the difficulty of collecting representative baseflow samples from such a small flow rate (i.e., picking up some particulates from the bottom of the pipe).

Concentrations for other parameters also showed differences between storm and baseflow and between the two sites (Figure 7). Storm concentrations for *E. coli*, *Enterococcus*, and Fecal Coliforms were higher than for baseflow. Comparing the two sites, they were higher for the Lanvale site during baseflow but for stormwater runoff the bacterial concentrations were higher at the Baltimore site. Total copper, lead and zinc concentrations were much higher for stormwater runoff than for baseflow at the Baltimore site, but not at the Lanvale site, where they were similar during baseflow and stormflow. Baltimore storm runoff Cu, Pb and Zn concentrations were higher than at Lanvale, but during baseflow were higher than Lanvale only for Cu. BOD concentrations were very high for stormwater runoff at both the Baltimore and Lanvale sites. The baseflow BOD mean concentration at Baltimore was low, but high for the Lanvale site.

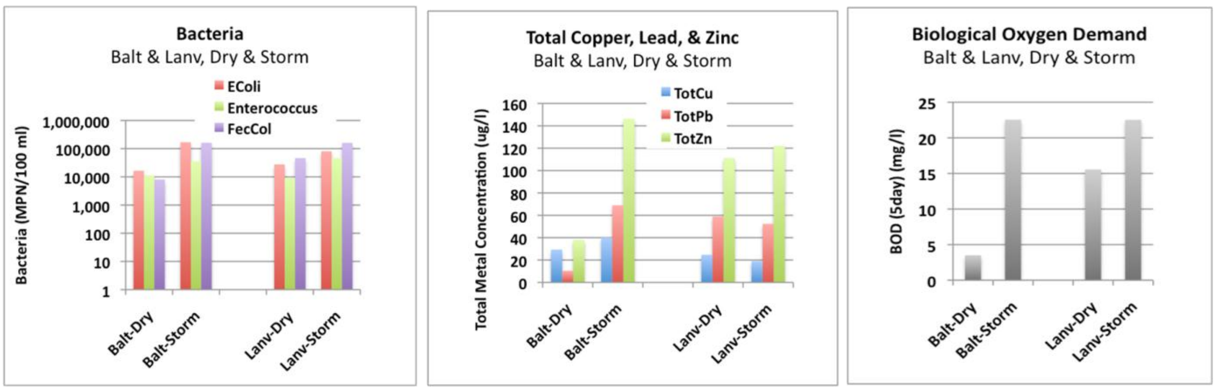

Figure 7. Baltimore and Lanvale catchments, wet (Storm) and dry weather (Dry) flows, for bacterial (left), copper, lead and zinc (middle), and BOD concentrations (right).

Annual Loads

The data also showed important patterns with respect to baseflow vs. stormflow loads (Figure 8). In the Baltimore catchment (with a strong baseflow), half or more of the annual load for SO_4 (71%), NO_3-N (70%), TN (53%), PO_4-P (60%) and TP (37%) was carried in the baseflow, whereas in the Lanvale catchment (which had a very small baseflow), almost the whole load was transported during storm events (ca. 97 to 99 %). Since Lanvale lacked both a strong baseflow and experienced less stormflow runoff, Baltimore had mean total annual loads (across years) that were much greater (e.g., for TN, 57 vs 6.1 kg/ha/yr). This was the case for all of the constituents, and the total mean annual loads at the Lanvale site were 12% or less than those at the Baltimore Site (SO_4 ,7%, NO_3-N,7%, TN 11%, PO_4-P 6%, and TP, 12%).

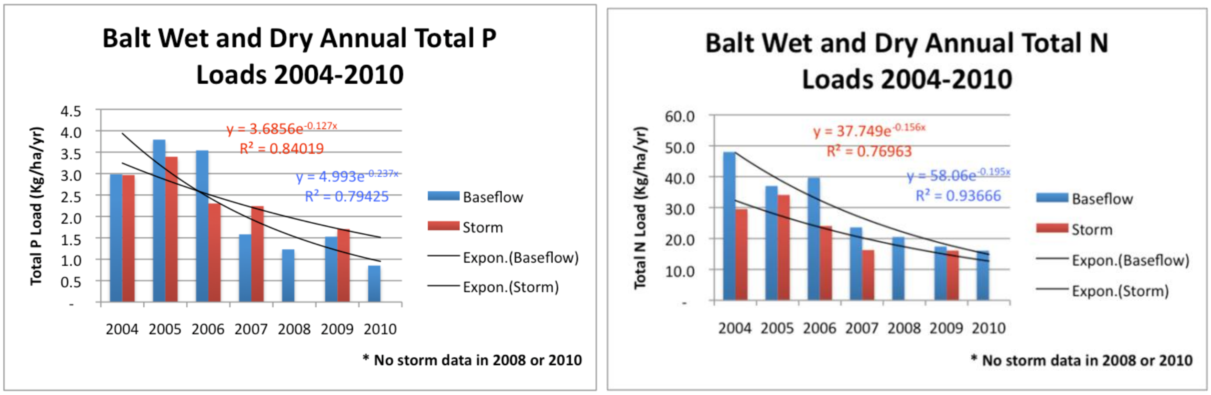

Figure 8. Baltimore wet and dry total phosphorus and total nitrogen loads from 2004 to 2010.

DISCUSSION AND CONCLUSIONS

Annual Loads

The Baltimore loads were very high, on an areal basis (i.e., kg/ha/yr). For example, the TN and TP loads were much greater than loads previously measured for nearby suburban, forested and agricultural small watersheds in the BES LTER network (Kaushal et al, 2008; Duan et al, 2012). For TN they were greater by factors of 6.3, 28.6, and 1.5, and for TP by factors of 10.8, 186 and 21.2, respectively. At the Baltimore site, the baseflow part of the annual TN loads alone were greater by factors of 3.2, 14.4, and 0.7, respectively. To put these baseflow loads into perspective, a leakage rate of 20% of the sewage within the Baltimore catchment could plausibly explain the loading rates for TN and TP (using typical per capita sewage loads). The high concentrations of sulfate, nitrogen, phosphorus, bacteria and BOD do suggest that sewage leaks, either through illicit connections or via contaminated groundwater infiltrating into storm drain pipe joints are playing an important role in the loadings.

The Lanvale loads, even though they did not have a large baseflow component, also had relatively high areal loads compared to the same three BES LTER suburban, forested and agricultural small watershed streams. For TN they were greater by factors of 0.67, 3.0, and 0.16, and for TP by factors of 1.3, 22 and 2.5, respectively.

The Baltimore, and to a lesser extent the Lanvale catchment are “hot spots” for pollutant export, generally with nutrient loads that resembled those of a typical agricultural watershed more than a typical urban or suburban residential watershed.

Ultra-urban Catchment Typology?

Our experiences in these two WS263 catchments, which despite a large loss in population, had large stormwater and dry weather flow pollutant loadings, beg the question of whether old ultra-urban catchments represent a unique type of small headwater catchment. If these catchments are typical of older ultra-urban headwater drainage systems, we may be missing an important source of pollutant loadings in the urban landscape. Much more data is needed to ascertain whether this is the case, but if it is, there would be value in taking a multi-dimensional “urban watershed continuum" approach to characterizing the hydrology of urban watersheds (Kaushal and Belt, 2012) that recognizes the 3 dimensional nature of highly connected urban catchments as well as their propensity to change over time. This framework builds on what we know about the structure and function of urban streams (Paul and Meyer, 2001; Walsh et al., 2005; Wenger et al., 2009) and considering watersheds as three-dimensional entities that include buried streams as well as all of the engineered urban water systems may be a new and useful way to optimize management efforts when below ground loads rival those of surface runoff.

Temporal Variance and BMPs (Best Management Practices)
There was a large temporal reduction in concentrations after 2006 at Baltimore, where nutrient concentrations and loads showed a significant reduction (eg.,TP and TN, Figures 5, 6, 8). The annual loads in the latter part of the sampling record (i.e., 2004-2006 vs. 2007-2010) decreased for all constituents by about one third to two thirds, far in excess of load reductions expected from six newly installed stormwater runoff micro-BMPs, which in total only received runoff drainage from 12% of the catchment impervious surface area. So far, conversations with Baltimore City DPW and NGOs (non-governmental organizations) have not revealed any known reason for this reduction (e.g., fixing a sewer leak). This, along with the high below-ground loads for various parameters, suggests that the urban water infrastructure play an important role. In Baltimore City, stormwater outfalls often have baseflows during dry weather whereas upstream catchments in Baltimore County show the opposite trend, with dry weather flows being a relatively rare occurrence (unpublished data). At the BES LTER Rognel Heights storm drain site, there have been periods (e.g., the 1999-2000 water years) when there were consistent dry weather baseflows, even during drought conditions (personal communication, Ed Doheny, US Geological Survey). There were also times when sewage was observed to upwell through cracks in the street surface just above the gage (personal observation). This and the water quality indicated the presence of sewage in the storm drain (BES LTER data). Sewage has been shown to be a common source for nitrate nitrogen in Baltimore streams (Kaushal et al. 2011). In WS263, the magnitude of the below-ground loads and their reductions for both the Baltimore, as well as the Lanvale site (which had no BMPs installed), suggest that sewage leaks and possibly potable water pipe leaks might play an important role, and that there may be a large scale, hydrologic driver involved that caused a change in state (e.g., groundwater levels that were lowered below a critical elevation). Future work aimed at elucidating this will require the use of tracers and isotopes and a detailed analysis of the urban water systems in the area.

It was hoped that the newly installed BMPs (see Hager et al, in-press) in the Baltimore catchment were the reason for the temporal load reductions seen after 2006. However these reductions were far in excess that which could be optimistically expected from the six micro-BMPs installed in the catchment. Moreover, since there was also a large below-ground reduction component, BMPs that infiltrate runoff could not account for this, and might even add to the groundwater quality problems (Clark and Pitt, 2007), if there were flowpaths leading back to the storm drains in a short-circuiting process, so groundwater dynamics may well be important. Furthermore, the magnitude of the loads and their reductions for both the Baltimore, as well as the Lanvale site (which had no BMPs installed) suggest that sewage leaks likely play an important role. These are residential catchments, with no known illicit connections that could account for the high pollutant concentrations, and this adds to the notion that the transfer of these loads to the storm drains are mediated by groundwater flows, and that there may be larger scale, hydrologic drivers involved than single point inputs within the pipes. Certainly urban interactions in the watershed and along stream channels can be complex and create large variances spatially (Kaushal et al. 2011; Sivirichi et al. 2011) and it may be that some of this complexity originates far upstream, in the upland urban water infrastructure.

Ultra-urban Headwater Catchments and Green Infrastructure

This super connectivity between the surface and subsurface in urban catchments may well increase in the future, with the growing interest in "greening" efforts as part of infiltration-based stormwater management programs. Trees and other vegetation perform valuable ecological services in greening efforts, and are used to reduce the impacts of urban runoff on receiving waters. Strong eco-hydrological foundations for stormwater management BMPs such as those in WS263 would likely increase the effectiveness of greening-based watershed management efforts in highly urbanized areas. For example, consideration of urban tree physiological traits such as their ability to transpiration water back into the atmosphere might be important (e.g., Pataki et al., 2011a; 2011b). Removal of soil-water and ground water by urban trees between storms could prevent the infiltration of water into urban basements as well as procure additional soil capacity in stormwater management facilities, maximizing the infiltration of stormwater runoff. At the other end of the management spectrum, the use of trees in stormwater management in ultra-urban neighborhoods opens the door for hands-on interaction by residents in determining people-nature connections, since micro-BMPs become, by design, part of the immediate landscape of residents. These green stormwater facilities might also warrant consideration as an educational resource for schools searching for economical means to conduct field trips and establish inquiry-based science education curricula in the students' own neighborhoods. The engineered water system context for these could open up new frontiers for teaching ecology in ways that are more relevant to students and residents. Such neighborhood-science interactions have already seen interest by the ecological science community, especially at the urban LTER projects (e.g., Pickett et al., 2008, Hager et al., in press) and the use of stormwater facilities is a natural nexus doing research that has both scientific and applied data objectives. The intimacy of these "neighborhood BMPs" might well, through a greening approach to urban stormwater management, pave the way for strengthened connections and interactions between a wide array of people, their natural resource organizations and scientists (Figure 9).

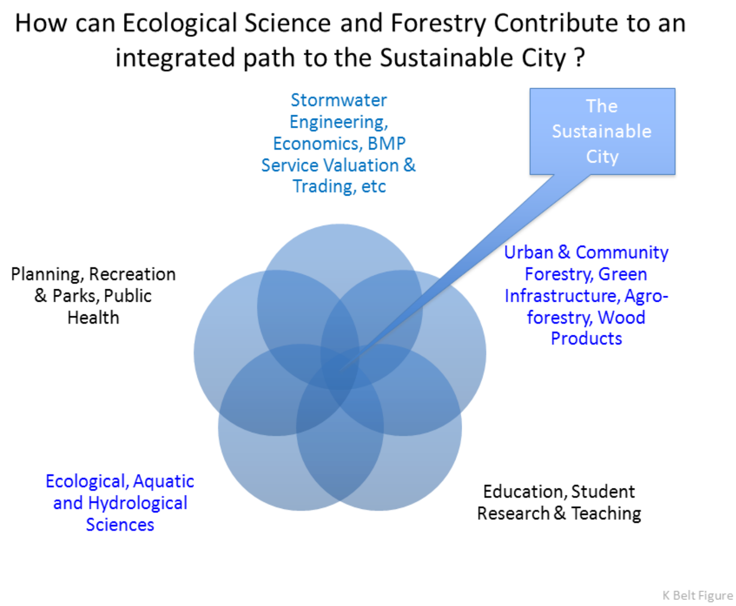

Figure 9. The potential incorporation of ecological science knowledge and approaches to stormwater management efforts in urban areas could encourage diverse groups of professionals to come together to create a more sustainable, integrated approach to stormwater management, as well as stronger community involvement and ownership.

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