# Effects of Urbanization on Stream Ecosystems

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## ABSTRACT

Studies on the effects of urbanization on stream ecosystems have evolved from documenting impacts to attempting to understand the driving factors responsible for stream conditions. In 1999, the U.S. Geological Survey's National Water-Quality Assessment Program initiated a series of pilot studies to assess the effects of urbanization on physical habitat, biotic assemblages (algal, fish, invertebrate), and water chemistry. The relations among varying intensities of basin urbanization and stream ecology were investigated in three metropolitan areas of the United States: the humid Northeast around Boston, Massachusetts, the humid Southeast around Birmingham, Alabama, and the semiarid West around Salt Lake City, Utah. Of the 28 physical variables describing channel morphology, hydraulic properties, and streambed conditions examined, none were significantly correlated with urbanization intensity in all three study areas. Urbanization effects on stream habitat were less apparent for streams in Salt Lake City and Birmingham due to influence of basin slope (Salt Lake City) and climate (drought in Alabama) on modifying hydrology of streams. In urban streams, the relative abundance of pollution-tolerant algal species was higher than in the less impacted streams. Of the various structural attributes of the algal assemblages investigated, species composition changed along gradients of urban intensity in a more consistent manner than algal biomass or diversity. Fish species richness decreased significantly with increasing urbanization in Birmingham and Boston (fish were not sampled in Salt Lake City due to low native diversity). Percent endemic species richness decreased significantly with increasing urbanization only in Birmingham, whereas percent fluvial specialist species decreased significantly with increasing urbanization only in Boston. Nearly linear patterns (no threshold response) were observed in Birmingham. Threshold responses were observed in Boston, with periodic increases and decreases in species richness along the urban gradient. Invertebrate communities exhibited similar and strong responses to urbanization in Boston and Birmingham. Although responses were evident in Salt Lake City, they were confounded by extensive hydrologic modifications in the basin and a strong elevation gradient associated with development along the Wasatch Range. Effect thresholds for invertebrate assemblages at 5-18% total impervious surface area have been reported previously, however, the results did not indicate that an effect threshold exists at low levels of urbanization.

## INTRODUCTION

The link between urbanization of a watershed and changes in hydrology, geomorphology, water quality and ecology are well documented. Reviews of hydrologic and geomorphic effects of urbanization can be found in Leopold (1968), Hammer (1972), and Graf (1975). More comprehensive reviews including impacts to water quality and stream biota can be found in Klein (1979), Heaney and Huber (1984), and Pitt (2002).

Urban stormwater pollution contributes greatly to the overall degradation of our Nation's waters. Urban lands represent only a small component of human-engendered landscape alteration in the United States (US), but these lands have a disproportionate effect on stream health. It is estimated that an urbanized basin impairs three times the length of stream that would be impaired by a similar amount of agricultural land (Natural Resources Conservation Service, 2000; U.S. Environmental Protection Agency, 2000). The extent of urbanized land also is increasing rapidly. Consequently, urbanization is an important source of stream impairment for streams in the US, and will continue to increase for the foreseeable future. Understanding how urbanization affects physical, chemical, and biological characteristics of streams and the similarities and differences in these effects throughout the US is important for managing and protecting aquatic resources.

The purpose of this paper is to provide an overview of the evolution of approaches used to document impacts of urbanization on stream ecology, highlight critical design elements incorporated into the U.S. Geological Survey's National Water Quality Assessment (NAWQA) Program urban land-use studies, and provide some initial results of pilot studies. The elements incorporated into the NAWQA studies are designed to support moving beyond documenting impacts to determining the intensity of development that brings about ecological change and identifying the interaction of stressors and environmental factors that drive the processes that result in stream degradation.

## EVOLUTION OF APPROACHES

The effect of urbanization on stream ecology is the result of interrelated impacts of hydrology, water quality, and habitat. Early studies relating urban effects to changes in biological communities were conducted in cities where sanitary sewage is a large component of runoff. The impacts of urban stormwater runoff, independent of the effects of sewage and industrial effluents, have only come to be recognized in recent decades (Heany and Huber, 1984). The number of urban stream studies has increased substantially in recent years, and the effects of urbanization are well documented for selected urban areas (Paul and Meyer, 2001; Pitt, 2002). Most of these studies have documented a degradation of biological communities associated with increases in urbanization with urban streams characterized by the high abundance of a few tolerant taxa.

A few studies have used historical data to assess urban impacts. Wichert (1994, 1995) noted that although some improvements in fish community structure were associated with point-source controls, fish communities in heavily urbanized streams were dominated by a small number of tolerant species. An analysis of three streams near Seattle, Washington showed two urbanized streams had greater flood frequencies and a declining trend in numbers of spawning salmon compared to a forested watershed. Wang et al. (2000) compared watershed land-use and fish community data collected between the 1970s and 1990s and found that the numbers of fish species per site and metrics of fish community health were consistently low in watersheds with greater that 10% impervious surface in the basin. He concluded that although agricultural land uses often degrade stream fish communities, agricultural land impacts generally are less severe that those from urbanization.

Due to the lack of and difficulty in obtaining historical data collected with comparable methods in a sufficient number of watersheds, an increasing number of studies have utilized a space-for-time or gradient approach. The gradient approach is accomplished by studying a number of watersheds with different urban land-use intensities. Utilizing a space-for-time approach, Finkenbine et al. (2000) found urban watersheds in Vancouver, British Columbia, to have less fine material and slightly higher values of intragravel dissolved oxygen than rural streams. Overall stream quality in terms of supporting fish communities was lower in urban areas because of uniformly low summer base flow and scarce large woody debris. Sonneman et al. (2001) and Walsh et al. (2001) found diatoms and macroinvertebrates to be sensitive indicators of urban-derived impacts. Roy et al (2003) found taxa richness and other biotic indices were negatively related to urban land cover in the Etowah River basin, Georgia. The results were consistent over a range of basin sizes from 15 to 100 km2. Fitzpatrick et al. (2004) used two approaches to examine the effects of urbanization on biotic integrity. Historical fish community data was examined for historical trends and compared to urban growth. This historical approach was supplemented with an examination of biotic integrity at 43 streams having a wide range of urban land and population density. Fish and macroinvertebrate index of biotic integrity (IBI) scores ranged from poor to excellent in agricultural/rural streams, but streams with more than 10% watershed urban land had fair or poor index scores. A qualitative habitat index did not decrease with increasing urban land use.

## GRADIENT DESIGN

Investigation of responses to a gradient of urban land-use intensity requires a specific design in order to succeed. Careful thought must be given to defining the gradient of interest and then, through careful site selection, controlling for other gradients (e.g., gradients of natural features such as climate, geography, soil characteristics, stream size, hydrologic variability) so that they do not overwhelm the land-use (anthropogenic) gradient of interest. This is particularly important for ecological studies since many natural gradients (e.g., elevation, stream size, and climate) are known to have dramatic effects on the distribution of organisms even in the absence of anthropogenic influences.

In both the Sonneman and Walsh studies data analysis was confounded by differences in natural watershed characteristics known to influence species distribution. Roy et al. (2003) analyzed invertebrate functional group changes and environmental variables to determine important driving differences. The results of a non-metric multidimensional scaling ordination were highly related to slope. Fitzpatrick et al. (2004) found different responses in the number of intolerant fish species and in basins with loamy/sandy deposits compared with clayey surficial deposits. These results highlight the importance of increasing the signal-to-noise ratio (urban-to-environmental factors) by minimizing the impact of factors that influence species distributions.

Understanding and comparing urban effects on streams and associated aquatic assemblages can also be complicated by how urban influences are quantified or defined (e.g., human population density, percent urban land, percent impervious area, etc.). Most studies have used a single measure of urban intensity such as population density, percent urban land, and percent imperviousness (Arnold and Gibbons, 1996) to interpret responses to urbanization. Yoder and Rankin (1996), however, noted that interpretation of ecosystem effects could vary depending on which single measure was used to quantify urban effects. Although impervious area was commonly used to represent urban intensity, Arnold and Gibbons (1996) and Karr and Chu (2000) suggested that impervious area alone does not account for all aspects of urbanization. Patterns of development within a metropolitan area are a function not only of the amount of developed land, but also of differences in infrastructure (e.g., roads, sewers, stormwater drainage), human population, and socioeconomic (e.g., income, housing) characteristics (McMahon and Cuffney, 2000). Multimetric indices have been used to describe the overall condition of complex systems (Karr and Chu, 1999) and land-use intensities (Ometo et al., 2000; Morley and Karr, 2002). A multimetric indicator of urban intensity combines individual condition measures that provide distinct information about the different dimensions of complex systems (McMahon and Cuffney, 2000). This approach aids integration of multiple, commonly used sources of information about the urban landscapes such as land cover, infrastructure, population, and socioeconomic variables into a single measure of urban intensity index (McMahon and Cuffney, 2000; Cuffney et al., 2000).

Although it is widely documented that urban streams are degraded, there is little scientific understanding of how anthropogenic stressors interact to drive the patterns and processes that result in stream degradation. In addition, the degree to which stream ecosystems respond or are susceptible to anthropogenic stressors engendered by urbanization varies as a function of the natural environmental setting. In order to address the wide range of urban landscapes across the Nation and to evaluate relations between responses and landscape features, it is necessary to evaluate the impacts of urbanization across areas with different watershed characteristics. This is especially important with regard to landscape characteristics that influence flow generation and subsequent transport in the watershed. There has been, however no nationally scaled scientific study of factors that influence the degree to which streams are at risk of degradation by stressors from urbanization. As a result, water-quality managers will continue to be faced with investing more public resources to mitigate or restore beneficial uses to streams affected by urban land uses without having the scientific information useful to understanding the ecological consequences of their choices.

## NAWQA URBAN LAND-USE STUDIES

In 1999, NAWQA initiated a series of pilot studies that used a common design to examine the regional effects of urbanization on aquatic biota (fish, invertebrates, and algae), physical habitat, and water chemistry. These urban land-use gradient studies were conducted in three metropolitan areas: Boston, Massachusetts area (a humid, cool, gently rolling environment in the Northeast); Birmingham, Alabama area (a hot, humid, ridge and valley environment in the Southeast); and Salt Lake City, Utah area (a cool, semi-arid, mountainous environment of the intermountain West. Based on knowledge gained during these pilots, additional studies were initiated or are planned (Couch and Hamilton, 2002). Hydrologic landscape regions (Winter, 2001) and ecoregions (Omernick, 1987) were used to evaluate environmental settings across the US to select potential areas for study. Studies were initiated in Atlanta, Georgia; Raleigh-Durham, North Carolina; and Denver, Colorado in 2001 and in Portland, Oregon; Dallas-Fort Worth, Texas; and Milwaukee, Wisconsin in 2004.

The overall approach of the ULUG studies was to examine a common set of hydrologic, geomorphic, chemical, habitat, and biological characteristics of streams over a range (gradient) of urban land-use intensities. Such gradient studies take a space-for-time approach, which relies on assessment of a number of streams with different degrees of watershed urbanization. The objective is to identify landscape features most important in determining physical, chemical, and biological responses along the gradient of urban land-use intensity. The landscape features (signals) that drive physical, chemical, and biological responses can be determined by minimizing the influence of additional factors (noise) known to influence hydrology, constituent transport, and ecological communities (e.g., precipitation, evapotranspiration, soil permeability, geography). Landscape features strongly associated with changes in water-quality conditions and that can be effectively manipulated become candidates for managing and regulating the resource.

Within each environmental setting, a network of approximately 30 basins representing a gradient of urban land-use intensity was used to assess the relation between urban intensity and in-stream physical, chemical, and biological responses. The following process, described in detail in Mahon and Cuffney (2000), was followed to select basins within a relatively homegenous environmental setting: 1) Identify a population of similarly sized basins utilizing digital elevation models; 2) Assemble information on basin characteristics (population, socioeconomic, and landscape data for basins) from GIS coverages; 3) Derive an index of urban intensity to rank sites along an urban gradient; 4) Develop an environmental framework based on natural features, such as slope, soils, surficial geology, ecoregion; and select a common setting for basins; 5) Conduct site reconnaissance to locate (latitude and longitude) sampling sites; 6) Recalculate information on basin characteristics and urban intensity index based on latitude and longitude of sampling sites; and 7) Select sites that represent a gradient of urban intensity.

The results of the first three pilot studies are being published by the American Fisheries Society (Effects of urbanization on stream ecosystems; L. R. Brown, R. H. Gray, R. M. Hughes, and M. R. Meador, editors). Comparisons of basin environmental and urban characteristics for the pilot studies Birmingham, Salt Lake City, and Boston are provided in Tate et al. (in press).

Twenty-eight physical variables describing channel morphology, hydraulic properties, and streambed conditions were examine and none were significantly correlated with urbanization intensity in all three study areas (Short et al., in press). Urbanization effects on stream habitat were less apparent for streams in Salt Lake City and Birmingham owing to the strong influence of basin slope (Salt Lake) and drought conditions (Birmingham) on local flow regimes. Streamflow in the Boston study area was not unduly influenced by similar conditions of climate and physiography, and habitat conditions in these streams were more responsive to urbanization. In Boston, urbanization contributed to high discharge, channel deepening, and increased loading of fine-grained particles to stream channels. The influence of basin slope and climate on modifying hydrology of streams in Salt Lake City and Birmingham limited the ability to effectively compare habitat responses among different urban settings and to identify common responses that might be of interest to restoration or water management programs. Despite some successes in applying the urban intensity model to identify habitat responses to urbanization, this study would have benefited from a better understanding of factors affecting hydrologic connectivity of streams in the study areas.

Algal responses to urbanization differed considerably among the three study areas. Of the various structural attributes of the algal assemblages, species composition changed along gradients of urban intensity in a more consistent manner than algal biomass or diversity. In urban streams, the relative abundance of pollution-tolerant species was higher than in the less impacted streams. Shifts in assemblage composition were associated primarily with increased levels of electrolytes, nutrients, and with alterations in physical habitat, such as flow regime (Potapova et al., in press)

Because of the low number of taxon present in the basin, fish community assessments were not used in the Salt Lake City study. Fish species richness decreased significantly with increasing urbanization in Birmingham and Boston. Percent endemic species richness decreased significantly with increasing urbanization only in Birmingham, whereas percent fluvial specialist species decreased significantly with increasing urbanization only in Boston. Differences between fish assemblage responses to urbanization in Boston and Birmingham appeared to be related to differences in nutrient enrichment, habitat alterations, and invasive species. A nearly linear pattern with species richness and with endemic species richness was found in Birmingham. In contrast, analysis of the Boston data indicated a non-linear pattern with total species richness, indicating periodic increases and decreases in species richness (Meador et al., in press).

Invertebrate communities exhibited similar and strong responses to urbanization in Boston and Birmingham (Cuffney et al., in press). Although responses were evident in Salt Lake City, they were confounded by extensive hydrologic modifications in the basin and a strong elevation gradient associated with development along the Wasatch Range. Richness metrics were better indicators of urbanization than were density metrics. Metrics that were good indicators were specific to each study except for a richness-based tolerance metric and one benthic IBI.

Effect thresholds for invertebrate assemblages at 5-18% total impervious surface area have been reported previously (Klein, 1979; Jones and Clark, 1987; Schueler, 1994; Booth and Jackson, 1997; May et al., 1997; Kennen and Ayers, 2002; Morse et al., 2003). The results of our ULUG studies, did not indicate that an effect threshold exists at low levels of urbanization. That is, the assemblages did not show any evidence of being able to resist or compensate for changes brought about during the initial phases of urbanization. Instead, responses can best be described as linear, with degradation of the invertebrate assemblage beginning as soon as the native vegetation begins to be replaced with roads and buildings. The ULUG data provided no evidence to indicate that there is a level of urban intensity that has no effect on invertebrate assemblages. Thresholds at higher levels of urban intensity also are rare for invertebrates. Only three high-level (exhaustion) thresholds were evident in more than 400 responses (metrics, indices, ordinations) examined; and all of these thresholds occurred in Boston. Consequently, response thresholds cannot be described as a common feature of invertebrate responses to urbanization.

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