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Urbanization and stream ecology: five years later

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The world is becoming ever more urban. More than 50% of the global population currently lives in cities, and the percentage continues to rise (United Nations 2005). Moreover, the rate of conversion of land to urban uses exceeds the rate of population growth. For example, in the US, population increased 17% and urban land use increased 34% between 1982 and 1997 (Alig et al. 2004, United Nations 2005). The increasing ecological footprint of urban areas and the disproportionate burden that these expanding urban areas place on natural ecosystems has fueled a growing interest in sustainability of urban areas (Grimm et al. 2008).

Urban ecology is becoming an integrated scientific discipline that is advancing through interdisciplinary research approaches (Pickett et al. 2008). Urban ecology has attracted academicians and a broad cross-section of politicians, policy-makers, planners, scientists, and others interested in natural resource management (Palmer et al. 2004), and research on urban streams has proliferated (reviewed by Paul and Meyer 2001, Walsh et al. 2005, Wenger et al. 2009). Studies of urban streams have ranged from characterizations of urban impacts (e.g., effects of urbanization on stream fishes) to integrated, management-focused research (e.g., potential to mitigate urban effects by disconnecting stormwater pipes from streams). In response to the growth of urban stream research, scientists from around the world gathered in Melbourne, Australia, in 2003 for the 1st Symposium on Urbanization and Stream Ecology (SUSE) to identify key gaps in our knowledge of urban effects on streams. A subset of papers from that meeting was published in a special issue of the *Journal of the North American Benthological Society* (*J-NABS* 24[3]).

Five years later, in May 2008, the 2nd SUSE was convened in Salt Lake City, Utah. The symposium had 116 attendees from 8 countries, and >30 research talks were presented. A major goal of the meeting was to refine and test the conceptual model of the urban stream syndrome (Walsh et al. 2005) and to identify and prioritize unanswered research questions in urban stream ecology (Wenger et al. 2009). Papers in this special series of *J-NABS* are primarily from that meeting. The authors in this series explored a range of features of a revised conceptual model (Wenger et al. 2009) and tested its predictions on topics including physical/chemical stressors in urban streams, biological responses, and urban stream management. The series combines novel research papers on understudied topics (e.g., aquatic insect dispersal; Smith et al. 2009) and in understudied regions (e.g., tropical streams; Ramírez et al. 2009) with synthesis papers that compile research results from various spatial contexts (Brown et al. 2009). Together, the papers highlight differences in the urban stream syndrome

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around the world, thereby helping us to understand the spatial and temporal drivers of variable urban stream responses.

The urban stream syndrome is characterized by geomorphic and hydrologic alterations to streams (Walsh et al. 2005). These changes typically include increased flashiness, channel enlargement, and reduced base flow. However, increased flashiness of flows, one of the most consistently reported signals of the urban stream syndrome, was not a strong factor in urban streams in tropical Puerto Rico (Ramírez et al. 2009). Urban-induced channel enlargement also was not found in Puerto Rico (Ramírez et al. 2009) and was variable among streams in 9 US metropolitan areas (Brown et al. 2009). This variation probably is the result of differences in rainfall, physiography, geology, engineered modification of channels, landuse legacies, or phase of urban development among urbanizing catchments. Moreover, reduced base flow as a result of reduced infiltration was not observed by Roy et al. (2009), who demonstrated an increase in perennial stream length in urban areas, presumably because of decreased water abstraction via transpiration in deforested urban areas. Roy et al. (2009) also explored a feature of the urban stream syndrome, loss of headwater streams through burial and piping, that was not emphasized in the original model of Walsh et al. (2005).

Other stressors examined by authors of papers in this series were generally consistent with the urban stream syndrome model. Increased stream temperature was observed in the tropical streams of Puerto Rico (Ramírez et al. 2009). Elevated salinity was reported from New Hampshire, where road deicers are applied in winter, although the authors suggest that differences in climate and corresponding hydrologic alteration can affect the severity of abiotic shifts in the urban environment (Daley et al. 2009). Altered riparian cover typically leads to reduced terrestrial leaf inputs to streams, but Roberts and Bilby (2009) reported a shift in riparian forest composition from coniferous to deciduous trees and a resultant increase in N and P loading to streams in the Puget Lowland of the northwestern US.

Biological responses to urbanization range from broadly consistent to highly variable or understudied. Algal assemblages respond inconsistently to urbanization (Walsh et al. 2005, Brown et al. 2009). Brown et al. (2009) suggested that algae respond to water chemistry, which varies spatially in response to historical land cover (e.g., forest vs agriculture) and current land use, and varies temporally in response to frequency of storms. Responses of fish assemblages to urbanization also are variable. Fish assemblage composition was explained by urban density in only 4 of 9 US metropolitan areas studied by Brown et al. (2009). Weak relationships in some metropolitan areas probably were a result of landuse legacies, particularly from agriculture (Brown et al. 2009). Fish assemblages in Puerto Rico were unaffected by urban land use, possibly because native fishes in Puerto Rican streams are diadromous, and this life-history trait might permit escape from or tolerance of unfavorable conditions (Ramírez et al. 2009). In contrast, loss of sensitive macroinvertebrate species is a consistent response to urbanization (Brown et al. 2009, J. Carter et al. 2009, Helms et al. 2009, Ramírez et al. 2009, Steuer et al. 2009, Walsh and Kunapo 2009). Brown et al. (2009) and J. Carter et al. (2009) reported absence of macroinvertebrate resistance to low levels of urbanization, but Walsh and Kunapo (2009) suggested that mitigation of urban impacts would be possible if hydraulically efficient stormwater flow paths were altered. Smith et al. (2009) explored the potential effects of urbanization on terrestrial life-cycle stages of aquatic insects (e.g., emergence, adult survival, migration, and recruitment) and found that limited dispersal among streams in urban areas could negatively affect restoration potential. Combined, these results highlight the variability in ecosystem responses and continued need for research directed at understanding mechanisms of response in the urban stream syndrome (Wenger et al. 2009)

Authors of some papers in this series described ways to elucidate mechanistic links between stressors and responses. Steuer et al. (2009) identified small-scale hydraulic metrics as strong correlates of macroinvertebrate assemblage composition and posited that hydraulic metrics should be stronger indicators than larger-scale hydrologic metrics. The multimodel inferential approach used by Walsh and Kunapo (2009) demonstrated the utility of spatial modeling of hydrologic flow paths from impervious surfaces and septic tanks for mechanistically linking urban sources of stress with instream responses in macroinvertebrate assemblages and bacterial and N concentrations. These and other novel approaches to identifying proximate causes of ecosystem responses are essential to guide effective and efficient management strategies.

The studies in this series advance the field of urban stream ecology by highlighting variability in stressors and responses of the urban stream syndrome, but we still lack the tools to prescribe management strategies for attaining desired ecosystem states (Wenger et al. 2009). Some recent research has focused on use of macroinvertebrate assemblages to guide management practices in urban streams. Seasonal change in macroinvertebrate assemblages was smaller in urban than in nonurban streams (Helms et al. 2009). Thus, macroinvertebrate samples collected at any time of the year might be useful for assessing urban impacts. J. Carter et al. (2009) described a new approach to screening macroinvertebrate metrics and used biological potential (defined by quantile regression using the 90th percentile regression line) to assess the relative condition of sites on a local scale. T. Carter et al. (2009) presented experimental designs that could be used to evaluate the relative effectiveness of low-impact development practices, best management practices, and adaptive management approaches that promote protection or restoration of urban streams. Stream ecologists and managers must work together to use up-to-date scientific knowledge and tools to create effective ecological solutions for maintaining stream functions in this urbanizing world.

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