Urban Ecosyst
DOI 10.1007/s11252-010-0131-x

A generalized watershed disturbance-invertebrate relation applicable in a range of environmental settings across the continental United States

Jeffrey J. Steuer

Abstract It is widely recognized that urbanization can affect ecological conditions in aquatic systems; numerous studies have identified impervious surface cover as an indicator of urban intensity and as an index of development at the watershed, regional, and national scale. Watershed percent imperviousness, a commonly understood urban metric was used as the basis for a generalized watershed disturbance metric that, when applied in conjunction with weighted percent agriculture and percent grassland, predicted stream biotic conditions based on Ephemeroptera, Plecoptera, and Trichoptera (EPT) richness across a wide range of environmental settings. Data were collected in streams that encompassed a wide range of watershed area (4.4–1,714 km^2), precipitation (38–204 cm/yr), and elevation (31–2,024 m) conditions. Nevertheless the simple 3-landcover disturbance metric accounted for 58% of the variability in EPT richness based on the 261 nationwide sites. On the metropolitan area scale, relationship r^2 ranged from 0.04 to 0.74. At disturbance values <15 the EPT rate of decrease was ~10 times greater than at disturbance values >15. Future work may incorporate watershed management practices within the disturbance metric, further increasing the management applicability of the relation. Such relations developed on a regional or metropolitan area scale are likely to be stronger than geographically generalized models; as found in these EPT richness relations. However, broad spatial models are able to provide much needed understanding in unmonitored areas and provide initial guidance for stream potential.

Keywords Urbanization · Agriculture · Disturbance · Macroinvertebrates · EPT richness

---

This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first three months after its submission to Urban Ecosystems.

Electronic supplementary material The online version of this article (doi:10.1007/s11252-010-0131-x) contains supplementary material, which is available to authorized users.

J. J. Steuer (✉)
U. S. Geological Survey, Wisconsin Water Science Center, 8505 Research Way, Madison, WI 53562, USA
e-mail: jjsteuer@wisc.edu

Introduction

It is widely recognized that urbanization can affect ecological conditions in aquatic systems (Paul and Meyer 2001). Numerous studies have identified impervious surface cover as an indicator of urban intensity and as an index of development at the watershed, regional, and national scale (Bressler et al. 2008; Schueler et al. 2009). As processors of nutrients and organic energy macroinvertebrates have been used as a monitor of overall instream health (Gore et al. 2001). Studies have also documented the decline of benthic community, including Ephemeroptera, Plecoptera, and Trichoptera (EPT) richness with increased urbanization for specific geographic regions such as Rocky Mountain streams (Maxted 2000), Anchorage, Alaska (Ourso and Frenzel 2003), North Central Georgia (Roy et al. 2003), and Melbourne, Australia (Walsh et al. 2005).

Watershed imperviousness is an easily measureable, commonly used, well understood land-use metric that integrates cumulative water resource impacts (Arnold and Gibbons 1996). Direct connection of imperviousness to the stream has been identified as important to stream ecological condition (Walsh et al. 2005). Schueler et al. (2009) noted "impervious cover has unique properties as a watershed metric in that it can be measured, tracked, forecasted, managed, priced, regulated, mitigated, and in some cases, even traded. IC is a common currency that is understood and applied by watershed planners, stormwater engineers, water quality regulators, economists, and stream ecologists alike." The objective of this study was to determine whether watershed percent imperviousness when applied in conjunction with percent agriculture and percent grassland improved association with stream biotic conditions based on EPT richness on a national scale. This effort may be one of the first to develop a relation between a generalized land disturbance metric and a common stream biologic metric (EPT richness) applicable across the continental United States.

Methods

This study examined landcover and stream ecological conditions in nine metropolitan areas across the continental United States (Fig. 1) that represent wide physiographic and climatic settings (Table 1). In each metropolitan area, 28–30 similarly-sized watersheds, typically drained by 2nd to 3rd order streams (generally less than 50 km^2) were selected to maintain relatively homogeneous natural environmental features (e.g., ecoregion, climate, elevation, stream size) and encompassed basins with little or no urban development to basins with maximum development (Falcone et al. 2007). The amount of imperviousness within a basin and upstream of the sampling point, ranged from 0 to 55 percent (Supplemental Table 1).

Invertebrate community data were collected within each of the nine metropolitan areas in up to 30 stream reaches (n=261). Sampling reaches in each metropolitan area were selected from watersheds along gradients of increasing urbanization and were sampled during an index period appropriate for each geographic area between 1999 and 2004. Index periods were chosen to represent the optimal time to collect biological data and were based on multiple factors, such as life history attributes of the organisms to be sampled and predictable hydrologic conditions that allowed safe and effective sampling (Cuffney et al. 1993). Invertebrate data were collected from these reaches using standard U. S. Geological Survey program data-collection methods (Moulton et al. 2002) in which one semi-quantitative sample was collected from either rock or woody debris and a separate

Fig. 1 Location of nine metropolitan areas in the United States sampled as part of the U.S. Geological Survey National Water-Quality Assessment Program study on the effects of urbanization on stream ecosystems, 1999–2004

qualitative sample was collected from all available habitats at each site. The two collections were combined to determine Ephemeroptera, Plecoptera, and Trichoptera (EPT) richness. EPT were selected as the endpoint metric as collectively these groups are pollution intolerant, good indicators of stream condition, sensitive to changes in stream conditions related to impervious cover, provide a critical link to the fish community and are commonly used by various State and national assessment programs (Gore et al. 2001; Fore et al. 1996)

Information on landcover, based on 30-m resolution satellite imagery, was obtained from National Land Cover Data 2001 (NLCD01) dataset classification scheme and protocols (U. S. Geological Survey 2005) and was compiled using geographic information system (GIS) software. Impervious cover, estimated from each 30-m pixel, was ground-truthed from 60 random samples digitized from high-resolution (0.3-m) orthoimagery in each of six metropolitan areas.

A univariate EPT richness scatterplot was initially constructed with percent imperviousness in the watershed as the independent variable and a fitted logarithmic regression model; 0.1% was added to the independent variable for logarithmic transformation (Data Desk, version 6.1; Data Description, Inc., Ithaca, New York[1]). Subsequently, percent agriculture in the watershed was added as part of the independent variable and iteratively weighted to maximize the coefficient of determination (r^2) of the logarithmic model; ~0.15 was the optimal coefficient. The procedure was repeated with percent grassland added to the independent variable (imperviousness(%) + 0.15*agriculture(%)); ~0.15 was also the optimal coefficient for grassland (%).

---

[1] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U. S. Government.

Table 1 Physiographic region, precipitation occurrence, noteworthy conditions during sampling, and summary statistics for select physical variables for the nine studied metropolitan areas in the United States

Metropolitan area (abbreviation)	Physiographic provinces (Fenneman and Johnson 1946)	Precipitation occurrence (Falcone et al. 2007)	Noteworthy conditions during hydrologic data collection	Reach water surface gradient (%) [mean (min-max)]	Mean annual precipitation for period 1980–1997 (cm) [mean (min-max)]	Drainage area (km^2) [mean (min-max)]	Mean elevation (m) [mean (min-max)]	Number of basins in metropolitan area
Portland (POR)	Pacific Mountain, Pacific Border, Cascade-Sierra Mountains	Snowmelt in spring, rainfall October-April	None	0.60 (0.11–1.7)	154 (116–204)	49.2 (17.1–103.8)	222 (53–621)	28
Salt Lake City (SLC)	Rocky Mountain System, Middle Rocky Mountains; Intermontane Plateaus, Basin and Range	Snowmelt in winter/spring major runoff source, scattered light thunderstorms in summer	Flow affected by reservoirs, interbasin transfers, and diversions	1.1 (0.46–2.6)	65 (60–73)	364.5 (8.8–1714.4)	1,435 (1,370–1,504)	30
Denver (DEN)	Interior Plains, Great Plains; Rocky Mountain System, Southern Rocky Mountains	Snowmelt in spring, rainfall April–September	Flow affected by reservoirs, interbasin transfers, and diversions	not measured	43 (38–46)	89.8 (4.4–558.6)	1,713 (1,535–2,024)	28
Dallas (DFW)	Atlantic Plain, Coastal Plain	Rainfall spring and summer	None	0.19 (0.008–0.98)	104 (96–111)	85.3 (26.8–291.4)	170 (124–220)	28
Milwaukee-Green Bay (MGB)	Interior Plains, Central Lowland	Snowmelt March–May, rainfall May–September	None	0.31 (0.02–0.63)	86 (81–91)	45.5 (16.3–100.3)	237 (202–270)	30
Birmingham (BIR)	Appalachian Highlands; Valley and Ridge, Plateaus, Piedmont	Rainfall—frontal systems in winter, thunderstorms in summer/fall	Severe drought	0.38 (0.14–0.66)	146 (141–152)	31.8 (4.7–66.1)	233 (162–324)	28
Atlanta (ATL)	Appalachian Highlands, Piedmont	Rainfall—frontal systems in winter, thunderstorms in summer/fall	Wet year	0.19 (0.04–0.59)	134 (124–140)	89.9 (43.2–146.3)	286 (193–350)	30
Raleigh (RAL)	Appalachian Highlands, Piedmont	Rainfall distributed throughout the year	Wet year	0.63 (0.26–1.3)	120 (115–125)	22.3 (4.9–82.5)	184 (89–284)	29
Boston (BOS)	Appalachian Highlands, New England	Snowmelt March–May, rainfall May–September	None	0.64 (0.12–1.6)	123 (115–136)	75.7 (45.9–124.6)	113 (31–236)	30

Results and discussion

Overall, EPT richness declined with increasing watershed imperviousness (Fig. 2a) albeit with a wedge shape commonly observed with ecological data across large spatial scales. Such data are frequently defined by an upper limit, action due to multiple factors or rural areas dominated by agriculture (Thomson et al. 1996; Carter and Fend, 2005; Wang et al. 2001). A similar wedge-shaped invertebrate response to urbanization was recently observed in three regions across the United States (Paul et al. 2008). Variability of stream quality uncertainty has been found greatest for impervious cover less than 10%; a range in which other watershed metrics such as forest cover, road density, and cropping practices may also be important (Schueler et al. 2009; Wang et al. 2001). Similarly, the greatest variability in EPT richness in this study was between 0 and ~12% imperviousness (Fig. 2a). Many of the sites with low EPT richness and low imperviousness, which plotted in the lower left scatterplot region, had substantial agriculture and grassland landcover (Supplemental Table 1).

The weighted addition of agriculture and grassland (0.15 the weight of imperviousness) to imperviousness substantially strengthened the relation between watershed disturbance and EPT richness, increasing the adjusted r^2 from 0.36 to 0.58 (Fig. 2b). Approximately two thirds of the EPT taxa were lost (~30 to ~10) in the first quarter of the generalized disturbance range. Sites with highest EPT richness were located in watersheds draining predominantly forest and wetland landcover (Supplemental Table 1). The following examples illustrate the utility of this index. Lost Creek in the Portland metropolitan area is predominantly forest and wetland (88%) which resulted in a low disturbance value of 0.7 and relatively high EPT richness (26 taxa). Conversely, the Kewaunee tributary watershed in Milwaukee-Green Bay is predominantly agriculture (86%), a disturbance value of 14.2, and reduced EPT richness (7 taxa). Similarly, Fivemile Creek in Birmingham has little agriculture or grassland (~1.5%) but 15% imperviousness, a disturbance value of 15.4 and comparatively reduced EPT richness (6 taxa).

Figure 3(a-i) illustrates the effect of including agriculture and grassland to the disturbance axis within individual metropolitan areas. In effect, data located in the left corner of the wedge scatter plot (imperviousness only; Fig. 2a) were translated proximate to the logarithmic trendline when agriculture and grassland are included as part of the disturbance axis. Substantial shifts between imperviousness only (small symbols) and the three landcover disturbance metric (large symbols) are clearly observed in the predominantly agriculture (Milwaukee-Green Bay, Dallas) and grassland (Denver) areas (Fig. 3b, e, and g respectively). Sites within Milwaukee-Green Bay that were predominantly agriculture (small symbols with x axis values ~0 and large symbols ~12) had wide variability in EPT richness (Fig. 3b, Supplemental Table 1).

The nine individual metropolitan areas had relations consistent with the overall national relation; all but one were significant at $p<0.05$ (Fig. 3a-i). Denver's relation, which occurred over the most limited range of the disturbance index (14–48) and in the flat portion of the logarithmic curve, was not significant ($p=.3101$). In general, relations were weakest in areas in which the non-urban watersheds were predominantly agriculture or grassland. Kashuba et al. (2009) utilized a hierarchical modeling analysis for the same metropolitan areas and concluded regional mean precipitation, air temperature and antecedent agricultural could be used to determine the slope of regional basin development-stream biology relations.

A piecewise regression ("broken-stick") model (Brenden et al. 2008; Toms and Lesperance 2003) which utilized the 3-landcover disturbance metric (inclusion of

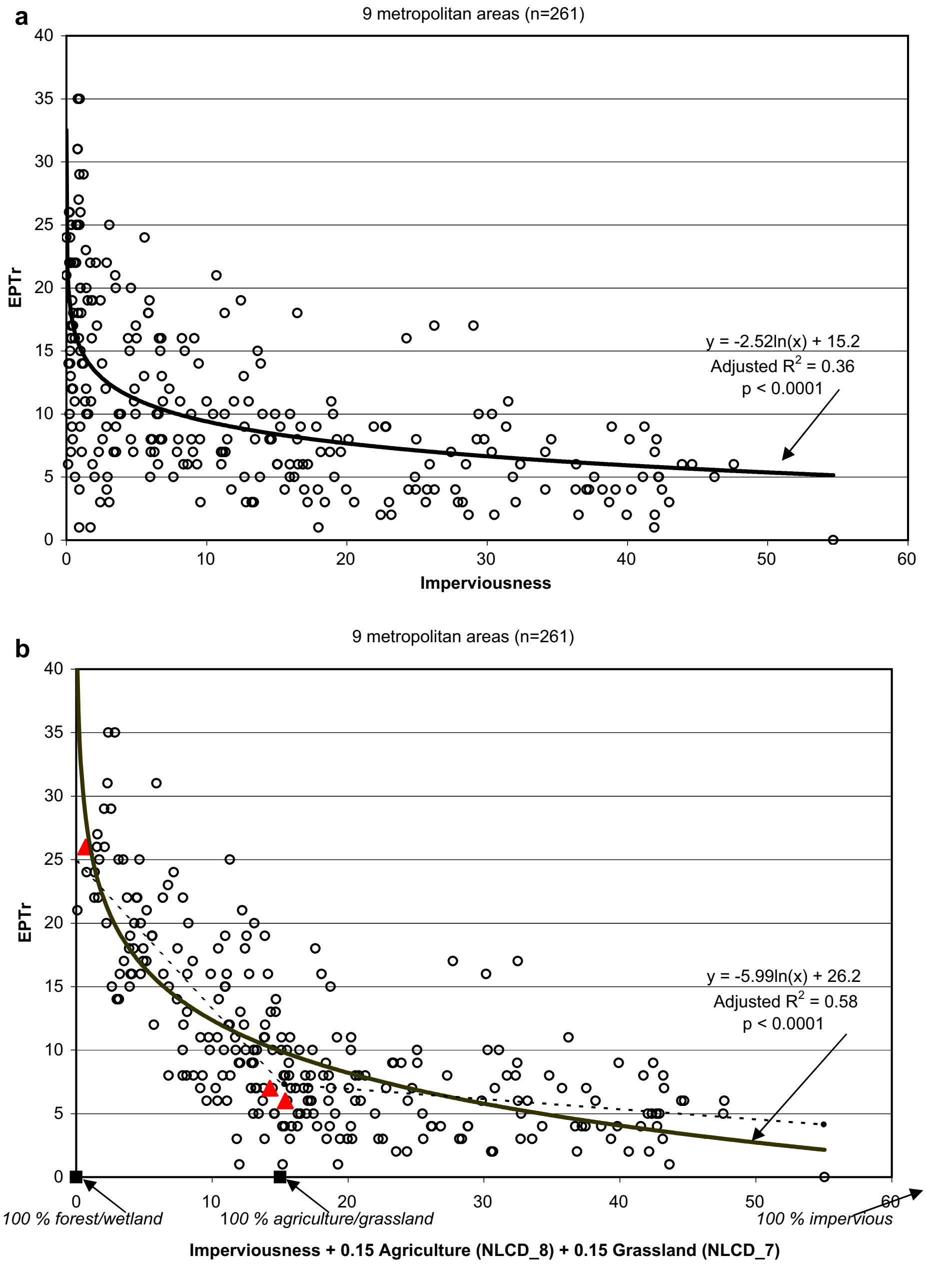

Fig. 2 Scatter plots of the invertebrate richness metric, EPTr, against imperviousness only (**a**) and the three landcover (imperviousness% +0.15 agriculture% +0.15grassland%) disturbance metric (**b**) for the combined 9 metropolitan area data set with logarithmic regression models. *Triangle symbols* identify selected sites discussed in text. *Dotted lines* are linear regressions for disturbance index < and >15

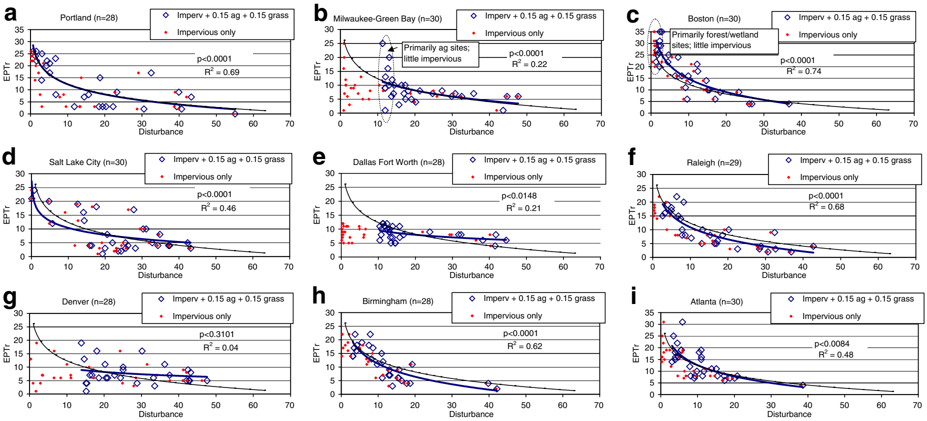

Fig. 3 Scatter plots for individual metropolitan areas of the invertebrate richness metric, EPTr, against two disturbance metrics; imperviousness only (small symbols) and the three landcover (imperviousness% +0.15agriculture% +0.15grassland%) metric. Logarithmic regression and *p* values for the three landcover metric are depicted (heavy curve). The combined nine metropolitan area data set logarithmic model (light curve) is included to enhance comparison

agriculture and grassland) identified the slope breakpoint at a disturbance value of ~15 (Fig. 2b). Linear regression in the disturbance region <15 had a slope of −1.1 ($p<0.001$); slightly more than one EPT taxa was lost with each unit increase of disturbance. For disturbance values >15 the EPT reduction was much more gradual—it required a >10 disturbance unit change for an EPT richness reduction of 1 taxa (slope = −0.08; $p=0.011$).

Although there are inherent sources of variability and error in both landcover and biologic variables, a strong disturbance-invertebrate relation was evident across the continental United States. For example, impervious surface estimation from satellite-acquired data resulted in a general underestimation of impervious surfaces in the Atlanta, Raleigh, and Dallas datasets as compared to the Denver, Portland, and Milwaukee-Green Bay datasets (Falcone and Pearson 2006). Additionally, the large-scale effort required biologic sampling be conducted on a single occasion at one stream reach, over a 5-year period, and in streams that encompassed a wide range of watershed area (4.4–1,714 km^2), precipitation (38-204 cm/yr), and elevation (31–2,204 m) conditions (Table 1). Nevertheless the simple 3-landcover disturbance metric accounted for 58% of the variability in EPT richness across the 261 nationwide sites.

Watersheds with disturbance values <~15 that undergo modest mitigation or improvement actions may experience large gains in EPT scores and presumable overall ecosystem health. For example, a stream in a predominantly agricultural and forest/wetland watershed may gain one additional EPT taxa with each 6.7% increment of agriculture land converted to forest or wetland. Likewise for urban and forest/wetland watersheds, one additional EPT taxa may be associated with each 1% increment of imperviousness converted to forest or wetland. This is consistent with a Maryland study in which predominantly agricultural streams had significantly more EPT taxa than urban streams (Moore and Palmer 2005). In contrast, watersheds scoring >30 may require substantial investment in mitigation actions to yield improvement because they are on the segment of the curve with the lowest slope. In general, it appears that forest and wetland cover are important for higher EPT scores. This may be especially important in stream's riparian zone with the accompanying canopy, organic matter, and wood debris (Moore and Palmer 2005).

Agreement between the nine metropolitan area relations and the national scale relation (Fig. 3(a-i)) is an indication the multi-region relation may be useful as one approximation of general EPT richness expectation throughout the continental United States. For unmonitored sites the relation provides one estimate of expected EPT richness. Alternatively, monitored sites with values substantially below the relation (Fig. 2b) may be examined for possible point source input or local habitat degradation. This study also confirms previous findings that single-event biologic sampling can be an effective, economical approach (Lammert and Allan 1999). From a purely scientific standpoint however, increased temporal sampling may improve model error.

Inclusion of management practices or detailed stressors within the disturbance metric will likely strengthen the relation and make it more management oriented. For example, points beneath the curve (lower than expected EPT richness) may have increased road density, impervious surface area concentrated near or connected to the stream, or treated with substances that affect stream biology (Wang et al. 2001; Mahler et al. 2005; U. S. Environmental Protection Agency 2008). Alternatively, agriculture in these watersheds may have higher than normal pesticide, nutrient or sediment input potentially reducing EPT (Allan 2004). Sites in the upper envelope (better than expected EPT richness) may have in place best management practices to mitigate the effects of imperviousness (i.e. raingardens, grass swales, disconnected imperviousness) or agriculture (buffer strips, no till practice, appropriate chemical treatment). Prior research has suggested the importance of riparian buffers in agricultural watersheds in supporting high macroinvertebrate diversity (Watzin and McIntosh 1999). Incorporation of such factors within the disturbance metric will shift data points on the independent axis and potentially strengthen the relation.

There is some indication that management practices may have greater EPT improvement potential in highly agricultural watersheds as compared to those that contain a high percentage of impervious surfaces. Wider EPT variance is observed at disturbance values of ~10 to 15 (often highly agricultural sites) as compared to sites with disturbance values >40 (Fig. 2b). This is especially noticeable at the scale of individual metropolitan areas. The low impervious but high agricultural Milwaukee-Green Bay sites (Fig. 3b) had a wider EPT range (1–25) than did the low impervious, high forest/wetland Boston sites (20–35).

Summary

Watershed percent imperviousness, a commonly understood urban metric was used as the basis for a generalized watershed disturbance metric that, when applied in conjunction with weighted percent agriculture and percent grassland, predicted stream biotic conditions based on Ephemeroptera, Plecoptera, and Trichoptera (EPT) richness. The relation was formulated over, and applicable to, both wet and dry periods and a range of physiographic settings. A threshold was identified (disturbance values <15) that defined a region of increased EPT richness change. The relation has the potential of being a strong management tool should future work include watershed management practices within the disturbance metric. Such relations developed on a regional or metropolitan area scale are likely to be stronger than geographically generalized models; as found in these EPT richness relations. However, broad spatial models provide much needed understanding in unmonitored areas and an initial guidance for stream potential.

Acknowledgements Many dedicated U. S. Geological Survey scientists and technicians collected, compiled, and managed the large amount of data used in this paper. Steven Zigler, Brian Gregory and Tom Schueler provided invaluable reviews of the draft manuscript.

References

Allan JD (2004) Landscapes and riverscapes: the influence of land use on stream ecosystems. Annu Rev Ecol Evol Systemat 35:257–284

Arnold CL, Gibbons CJ (1996) Impervious surface coverage: the emergence of a key environmental indicator. J Am Plann Assoc 62(2):243–258

Brenden TO, Wang L, Zhenming Su (2008) Quantitative identification of disturbance thresholds in support of aquatic resource management. Environ Manage 42(5):821–832

Bressler DW, Paul MJ, Purcell AH, Barbour MT, Rankin ET, Resh VH (2008) Assessment tools for urban catchments: developing stressor gradients. J Am Water Resour Assoc 45(2):291–305

Carter JL, Fend SV (2005) Setting limits: the development and use of factor ceiling distributions for an urban assessment using macroinvertebrates in effects of urbanization on stream ecosystems. Am Fish Soc Symp 47:179–191

Cuffney TF, Gurtz ME, Meador MR (1993) Methods for collecting benthic invertebrate samples as part of the National Water-Quality Assessment Program: U. S. Geological Survey Open-File Report 93–406

Falcone JA, Pearson D (2006) Land-cover and imperviousness data for regional areas near Denver, Colorado; Dallas-Fort Worth, Texas; and Milwaukee-Green Bay, Wisconsin—2001:U.S. Geological Data Series 221, 17 p

Falcone JA, Stewart JS, Sobieszczyk S, Dupree JA, McMahon G, Buell GR (2007) A comparison of natural and urban characteristics and the development of urban intensity indices across six geographic settings: U.S. Geological Survey Scientific Investigations Report 2007–5123, 133 p., accessed November 1, 2007 at http://pubs.er.usgs.gov/usgspubs/sir/sir20075123

Fenneman NM, Johnson DW (1946) Physical divisions of the United States. US Geological Survey, map

Fore LS, Karr JR, Wisseman RW (1996) Assessing invertebrate responses to human activities: evaluating alternative approaches. J North Am Benthol Soc 15(2):212–231

Gore JA, Layzer JB, Mead J (2001) Macroinvertebrate instream flow studies after 20 years: a role in stream management and restoration. Regul Rivers 17:527–542

Kashuba R, Cha Y, Alameddine I, Lee B, Cuffney TF (2009) Multilevel hierarchical modeling of benthic macroinvertebrate response to urbanization in nine metropolitan regions across the conterminous United States. U.S. Geological Survey Scientific Investigations Report 2009–5243, 88 p., accessed April 13, 2010 at http://pubs.usgs.gov/sir/2009/5243/pdf/sir2009-5243.pdf

Lammert M, Allan JD (1999) Assessing biotic integrity of streams: effects of scale in measuring the influence of land use/cover and habitat structure on fish and macroinvertebrates. Environ Manage 23 (2):257–270

Mahler BJ, Van Metre PC, Bashara TJ, Wilson JT, Johns DA (2005) Parking lot sealcoat: an unrecognized source of urban polycyclic aromatic hydrocarbons. Environ Sci Technol 39(15):5560–5566

Maxted J (2000) Effects of urbanization on the macroinvertebrate communities of small rocky mountain streams, and the benefits of riparian vegetation. U.S. EPA Cooperative Agreement No. 82444601

Moore AA, Palmer MA (2005) Invertebrate biodiversity in agricultural and urban headwater streams: implications for conservation and management. Ecol Appl 15(4):1169–1177

Moulton SR II, Kennen JG, Goldstein MR, Hambrook JA (2002) Revised protocols for sampling algal, invertebrate, and fish communities as part of the National Water-Quality Assessment Program. U.S. Geological Survey Open-File Report 02–150

Ourso RT, Frenzel SA (2003) Identification of linear and threshold responses in streams along a gradient of urbanization in Anchorage, Alaska. Hydrobiologia 501(1–3):117–131

Paul MJ, Meyer JL (2001) Streams in the urban landscape. Annu Rev Ecol Syst 32:333–365

Paul MJ, Bressler DW, Purcell AH, Barbour MT, Rankin ET, Resh VH (2008) Assessment tools for urban catchments: defining observable biological potential. J Am Water Resour Assoc 45(2):320–330

Roy AH, Rosemond AD, Paul MJ, Leigh DS, Wallace JB (2003) Stream macroinvertebrate response to catchment urbanization (Georgia, USA). Freshw Biol 48:329–346

Schueler TR, Fraley-McNeal L, Cappiella K (2009) Is impervious cover still important? Review of recent research. J Hydrol Eng 14:309–315

Thomson JD, Weiblen G, Thomson BA, Alfaro S, Legendre P (1996) Untangling multiple factors in spatial distributions: lilies, gophers, and rocks. Ecology 77:1698–1715

Toms JD, Lesperance ML (2003) Piecewise regression: a tool for identifying ecological thresholds. Ecology 84(8):2034–2041

U.S. Environmental Protection Agency (2008) Information on the toxic effects of various chemicals and groups of chemicals. http://www.epa.gov/R5Super/ecology/html/toxprofiles.htm# (accessed April 2010)

U.S. Geological Survey (2005) National Land Cover Database 2001 (NLCD01). accessed in December 2005 at http://www.mrlc.gov/mrlc2k_nlcd.asp

Walsh CJ, Fletcher TD, Ladson AR (2005) Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. J North Am Benthol Soc 24(3):690–705

Wang LZ, Lyons J, Kanehl P, Bannerman R (2001) Impacts of urbanization on stream habitat and fish across multiple spatial scales. Environ Manage 28(2):255–266

Watzin MC, McIntosh AW (1999) Aquatic ecosystems in agricultural landscapes: a review of ecological indicators and achievable ecological outcomes. J Soil Water Conserv 54:636–644