Small Streams in Large Cities: Neglected Links in Urban River Networks

J. L. Meyer*, M.J. Paul** and W.K. Taulbee***

* Institute of Ecology and River Basin Science and Policy Center, University of Georgia, Athens GA, USA
(E-mail: *meyer@sparc.ecology.uga.edu*)
** Department of Biology, Howard University, Washington DC, USA
(E-mail: *mikejpaul@hotmail.com*)
*** Department of Biology, University of California, Santa Barbara CA, USA
(E-mail: *taulbee@lifesci.ucsb.edu*)

Abstract
Urban development has resulted in the degradation or elimination of small streams. This has fundamentally altered the ecology of urban river networks. Patterns of human development interact with underlying natural features to impact key aspects of the ecology of small urban streams. We discuss examples of this for stream ecosystems in metropolitan Atlanta, Georgia, USA. Streams in Atlanta differ in their ability to remove nutrients from the water column: phosphorus removal decreases as the amount of fine benthic organic matter decreases and as percent urban land cover in the catchment increases. Less phosphorus uptake implies that more of the phosphorus coming from point and non-point sources is being transported to downstream ecosystems, where it can lead to eutrophication. Subtle differences in the nature of human activities on the landscape can also influence stream ecosystem function. For example, leaf breakdown rates differ in Atlanta streams flowing through catchments that differ in average home value. Human degradation and elimination of small urban streams reduces the quality of urban river networks. Not only do small streams provide society with valuable ecosystem services and influence the ecology of larger rivers, but also they provide a growing part of the human population their first experience with the natural world.

Keywords
Drainage density, ecosystem services, headwaters, nutrient uptake, urban streams

INTRODUCTION

Urban rivers have been a focus of ecological study for decades (e.g., Hynes, 1960), although much of the attention has been on declines in water quality and its ecological consequences in larger rivers. Here we focus on small urban streams that are essential, albeit often unrecognized, elements of urban rivers. The large, navigable urban river being celebrated in this symposium is but one part of an extensive river network, which arises from many small streams. Conditions in the large river reflect the physical, chemical and biological processes that occur in the many small streams comprising the network. These urban streams are fascinating ecosystems worthy of greater ecological attention. Ecological studies in urban streams will not only enhance scientific understanding of flowing water ecosystems, but also provide guidance for stream improvement.

Humans in the 21st century are an increasingly urban species; by 2030 over 60% of the world's population is projected to live in urban areas (U.N. Population Division, 1997). Much of that growth is not occurring in the urban center; over 60% of the U.S. population currently lives in suburbs, and suburbs are projected to account for 80% of future metropolitan growth (Bullard, 2000). Growth of suburbia has resulted in increasing urban "sprawl": the increase in area of urbanized land is greater than the increase in urban population in many regions of the U.S. For example, in the South, human population increased 22% from 1982 - 1997, whereas urbanized land increased 60% (Otto et al., 2002). The pattern in the Northeast is even more striking: population grew only 7% while urbanized land increased 39%. This trend in suburban growth is particularly troubling for waterways, because as urbanized land area increases, the number of small streams impacted by human development also increases.

In this paper we argue that the importance of small streams to larger rivers is not widely recognized, and that these streams are being eliminated as the urban landscape is developed. Loss of these ecosystems results in a loss of ecosystem services, which are the benefits supplied to human societies by natural ecosystems (Daily, 1997). One such service provided by streams is the retention and transformation of excess nutrients.

SMALL STREAMS ARE A VITAL PART OF URBAN RIVER NETWORKS

Mighty urban rivers arise from small streams, which comprise most of the length of channel in the network. For example, for every km of named larger streams in Ohio, there are more than five km of unnamed small tributaries (Ohio EPA, 2002). The fact that so many small streams are not named gives some indication of the value human society places on these ecosystems. As urban development proceeds, small streams are filled or piped and lost from the river network. Drainage density (km stream/km^2 catchment) in Rock Creek, Maryland U.S., decreased by 58% as the catchment was developed over five decades; drainage density decreased because of loss of low order streams in the network (Leopold, 1994). Drainage density in urbanizing catchments in metropolitan Atlanta, Georgia is one-third lower than in forested catchments in the same region (Meyer and Wallace, 2001). These significant losses of stream channels are a product of reasoning that has been called "the tyranny of small decisions" (Odum, 1982). Each individual decision to fill or pipe a stream seems like a small matter; however, the cumulative impact on river networks has been significant.

Ecosystems in metropolitan areas provide valuable ecosystem services that contribute to the quality of urban life (Bolund and Humhammer, 1999). Small streams provide a wide range of ecosystem services that include microclimate regulation, natural flood control, groundwater recharge, sediment retention, removal of excess nutrients and contaminants, and providing recreational opportunities for humans and habitats for unique biota as well as food resources for downstream ecosystems (Bolund and Hunhammer, 1999; Meyer and Wallace, 2001; Gomi et al., 2002). Quantifying the contribution of smaller streams to the ecosystem services provided by river networks offers a research challenge for the future. The experiment described in the next section is an example of the kinds of studies that are needed to better assess the role of urban streams in providing ecosystem services.

ECOSYSTEM SERVICES ARE PROVIDED BY URBAN STREAMS

We know a great deal about how urbanization impacts the physical, chemical and biological attributes of streams, but relatively little about how ecosystem processes are altered in an urban setting (Paul and Meyer, 2001). This is unfortunate because ecological processes such as nutrient uptake provide ecosystem services of value to society including cleansing water of excess nutrients. Small streams are sites for nutrient uptake and retention in river networks (Alexander et al., 2000; Peterson et al., 2001). Since nutrient uptake and retention varies with discharge and biotic activity, the hydrologic and biotic alterations associated with urbanization may result in altered rates of nutrient uptake in urban streams.

The removal of nutrients from flowing water can be quantified by measuring nutrient uptake length, the downstream distance traveled by an average nutrient molecule before it is removed from the water column (Newbold et al., 1981). Uptake length is determined by adding nutrients and a conservative tracer to a stream and using the downstream decline in concentration to determine uptake length (Webster and Ehrman, 1996).

Table 1. Characteristics of tributaries of the Chattahoochee River in which phosphorus uptake length was measured. Landuse information was derived from 1998 Landsat images (Natural Resources Spatial Analysis Lab, University of Georgia). Urban landuse includes high and low intensity urban as well as transportation.

Stream	Order	Catchment area (km^2)	% forest	% urban	Population (humans/km^2)
Snake Creek	3	92	71	7	29
Flat Shoals Creek	3	115	81	4	4
Nickajack Creek	3	54	33	65	876
Sope Creek	4	80	32	65	800
Rottenwood Creek	3	48	23	75	1050
Peachtree Creek	4	221	19	79	1252

Uptake length was measured in six third order streams in the Chattahoochee River network near Atlanta, Georgia, U.S. Two streams flow through forested catchments; the other metropolitan streams vary in extent of urbanization in their catchment (Table 1). Experiments were conducted during four spring and autumn seasons from autumn 1996 through spring 1998 using standard methods (Webster and Ehrman, 1996). Because chloride concentrations were high in the metropolitan streams, we used bromide (NaBr) as a conservative tracer. Bromide, phosphate (K_2HPO_4) and ammonium (NH_4Cl) enrichments were added to the streams over a 1 - 2 hr period with a Watson-Marlowe 504S peristaltic pump (1 L/min) to elevate concentrations two- to three-fold above background. Only phosphate uptake data are reported here. When the conservative tracer had reached plateau, seven sites along a 200 to 750 m reach were sampled below the point of nutrient addition. At each site, water was sampled at five points across the stream channel, filtered in the field, and analyzed for bromide (Dionex 2000i ion chromatograph) and soluble reactive phosphorus (SRP) (Wetzel and Likens, 2000). Stream width and depth was measured at each sampling site, and discharge was calculated from the bromide data. Twelve replicate samples of fine (< 1 mm) benthic organic matter were also taken with a stovepipe corer (0.044 m^2) to a depth of 10 cm in each season in all streams. The mean dilution-corrected SRP concentration at each site was plotted as a function of distance downstream. The negative inverse of the regression line fitted to these points is the uptake length (Webster and Ehrman, 1996). Uptake lengths are reported only for experiments where $p < 0.09$ for the regression. Two of the twelve experiments (17%) in forested streams and eight of the 21 experiments (38%) in metropolitan streams did not meet this criterion. This occurred when there was little change in SRP concentration with downstream distance (i.e. uptake lengths were much longer than the length of our study reach). It is noteworthy that this occurred more often in the metropolitan streams; this is further indication that uptake lengths in those streams were long.

Uptake length increases as stream discharge (Q) increases. Hall et al. (2002) provide data on phosphorus uptake length as a function of specific discharge [Q/width (m^2/min)] in forested streams of New Hampshire, USA. These uptake lengths were measured using the same methods reported here, except chloride was used as the conservative tracer. Data from Hall et al. (2002) are plotted in Figure 1 and used to predict expected uptake lengths in the Georgia streams based on their specific discharge. Most of the uptake lengths measured in forest streams were close to predicted values, whereas uptake lengths in the metropolitan streams were much longer than predicted (Figure 1). The deviation from predicted uptake lengths in the metropolitan streams increased as the percent of urban landuse in the catchment increased ($p < 0.05$). Deviations were also positively correlated ($p < 0.05$) with human population (number/km^2) in the catchment, impervious surface cover, and road density (km/km^2); they were negatively correlated with % forest cover. These variables are all highly inter-related, so it is not possible to attribute longer uptake lengths to a single landuse variable. Standing crop of fine benthic organic matter is one in-stream measure that was negatively correlated with deviations from predicted uptake length (Figure 2) and with urban landuse in the streams (Figure 3). Fine benthic organic matter serves as substrate for biological activity in streams. As catchment urbanization increases and amount of fine benthic organic matter decreases, phosphorus uptake lengths increase.

Longer phosphorus uptake lengths in small streams translate to higher phosphorus concentrations in the stream and in downstream ecosystems. Urban streams frequently have elevated phosphorus concentrations; two-thirds of US urban streams have total phosphorus concentrations above 0.1 mg/L, a level indicating eutrophication (Heinz Center, 2002). Longer uptake lengths imply that more of the phosphorus being added to streams by point and non-point sources is transported further downstream and will end up in larger rivers, reservoirs, and eventually estuaries. Essentially the stream is acting more like a pipe, transporting phosphorus downstream rather than retaining it and converting a highly available form of phosphorus (phosphate) to less available forms in biological tissues or detritus. The negative impacts of excess nutrients are well documented (Carpenter et al., 1998). Excess phosphorus concentrations in water bodies are often attributed solely to increased inputs of phosphorus from the catchment; however, these elevated concentrations occur not only because human activities have increased the amount of phosphorus entering streams, but also because human activities have altered ecological processes in the stream, reducing removal of phosphate from the water column.

VARIABILITY IN URBAN STREAMS

The ecology of streams in urbanizing catchments is a relatively new but rapidly growing field. Urban streams are characterized by altered geomorphology and hydrologic regime resulting from increased impervious surface cover, as well as increased loading of nutrients and contaminants; the combination of changes results in consistent declines in richness of stream biota (Paul and Meyer, 2001). Future insights in urban stream ecology are likely to come from studies that recognize the diversity of urban streams and explore the consequences of differences in the way humans have developed the landscape.

Ecologists studying terrestrial urban ecosystems have begun to explore the ecological consequences of these differences. Rather than simply relating a measure of ecological structure or function to the fraction of the landscape that is urban, as we did with phosphorus uptake lengths, greater explanatory power can be found by looking at the patch structure of urban development as well as socioeconomic and cultural factors such as past history of the watershed, age and type of urban development, lot size and home values (Pickett et al., 2001). The species richness of perennial vegetation in urban areas of Phoenix, Arizona USA, can be related to the socioeconomic status of its human inhabitants (Hope et al., 2003). Plant diversity in this urban area is a function of family income, median housing age, and whether the land had been previously farmed.

Studies in urban streams have only begun to explore how the diversity of human development patterns may influence stream processes. Leaf breakdown rates differ in Atlanta streams flowing through catchments that differ in average lot size and home value (Herbert, 2003). Leaf breakdown rates were greatest in reference streams, declined by a third in catchments characterized by smaller lot size and moderate home value, and declined by another third in catchments with the largest lots and most expensive homes (Herbert, 2003). Another example of stream research considering human development patterns in greater detail can be seen in Melbourne, where Walsh et al. (2001) are exploring changes in biogeochemical processes in streams as a result of different types of stormwater abatement techniques. The relationships between stream ecosystem function and more detailed descriptors of human society such as density and age of housing development or socioeconomic status of inhabitants are fruitful areas for future research.

CONCLUSION

Society neglects and eliminates small urban streams at its peril. Not only do small streams provide humans with valuable ecosystem services and influence the ecology of larger rivers, but urban streams also provide a growing part of the human population their first experience with the natural world. Urban streams can offer children an opportunity for learning and play (Berkowitz et al., 1999). For example, Adopt-A-Stream programs in the US provide students and community members an opportunity to learn about the streams in their neighborhoods and increase awareness of local environments. These programs are growing in number; the state of Georgia currently has over 200 active Adopt-A-Stream groups. Alert and interested citizens offer considerable hope for improvements in urban stream conditions.

Society has viewed urban streams as drains, gutters, ditches, and pipes; streams have been engineered and managed to move water off the landscape rapidly and efficiently. As both scientists and citizens learn more about urban stream ecology, that increased knowledge can be used to manage streams as ecosystems. That change in perspective should result both in improvements in stream conditions and in the ecosystem services provided by urban streams.

REFERENCES

Alexander, R.B., Smith, R.A. and Schwarz, G.E. (2000). Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. *Nature* **403**, 758-761.

Berkowitz, A.R., Nilon, C.H., and Hollweg, K.S. (eds.) (1999). *Understanding Urban Ecosystems: A New Frontier for Science and Education*. Springer, New York.

Bolund, P. and Hunhammer, S. (1999). Ecosystem services in urban areas. *Ecological Economics* **29**, 293-301.

Bullard, R.D. (2000). Anatomy of sprawl. In: *Sprawl City*, R. D. Bullard, G.S. Johnson and A.O. Torres (eds.), Island Press, Washington D.C., pp. 1-20.

Carpenter, S., Caraco, N., Correll, D., Howarth, R., Sharpley, A. and Smith, V. (1998). Non-point pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* **8**, 559-568.

Daily, G.C. (1997) What are ecosystem services? In: *Nature's Services: Societal Dependence on Natural Ecosystems*, G.C. Daily (ed.), Island Press, Washington D.C., pp. 1-10.

Gomi, T., Sidle, R. C. and Richardson, J. S. (2002). Understanding processes and downstream linkages of headwaters systems. *BioScience* **52**, 905-916.

Hall, R.O., Jr., Bernhardt, E.S. and Likens, G.E. (2002). Relating nutrient uptake with transient storage in forested mountain streams. *Limnology and Oceanography* **47**, 255-265.

Heinz Center. (2002). *The State of the Nation's Ecosystems*. Cambridge University Press.

Herbert, S. (2003). *The Impact of Lawncare Practices on Suburban Streams in Metropolitan Atlanta, Georgia.* M.S. Thesis, Institute of Ecology, University of Georgia.

Hope, D., Gries, C., Zhu, W., Fagan, W.F., Redman, C.L., Grimm, N.B., Nelson, A.L., Martin, C., and Kinzig, A. (2003). Socioeconomics drive urban plant diversity. *Proceedings of the National Academy of Sciences* 100: 8788-8792.

Hynes, H.B.N. (1960). *The Biology of Polluted Waters.* Liverpool University Press.

Leopold, L.B. (1994). *A View of the River.* Harvard University Press, Cambridge MA.

Meyer, J.L. and Wallace, J.B. (2001). Lost linkages and lotic ecology: rediscovering small streams. In: M.C. Press, N. Huntly and S. Levin (eds.) *Ecology: Achievement and Challenge*, Blackwell Science, pp. 295-317.

Newbold, J.D., Elwood, J.W., O'Neill, R.V. and VanWinkle W. (1981). Measuring nutrient spiraling in streams. *Canadian Journal of Fisheries and Aquatic Sciences* **38**, 860-863.

Odum, W.E. (1982). Environmental degradation and the tyranny of small decisions. *BioScience* **32**, 728-729.

Ohio Environmental Protection Agency. (2002). *Nonpoint source impacts on primary headwater streams.* State of Ohio Environmental Protection Agency, Division of Surface Water, Columbus, Ohio USA.

Otto, B., Ransel, K., Todd, J., Lovaas, D., Stutzman, H. and Bailey, J. (2002). *Paving Our Way to Water Shortages: How Sprawl Aggravates the Effects of Drought.* http://www.amrivers.org/landuse/sprawldroughtreport.htm.[accessed August 2003]

Paul, M.J. and Meyer, J.L. (2001). Streams in the urban landscape. *Annual Review of Ecology and Systematics* **32**, 333 - 366.

Peterson, B.J., Wolheim, W., Mulholland, P.J., Webster, J.R., Meyer, J.L., Tank, J.L., Grimm, N.B., Bowden, W.B., Vallet, H.M., Hershey, A.E., McDowell, W.B., Dodds, W.K., Hamilton, S.K., Gregory, S, and Morrall, D.J. (2001). Stream processes alter the amount and form of nitrogen exported from small watersheds. *Science* **292**, 86-90.

Pickett, S.T.A., Cadenasso, M.L., Grove, J.M., Nilon, C.H., Pouyat, R.V., Zipperer, W.C., and Costanza, R. (2001). Urban ecological systems: linking terresterial ecological, physical, and socioeconomic compoenents of metropolitan areas. *Annual Review of Ecology and Systematics* **32**, 127 - 157.

U.N. Population Division. (1997). *Urban and Rural Areas, 1950-2030 (The 1996 Revision).* United Nations, New York.

Walsh, C.J., Fletcher, T.D., Wong, T.H.F., and Breen, P.F. (2001). Developing predicitive ecological capacity for a stormwater management decision-making framework. In: *3rd Australian Stream Management Conference Proceedings.* I. Rutherford, F. Sheldon, G. Brierley, and C. Kenyon (eds.), vol. 2, Brisbane Qld, pp. 625-630.

Webster, J.R., and Ehrman, T.P. (1996). Solute dynamics. In: *Methods in Stream Ecology*. R.R. Hauer and G.A. Lamberti (eds.), Academic Press, pp. 145-160.

Wetzel, R.G., and Likens, G.E. (2000). *Limnological Analyses*, 3rd ed. Springer, New York.

FIGURE LEGENDS

Figure 1. Phosphorus uptake length (m) as a function of specific discharge [discharge/stream width (m^2/min)] in three types of streams: New Hampshire USA forest streams (x) (data from Hall et al., 2002), forest streams in Georgia (open circles), and metropolitan streams in Atlanta, Georgia (filled circles). The line is a regression based only on the data from forest streams in New Hampshire ($Y = 4.670 + 0.809\ X$, $p < 0.0001$).

Figure 2. Observed phosphorus uptake length in Atlanta metropolitan streams minus uptake lengths predicted from the equation in Figure 1. Deviations are plotted as a function of log of fine benthic organic matter (g AFDM/m^2). The regression line is $Y = 2251 - 940\ X$ ($p < 0.05$).

Figure 3. Log of fine benthic organic matter (g AFDM/m^2) as a function of % urban landuse in the catchment of six streams in Georgia. The regression line is $Y = 2.127 - 0.011\ X$ ($p < 0.0001$).