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The urban stream syndrome: current knowledge and the search for a cure

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Abstract. The term ''urban stream syndrome'' describes the consistently observed ecological degradation of streams draining urban land. This paper reviews recent literature to describe symptoms of the syndrome, explores mechanisms driving the syndrome, and identifies appropriate goals and methods for ecological restoration of urban streams. Symptoms of the urban stream syndrome include a flashier hydrograph, elevated concentrations of nutrients and contaminants, altered channel morphology, and reduced biotic richness, with increased dominance of tolerant species. More research is needed before generalizations can be made about urban effects on stream ecosystem processes, but reduced nutrient uptake has been consistently reported. The mechanisms driving the syndrome are complex and interactive, but most impacts can be ascribed to a few major large-scale sources, primarily urban stormwater runoff delivered to streams by hydraulically efficient drainage systems. Other stressors, such as combined or sanitary sewer overflows, wastewater treatment plant effluents, and legacy pollutants (long-lived pollutants from earlier land uses) can obscure the effects of stormwater runoff. Most research on urban impacts to streams has concentrated on correlations between instream ecological metrics and total catchment imperviousness. Recent research shows that some of the variance in such relationships can be explained by the distance between the stream reach and urban land, or by the hydraulic efficiency of stormwater drainage. The mechanisms behind such patterns require experimentation at the catchment scale to identify the best management approaches to conservation and restoration of streams in urban catchments. Remediation of stormwater impacts is most likely to be achieved through widespread application of innovative approaches to drainage design. Because humans dominate urban ecosystems, research on urban stream ecology will require a broadening of stream ecological research to integrate with social, behavioral, and economic research.

Key words: urbanization, streams, stormwater management, water quality, hydrology, ecosystem processes, imperviousness, restoration, urban ecology.

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Increasing urbanization across landscapes of the world has led to increased research on ecology in urban settings in the last 1 to 2 decades. Urban ecological studies have investigated both impacts of urban development on native ecosystems and the dynamics of urban environments themselves as ecosystems (Grimm et al. 2000). In both areas of research, streams of urban areas have an important part to play because their position in the landscape makes these ecosystems particularly vulnerable to impacts associated with landcover change. Furthermore, streams feature strongly in dynamics of urban ecosystems themselves as 1) habitats for a potentially diverse and productive biota, 2) carriers of water and processors of the materials in that water, and 3) important social and cultural foci for the human inhabitants of their catchments.

Changes to stream ecosystems wrought by urban land use have previously been reviewed (Suren 2000, Paul and Meyer 2001, Center for Watershed Protection 2003), but the new contributions in this series of J-NABS papers provide an opportunity for a new synthesis and re-evaluation of the links between urban land use and stream ecological structure and function. The papers in this series, and other recent papers, document the many ways in which streams draining urbanized catchments are ecologically degraded: a consistent suite of effects termed the ''urban stream syndrome'' by Meyer et al. (2005). We summarize symptoms of this syndrome from papers in this issue and from other recent studies, primarily from the US and Australia. Our aim is to clarify which symptoms show consistent trends across geographic regions and which require further study before conclusions and/or generalizations may be drawn. We also use papers from this series and elsewhere to identify mechanisms that may drive the symptoms of the urban stream syndrome, with the aim of identifying the best management actions to conserve streams in less-urbanized yet vulnerable catchments, and possibly to restore streams in existing urban catchments to an ecological condition more closely resembling streams not affected by urban land use.

A critical factor in restoration and conservation of urban streams and their catchments is the human population (Booth 2005), suggesting that effective management of these streams will require a broader perspective than traditional stream ecology, one that includes social, economic, and political dimensions. We present a broad framework for the study of urban streams more akin to the concepts of urban ecology (Grimm et al. 2000).

Our paper addresses the following questions:

1) Which of the reported symptoms of the urban stream syndrome show consistent patterns in urban areas, and which require more study before generalizations about conditions or effects can be made?
2) Which mechanisms drive the symptoms of the urban stream syndrome and what approaches should be used to further our understanding of these mechanisms?
3) What are appropriate goals for ecological restoration of streams in urban areas and what actions are required to achieve these goals?

The Urban Stream Syndrome

Consistent symptoms of the urban stream syndrome include a flashier hydrograph, elevated concentrations of nutrients and contaminants, altered channel morphology and stability, and reduced biotic richness, with increased dominance of tolerant species (Paul and Meyer 2001, Meyer et al. 2005). These ecological effects often are accompanied by other symptoms not observed in all urban areas, such as reduced baseflow or increased suspended solids (Table 1, Fig. 1, and see below). Symptoms that do show consistent increases or decreases with urban land use may still vary between cities in the degree to which they change and in the level of urbanization at which a change in the symptom is observed. Identifying factors that drive such differences between cities may help in the search for strategies to alleviate the syndrome.

Physicochemical processes

Hydrologic change.—Changes to hydrographs are perhaps the most obvious and consistent changes to stream ecosystems influenced by urban land use, with urban streams tending to be more ''flashy'', i.e., they have more frequent, larger flow events with faster ascending and de-

TABLE 1. Symptoms generally associated with the urban stream syndrome. Consistent response are those observed in multiple studies, whereas inconsistent responses are those that have been observed to increase (↑), decrease (↓), and/or remain unchanged with increased urbanization. Limited research implies the need for more studies before concluding whether responses are consistent or inconsistent.

Feature	Consistent response	Inconsistent response	Limited research
Hydrology	↑ Frequency of overland flow ↑ Frequency of erosive flow ↑ Magnitude of high flow ↓ Lag time to peak flow ↑ Rise and fall of storm hydrograph	Baseflow magnitude	
Water chemistry	↑ Nutrients (N, P) ↑ Toxicants ↑ Temperature	Suspended sediments	
Channel morphology	↑ Channel width ↑ Pool depth ↑ Scour ↓ Channel complexity	Sedimentation	
Organic matter	↓ Retention	Standing stock/inputs	
Fishes	↓ Sensitive fishes	Tolerant fishes Fish abundance/biomass	
Invertebrates	↑ Tolerant invertebrates ↓ Sensitive invertebrates		Secondary production
Algae	↑ Eutrophic diatoms ↓ Oligotrophic diatoms	Algal biomass	
Ecosystem processes	↓ Nutrient uptake	Leaf breakdown	Net ecosystem metabolism Nutrient retention P:R ratio

scending limbs of the hydrograph. The primary driver of these changes occurs from a combined effect of increased areas of impervious surfaces and more efficient transport of runoff from impervious surfaces by piped stormwater drainage systems (Dunne and Leopold 1978, Fig. 1). Total catchment imperviousness (TI) has commonly been used as an indicator of this class of hydrologic change, although the influence of TI on stream hydrographs varies substantially with permeability of pervious parts of the catchment (Booth et al. 2004) and with how much of the impervious area drains directly to streams through pipes rather than draining to the surrounding pervious land (Walsh et al. 2005).

Increased flashiness is a useful descriptor for hydrologic effects of urban land use, but differences exist in how scientists have measured this effect. Konrad and Booth (2002) proposed a hydrologic metric (T_{Qmean}) as a predictor of urban-related stream degradation (see also Booth 2005). This metric quantifies the proportion of

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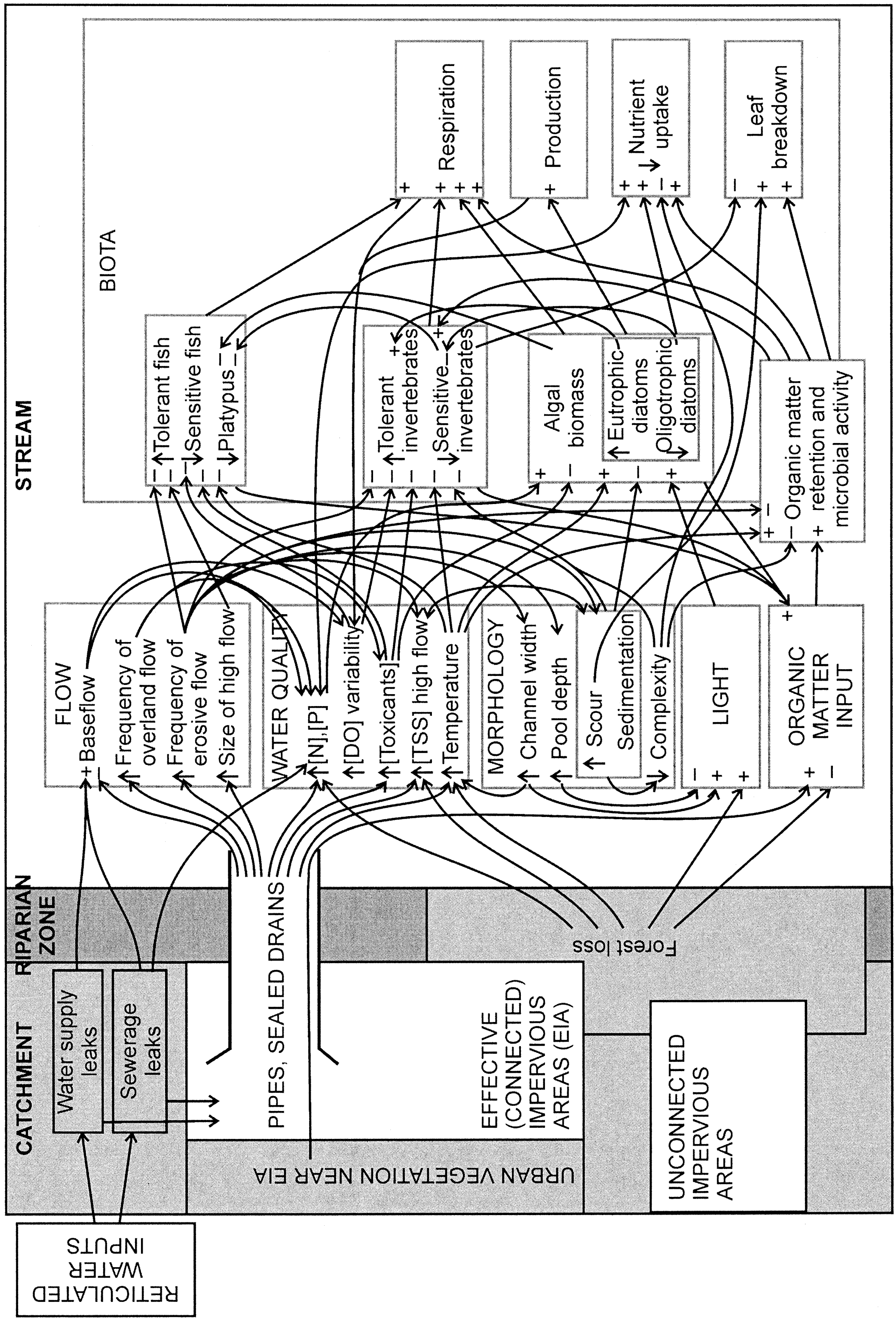
FIG. 1. Conceptual model of mechanisms of the major urban impacts on stream ecosystems. Impacts are many and interactions are complex, but most changes are driven by stormwater runoff from impervious surfaces delivered through pipes and sealed drains. Impacts of the loss of riparian forest (dark shading) are comparatively fewer and less severe than impacts of effective impervious areas. Landuse changes, such as forestland conversion, construction of impervious surfaces, or leakage of reticulated water systems are hypothesized to have little or no impact on receiving streams if they are buffered by pervious surfaces (light and dark shading). Trends consistently observed in urban areas within boxes on the right half of the figure are indicated by vertical arrows, whereas attributes showing different trends among urban areas are drawn without vertical arrows. Arrows linking attributes indicate hypothesized causal relationships, and the direction of the effect is indicated by + or –.


STREAM
BIOTA
Tolerant fish
Sensitive fish
Platypus
Tolerant invertebrates
Sensitive invertebrates
Algal biomass
Eutrophic diatoms
Oligotrophic diatoms
Organic matter retention and microbial activity
Respiration
Production
Nutrient uptake
Leaf breakdown
FLOW
Baseflow
Frequency of overland flow
Frequency of erosive flow
Size of high flow
WATER QUALITY
[N],[P]
[DO] variability
[Toxicants]
[TSS] high flow
Temperature
MORPHOLOGY
Channel width
Pool depth
Scour
Sedimentation
Complexity
LIGHT
ORGANIC MATTER INPUT
CATCHMENT
RIPARIAN ZONE
Water supply leaks
Sewerage leaks
PIPES, SEALED DRAINS
EFFECTIVE (CONNECTED) IMPERVIOUS AREAS (EIA)
URBAN VEGETATION NEAR EIA
Forest loss
UNCONNECTED IMPERVIOUS AREAS
RETICULATED WATER INPUTS

time mean discharge is exceeded, and also captures the increased frequency of high flows identified by Roy et al. (2005) and Walsh et al. (2005) to exert a strong ecological effect. In Fig. 1, we describe this aspect of flashiness as the increased frequency of erosive flows large enough to cause hydraulic disturbance to biota (Booth 2005, Roy et al. 2005), and that are also likely to cause channel incision and bank erosion (MacRae and Rowney 1992, and see below). Walsh et al. (2005) identified the increased frequency of smaller, overland flow events as another aspect of flashiness to be of potentially great ecological importance (Fig. 1). Rain events of a few millimetres are unlikely to cause large hydraulic stress in streams, even if their catchments are highly impervious. However, such frequent events may impair stream biotic assemblages by delivering chemical, and perhaps thermal, effluents. The relative importance of erosive flow events and smaller overland flow events to ecological change in urban streams requires further research.

Increased peak flows during high-flow events constitute another feature of the hydrograph consistently affected by urban land use. Until the recent past, typical stormwater management has been to control runoff from a 1- to 2-y average recurrence interval storm event or larger, so that peak flow rates do not exceed predevelopment conditions (e.g., Victorian Stormwater Committee 1999, Roesner et al. 2001). However, the ecological benefits of managing increased peak flow of such large floods may be small (see ''Morphological change'' section below and Fig. 1).

Urbanization does not affect instream baseflows consistently among urban areas of the world (Konrad and Booth 2002, Nilsson et al. 2003, Roy et al. 2005). Reduced infiltration resulting from increased catchment impervious surfaces tends to reduce baseflows, although this effect may be counteracted by leakage of water supply or sewerage infrastructure, which may import water from outside the catchment (Fig. 1). Operation of impoundments also may influence baseflow (Roy et al. 2005). However, where counteracting effects of catchment conditions on baseflow discharges are minimal, reduced baseflow from urbanization usually compounds water chemistry problems, such as by increasing diel variation in dissolved oxygen and temperature (Fig. 1).

Water chemistry change.—Increased concentrations and loads of several chemical pollutants in stream water appear universal in urban streams, often occurring even at low levels of catchment urbanization (Hatt et al. 2004). Even in regions where the ecological importance of stormwater-derived pollution is minor (Booth et al. 2004), positive correlations have been observed between catchment urbanization and concentrations of some streamwater pollutants (Horner et al. 1997). Urban catchments in the southwestern US, however, may show high variation in streamwater nutrient concentrations, and may even exhibit transient nutrient limitation (Grimm et al. 2005). Obviously, the problems of urban-induced water-quality impairment will be much greater in areas where sewage and industrial effluents are poorly managed (e.g., Schoonover et al. 2005), although controlling such impairment without addressing stormwater impacts is unlikely to ameliorate all water-quality problems (Hatt et al. 2004).

Variation in water chemistry changes within and among urban areas with increasing urban land use can result from several causes: natural climatic or geological differences (e.g., urbanization increased conductivity in streams of eastern Melbourne, Australia, but diluted the more saline streams to the northwest of Melbourne, Walsh et al. 2001); from historical differences in land use that predate urbanization (Frost 1993, Iwata et al. 2003); or from differences in the age of urban land use (e.g., sediment loads may decline in streams draining older urban areas, Finkenbine et al. 2000).

The above causes of variation in water chemistry trends are primarily associated with features determining the supply of pollutants. Water chemistry will also be influenced by variability in the efficiency of catchment and instream processes to retain nutrients. The importance of managing urban catchments and streams to maximize such processes is discussed below.

Morphological change.—The width and depth of stream channels adjust in response to long-term changes in sediment supply and flow regime, unless the channels are subject to constraints such as unerosive bedrock (Dunne and Leopold 1978). Stormwater management policies designed to control the maximum flow rates from large events (as discussed above) were primarily targeted to reducing channel erosion. However, frequent, smaller high-flow events in conventionally drained urban catchments may be more important causes of channel incision and resultant ecological impacts than infrequent, larger events (MacRae and Rowney 1992, Fig. 1). Influence of more frequent, small events likely also explains the common observation of disproportionate increases in channel erosion with only minor increases in discharge (Neller 1989, Booth 1990). Because of this hydrologic effect, or because direct engineering intervention often straightens channels or lines them with impermeable surfaces, reduction in channel complexity, and thus instream habitat, appears an almost universal symptom of the urban stream syndrome. In turn, channel incision and simplification, including reduction in hyporheic flow (Grimm et al. 2005) and hydrologic isolation from riparian vegetation (Groffman et al. 2003), often have important effects on several instream ecological processes (Fig. 1).

Organic matter input and retention.—Streams of the Atlanta, Georgia, region with high catchment urbanization showed low organic matter retention and high leaf breakdown rates (Paul 1999, Meyer et al. 2005), primarily because of increased scour rather than from an alteration in biotic processes. However, low organic matter storage has not been reported in all urban streams. For example, standing stocks of coarse particulate organic matter (CPOM, primarily leaves) in an Australian urban stream were significantly higher than in rural reference streams (Miller and Boulton 2005). Increased mass of instream organic matter in this study apparently resulted from increased leaf fall from many deciduous trees lining upland streets, which were connected to the channel by stormwater pipes. In both Atlanta and Australia, shredder macroinvertebrates were less abundant in urban streams than in rural streams (Paul 1999, Miller and Boulton 2005). Therefore, although physical processes may reduce organic matter retention in urban streams, this trend may be countered by reduced biotic processing through loss of shredding macroinvertebrates. Evaluation of organic matter levels in streams of urban catchments must consider changes to supply (both from riparian and catchment sources) and retention processes (Fig. 1).

Biological composition

Algae.—Increased nutrient concentrations in streams impacted by urbanization (e.g., Lee and Bang 2000, Hatt et al. 2004) can promote increased algal biomass. However, such a stimulatory effect on algal growth may be countered by increased flow disturbance (shear stress and scouring), turbidity, or depth within incised urbanized channels, increased toxicity from contaminated sediments (Paul and Meyer 2001), or even by direct, deliberate application of algicides into waterways (Grimm et al. 2005, Fig. 1).

Few studies have directly assessed the effect of urbanization on algal biomass. In urban streams of eastern Melbourne, Australia, Taylor et al. (2004) demonstrated an increase in biomass with increased urban density and drainage connection. In that study, increased surface light resulting from widened channels was countered by increased light attenuation in the channels deepened by incision (Fig. 1). Increased biomass was inferred to result from increased frequency of small storm flow events with high P concentrations. In contrast, in streams of western Georgia, USA, along an urbanization gradient, high streamwater N and P in urban catchments did not consistently increase algal biomass, likely because of concomitant increases in flow disturbance and scour (B. S. Helms and J. W. Feminella, Auburn University, unpublished data). No urban-related increase in algal biomass was observed in a study of Pennsylvanian streams (Hession et al. 2003a). Increased algal biomass as observed by Taylor et al. (2004) is less likely to occur in regions where, in the absence of urban impacts, streams are not nutrient-limited.

Compared with algal biomass, there are more studies of the effects of urbanization on algal community composition, although patterns appear inconsistent across geographic regions. Munn et al. (2002) documented a shift from forested streams dominated by cyanobacteria to diatom-dominated urban streams, whereas Taylor et al. (2004) noted a shift from diatom-dominated forested streams to urban streams with greatly increased biomass of filamentous algae. Changes in diatom composition from oligotrophic to eutrophic species have been commonly reported (Chessman et al. 1999, Winter and Duthie 2000, Sonneman et al. 2001, Newall and Walsh 2005). Such assemblage shifts have often been reported as showing no change in species richness (Sonneman et al. 2001, Newall and Walsh 2005) or a eutrophication-associated increase in species richness (Chessman et al. 1999).

Macroinvertebrates.—Benthic macroinvertebrate assemblages are perhaps the most widely studied aspect of urban stream ecosystems (e.g., Chessman and Williams 1999, Walsh et al. 2001, Morley and Karr 2002, Stepenuck et al. 2002, Roy et al. 2003, Wang and Kanehl 2003, Wang and Lyons 2003, Miltner et al. 2004, Walsh 2004, and see Paul and Meyer 2001). In virtually all studies, sensitive species were absent or less abundant in streams draining urban areas. Globally, streams in urban areas are characterized by species-poor assemblages, consisting mostly of disturbance-tolerant taxa. Assemblages of highly degraded streams within urban catchments are numerically dominated by a few species of oligochaetes (typically tubificids, lumbriculids, and naidids) and chironomids. We know of no studies where any other pattern has been reported.

Because macroinvertebrate assemblages have been so widely studied and show consistent community shifts with catchment urbanization, this group of biota is arguably the most useful one for comparing interregional variation in response to urban land use. Variation in the shape and slope of relationships between macroinvertebrate and landuse variables across cities of contrasting climatic, physiographic, and social conditions is one area of potentially fruitful research. Less-studied research areas concerning macroinvertebrate response to urban land use include secondary production, and the potential for recovery of macroinvertebrate assemblages in highly degraded streams.

Fish.—Most studies have found that stream fish assemblages respond to catchment urbanization in a similar pattern to macroinvertebrates: a loss or reduced abundance of sensitive species, and a less diverse assemblage numerically dominated by disturbance-tolerant species (e.g., Roth et al. 1996, Wang and Lyons 2003). Such a trend was observed in streams of Atlanta (Roy et al. 2005), and in streams of the eastern Piedmont physiographic region of Maryland (Morgan and Cushman 2005). Similar results were reported in lower Piedmont streams of the southeast where fish health (as indicated by % of fish with eroded fins, lesions, or tumors), and proportions of sensitive breeding guilds (% lithophilic spawners) decreased with increasing urbanization (Helms et al. 2005). However, in the Coastal Plains physiographic region of Maryland the observed shift from sensitive to tolerant fish species was not accompanied by a reduction in species richness or abundance (Morgan and Cushman 2005). Shifts in assemblage structure seem universal, but such shifts may not always result in reduced species richness or abundance. In fact, highly abundant populations of tolerant species may be supported (Walters et al. 2003, but see Swift et al. 1986). As with macroinvertebrates, opportunities exist to better understand interregional patterns of fish assemblage response to urban land use, and the potential for recovery of fish assemblages in degraded streams.

Less-studied biota.—In their review, Paul and Meyer (2001) identified stream macrophytes as a group in which the response to urban land use has been little studied; this deficiency remains unchanged. The response to urbanization of higher vertebrates relying on stream resources is even less studied. In our series, influence of urban land use limiting distributions of the platypus, *Ornithorhynchus anatinus*, has been reported for the first time (Serena and Pettigrove 2005). The authors presented 3 hypotheses to explain lower abundance of platypus in urban sites: reduced feeding efficiency from increased algal growth in degraded streams, reduced abundance of preferred prey (generally sensitive invertebrate taxa), or bioaccumulation of toxicants, which may reduce survivorship and/or reproduction (Serena and Pettigrove 2005, Fig. 1).

Ecosystem processes

Nutrient processing.—Nutrient uptake was reduced in more urbanized streams of both Georgia (Meyer et al. 2005) and desert streams of Arizona and New Mexico (Grimm et al. 2005). In Atlanta streams, reduced uptake likely occurred because of reduced abundance of fine benthic organic matter, which decreased as catchment urbanization increased (Meyer et al. 2005). In desert streams, reduced uptake rates in urban streams were attributable to reduced channel complexity (hence reduced transient zone storage), and possibly reduced primary productivity, with the latter likely occurring from direct application of algicides into streams (Grimm et al. 2005).

Inwood et al. (2005) found higher sediment denitrification rates in urban streams than in forested streams, although sediment denitrification in urban streams removed a smaller proportion of stream NO_3-N load than was the case in forested streams. Groffman et al. (2005) demonstrated that debris dams high in organic matter in highly urbanized streams could act as hot spots (McClain et al. 2003) for denitrification. High denitrification rates were associated with high NO_3–N concentrations, suggesting an important feedback mechanism between instream processes and water chemistry. However, the relative importance (and sustainability, Booth 2005) of such instream hot spots for denitrification compared with those elsewhere in the catchment (Grimm et al. 2005) remains unclear. For example, it is logistically difficult to maintain a high abundance of organic debris dams in urban streams with flashy, high stormflows, so this restoration measure may be prohibitive. Alternatively, dispersed stormwater control structures, drainage ditches, and other human structures that foster anaerobic conditions may function as denitrification hot spots in the catchment (Groffman and Crawford 2003).

Production and respiration.—Only a handful of studies have reported on the degree to which stream metabolism varied with catchment urbanization (Paul 1999, Meyer et al. 2005). Neither gross primary production (GPP), community respiration (CR), nor net ecosystem metabolism were associated with urbanization in Piedmont streams draining Atlanta (Meyer et al. 2005), and a similar result was reported from headwater urban streams from the same region (Gibson 2004). However, in a large river in suburban Atlanta, regulation of water withdrawals and the proportion of discharge as wastewater effluent appeared to control GPP and CR (Gibson 2004). Further research is required to test if a similar lack of trend is observed in streams where algal biomass increases with increasing urbanization (e.g., Taylor et al. 2004). In such streams, there is evidence of a shift of the dominant microbial pathways for C and nutrient processes from diverse sources to one dominated more by algal C (Harbott and Grace 2005).

Mechanisms Driving the Urban Stream Syndrome

Catchment sources of stress

The complexity of urban land use and the multitude of associated human activities present challenges for understanding the mechanisms by which urban impacts change ecological structure and function (Booth et al. 2004). Urban-derived stressors not only interact with each other, but stressors also may covary because many can originate from the same large-scale source (Fig. 1). Based on the available correlational evidence, primarily of spatial patterns, impacts of urban land use on aquatic ecosystems can be ascribed to a few major large-scale sources. Symptoms of the urban stream syndrome that appear to occur consistently across regions are predominantly driven by urban stormwater runoff, which, in almost all urban areas of the world, has traditionally been managed for flood control by direct piped connection between impervious surfaces and streams (Fig. 1). Therefore, it is likely that stormwater impacts are the primary driver behind the often-reported correlations between stream condition and catchment imperviousness.

Other anthropogenic impacts that may or may not be associated with urban land use may obscure the relationship between stream condition and imperviousness. For instance, Miltner et al. (2004) found that effects of combined or sanitary sewer overflows, wastewater treatment plant effluents, and legacy pollutants occurred independently of the urban density gradient in Ohio streams. When sites affected by such allied stressors were included, associations between biotic integrity and urban density were obscured (Miltner et al. 2004). Relationships between ecological condition and catchment imperviousness also may vary between and within regions because of differences in the permeability of pervious parts of the catchment (Booth et al. 2004) or differences in management practices for land cover and drainage of impervious areas (Walsh et al. 2005).

Some urban impacts may influence only a subset of stream ecosystem attributes. Effects on baseflow will vary depending on the degree to which reticulated water supply or sewerage networks leak or spill into the stormwater drainage system or enter the natural subsurface flow pathways to streams (Fig. 1). Such leaks are unlikely to have any effect on other aspects of hydrology, and water supply leaks are unlikely to have substantial impacts on water quality. If sewerage leaks reach streams through subsurface flows, their impacts on streamwater quality will largely be limited to pollutants that have high mobility through soils, such as NO_3–N (e.g., Hatt et al. 2004). Differences in the extent to which infrastructure leakage affects streams may be a function of infrastructure design and age, as well as catchment physiography and climate.

Deforestation, particularly in the riparian zone, is often identified as an important driver of urban impacts to streams (e.g., Stephens et al. 2002, Booth 2005). Urban land use and riparian degradation usually covary (e.g., Morley and Karr 2002, Burton et al. 2005, King et al. 2005), with lowland urban development often resulting in restructuring or loss of riparian vegetation. Because of this covariance, direct evidence of the separate or relative importance of catchment urbanization compared with riparian land use is limited. In a study of paired reaches with and without riparian forest along an urban gradient in Pennsylvania, Hession et al. (2003a, b) found that the presence of riparian forest affected geomorphology, concentrations of bioavailable nutrients, and algal biomass independently of urban effects. In contrast, assemblage composition of diatoms, macroinvertebrates, and fishes were associated with the urban density gradient, but were less strongly affected by the presence of riparian forest (Hession et al. 2003a).

Riparian forests certainly have important ecological links to stream ecosystems through their influence on water chemistry, organic matter input, and shading (e.g., Pusey and Arthington 2003). It is conceivable, therefore, that loss of riparian forest may severely limit the potential for recovery of streams impacted by urban land use (Fig. 1). However, even in catchments with intact riparian forests, channel incision and increases in impervious surfaces and piped drainage can interact to significantly lower riparian water tables and, thus, potentially reduce the interaction between the riparian zone and pollutants moving in shallow groundwater flow from uplands (Groffman et al. 2002).

In one sense, piped stormwater drainage systems, typical of urban centers worldwide, serve to make large portions of urban catchments effectively riparian. In this context, rain, litter (leaf and human-derived), and pollutants that drop on or adjacent to impervious surfaces connected to drains are likely to be delivered directly to streams (Fig. 1). Therefore, we hypothesize that as the area of the catchment directly connected to streams by the piped drainage network increases, the relative influence of the true riparian zone on stream condition decreases.

There is some evidence, however, that the spatial configuration of urban land use and its proximity to the stream channel has an influence on stream ecological condition. King et al. (2005) demonstrated that urban land cover was a better predictor of macroinvertebrate composition if it was inversely weighted by the distance from the sampling site (i.e., modelling a larger effect for closer urban land use than for more distant urban land use). A diminution of effect with increasing distance could result from an increased probability of good riparian condition in sites with more distant catchment urban land use, allowing more urban runoff to be intercepted before reaching the stream. However, if the urban land use had conventional stormwater drainage networks that bypassed terrestrial pathways, this diminution of effect would more likely have resulted from instream processes dampening impacts with distance travelled along the stream rather than from protection afforded by riparian vegetation.

Relationships between instream ecological metrics and catchment metrics

Relationships between instream ecological condition and metrics of catchment land use such as TI have been interpreted in several ways (Fig. 2). The concept of a critical threshold of urban density beyond which the probability of degradation is greatly increased has been both championed (Beach 2001, Center for Watershed Protection 2003) and disputed (Booth et al. 2002). However, the possible shapes of relationships and the nature of such thresholds have not been clearly distinguished in this debate.

Booth et al. (2002) argued that a monotonic relationship between TI and stream condition was likely to be a more parsimonious representation than any other of the continuum of effects associated with increasing urban density, particularly if the distribution was considered a factor-ceiling distribution (i.e., a linear upper boundary of the distribution of data points; Thomson et al. 1996, Booth et al. 2004). However, even with a monotonic decline with increasing TI, a threshold of poor condition (i.e., streams reaching maximum degradation) at a level of catchment TI $<100\%$ is highly likely for

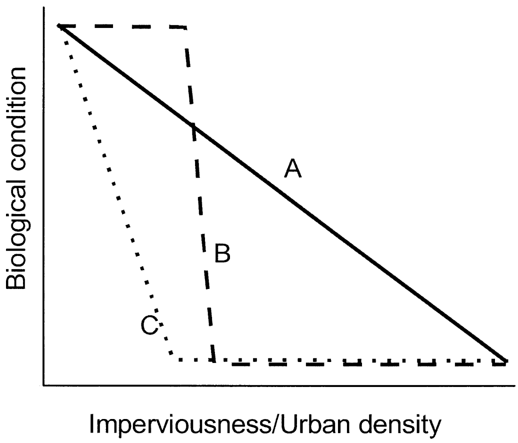


FIG. 2. Three models that have been applied to stream biological condition in response to catchment urbanization, often as a factor-ceiling distribution (Thomson et al. 1996), where most observations fall below the illustrated trendline. A.—A linear decline with increasing urban density (e.g., Booth et al. 2004). B.—An upper threshold switching to a lower threshold (e.g., King et al. 2005). C.—A linear decline with increasing urban density to a lower threshold (e.g., Walsh et al. 2005).

most ecological metrics. Therefore, the monotonic decline model advanced by Booth et al. (2002, relationship A in Fig. 2) is conceptually compatible with the linear-to-lower-threshold models of Walsh et al. (2005, relationship C in Fig. 2).

A stepped threshold relationship, where good stream ecological condition occurs up to a particular level of TI (often cited as 10%, Beach 2001) and beyond which degradation is highly likely (relationship B in Fig. 2), is consistent with observed distributions of ecological indicators in some studies (e.g., King et al. 2005, Walsh et al. 2005). The shape of the relationship between an ecological metric and a source of environmental stress may depend on the sensitivity of the response variable, the mode of action of a stressor (Allan 2004), or possibly the number and interactions of stressors. However, rather than being a function of ecological interactions, stepped threshold relationships could vary as a function of how landuse variables are measured, or the way urban areas have traditionally been built. For example, Walsh et al. (2005) reported streams of eastern Melbourne to be in good condition up to 12% TI, whereas streams with higher TI were consistently in poor condition, a distribution resembling a stepped threshold (relationship B in Fig. 2, see also King et al. 2005). However, this relationship became a linear decline to a threshold when effective imperviousness (EI) was used as the independent variable rather than TI (Walsh et al. 2005). Thus, the apparent threshold was a function of the proportion of impervious surfaces connected to the stream by pipes. In Walsh et al. (2005) and other studies, observed stepped-threshold relationships may be a function of how urban areas are developed, with widespread piped drainage networks only being installed universally beyond a certain level of development, rather than a relationship driven by ecological processes.

Walsh et al. (2005) found that a "linear-to-lower-threshold" model explained patterns of a wide range of ecological metrics, although water chemistry and algal-related metrics reached maximum levels of degradation at lower EI than did macroinvertebrate metrics. The degree to which these findings apply to other systems or geographic regions is unknown, and a key remaining question is if such changes in stream conditions, whether occurring linearly or as thresholds, are reversible. This knowledge is vital in understanding the potential for restoration of degraded streams because simple reversal of conditions may not be possible once a threshold is crossed.

Instream stressors and their interactions

The complex interactions of multiple urban-related stressors and various components of stream ecosystems result from a relatively few interrelated impacts arising from the way urban areas are currently built and managed (Fig. 1). The complexity of interactions among stream ecosystem components and catchment-scale processes underlines the argument of Booth (2005) that manipulating individual instream elements is unlikely to be self-sustaining unless large-scale catchment processes are also addressed. The importance of the catchment processes to the stream has long been recognized (Hynes 1975, Karr and Schlosser 1978), but often forgotten in the implementation of stream management.

A clearer understanding of the interrelationships portrayed in Fig. 1 is critical to guiding the actions required to reduce the impacts of urban land use. For example, stormwater managers tend to incorporate end-of-pipe hydrologic management to address erosive flows (e.g., retention basins and treatment ponds and wetlands), but without understanding the mechanism of the relationship between hydrologic alteration and biotic impairment (e.g., frequency of pollutant delivery, high-flow stresses to biota) there is no guarantee that such management strategies will work. The frequency of overland flow, hypothesized to be a critical stressor to streams (Walsh et al. 2005), is unlikely to be addressed adequately using end-of-pipe solutions, but would require dispersed, at-source approaches to treatment (Booth 2005, Walsh et al. 2005). Adaptive management of urban developments is one approach that could be used to assess the relative importance of differing parts of the hydrograph. In correlational studies of spatial patterns of land use, the use of partial Mantel tests in path analytical frameworks (King et al. 2005) is also a potentially useful approach to quantifying the importance of linkages portrayed in conceptual models such as Fig. 1.

Our understanding of stressor mechanisms and their interactions is limited by a lack of experimental (i.e., causal) evidence. The unravelling of the interactions between small-scale stressors may ultimately prove experimentally intractable. The common catchment-scale sources of many stressors suggest that more tractable understanding—providing more applicable management solutions—may lie in experimental manipulation at the catchment scale (Walsh et al. 2005). Such approaches are essential because almost all studies of the effects of catchment urbanization on stream ecology have been correlational, substituting time effects (i.e., tracking temporal stream conditions as catchments develop) with space effects (i.e., comparing contemporaneous stream conditions across contrasting catchment urbanization). Furthermore, correlational studies can be vulnerable to problems of covariance between urban land use and natural landscape features (Allan 2004).

The Search for a Cure: Priorities for Restoration and Protection of Urban Streams

Urban streams have the potential to provide precious natural resources to humans who live near them (Meyer et al. 2005). In many cities of the world this potential is far from fully realized because, historically, most urban development has involved transforming streams into drains or sewers. The primary goal for urban waterway management for most of the 20th century was the safeguarding of humans from floods and disease. Although such a goal must remain the first priority, traditional approaches to waterway management for public health and safety have been at the expense of other goals, such as public amenity and ecosystem health. New approaches to urban design and waterway management show great potential for achieving all public safety and amenity goals, together with goals of improved ecological condition in streams of many urban areas (e.g., Lloyd et al. 2002).

As the movement to restore urban streams grows, urban stream ecologists will be challenged to identify the primary mechanisms of degradation, the best management actions to reverse those mechanisms, and attainable goals for restoration (Hobbs and Norton 1996, Booth 2005, Palmer et al. 2005, Walsh et al. 2005). Further challenges involve engaging the human communities of urban areas to achieve a shared understanding of what is achievable and desirable to communities for their local streams. For example, urban stream attributes with limited ecological values, such as mowed grass riparian zones or paved streamside paths, may have amenity values for some urban communities (e.g., Tunstall et al. 2000). Sometimes, value placed in such altered, unnatural environments can be a product of people not missing what they never had (Rosenzweig 2003), and stream ecologists might play a role in educating communities on how streams more closely resembling natural conditions might be more desirable. However, for such education of urban communities to be effective, restoration actions and attainable restoration goals must be appropriately balanced (Table 2).

Streams in good condition in areas with moderate levels of catchment urbanization have been reported in many urban centers (e.g., Booth et al. 2004, King et al. 2005, Walsh et al. 2005), suggesting that protection of ecological structure and function is possible at this and lower levels of urbanization. Two key factors are likely to be causes of high variability in stream ecological condition with similar TI: 1) the distance between the reach and urban land use (King et al.

TABLE 2. Five groups of goals for restoration in urban areas (columns) and 5 classes of management action (rows) that could be taken, alone or in combination, to achieve restoration goals. Allied stressors include sanitary sewer overflows or leaks and point source or long-lived pollutants from earlier land uses (e.g., Miltner et al. 2004). Dispersed stormwater treatment is assumed to be extensive enough to reduce frequency of runoff from the catchment to near the pre-urban state (Walsh et al. 2005). The likelihood and magnitude of success are indicated by symbols: S = some improvement likely but long-term sustainability unlikely, *? = improvement likely in some cases, *, **, *** = likely improvement of increasing magnitude.

Restoration measure	Aesthetics/ amenity	Channel stability	Enhanced N processing	Improved ecological condition	
				Riparian	Instream
1. Riparian revegetation	S			S	
2. Instream habitat enhancement	S	S	S		
3. End of pipe stormwater treatment	*?		*		
4. Eliminate allied stressors	*?		*?		
5. Dispersed stormwater treatment		*	**		
3 + 4	*?		*		
5 + 4	*?	*	**		*
5 + 4 + 2	*	*	***		**
5 + 4 + 2 + 1	*	*	***	*	***

2005), and 2) the hydraulic efficiency of stormwater drainage (Walsh et al. 2005). Research and adaptive management is required to test if these factors are truly causal agents. Well-designed experiments are required to assess 1) response of stream structure and function to forestland conversion to urban land use under different drainage design and spatial arrangements, and 2) if structure and function can be restored by drainage retrofits in existing urban areas (Walsh et al. 2005).

In many cities, active programs exist for geomorphic stream restoration to stabilize incising streams and to protect nearstream property and infrastructure (Brooks et al. 2002, Nilsson et al. 2003). Such stream-based restoration measures are what Booth (2005) described as short-term, local-scale enhancement. A growing literature exists suggesting that such measures are unlikely to result in composition of urban stream invertebrate or fish assemblages becoming more similar to those in nonurban streams (Table 2, Walsh et al. 2005). However, the potential for instream structures to act as hot spots for nutrient processes (Groffman et al. 2005) suggests that some ecological benefit may be achieved by local-scale enhancement of stream habitat (Table 2). Effects of habitat-scale enhancement on ecological variables, such as organic matter retention and nutrient processing, need investigation, including the degree to which structures built for habitat enhancement are sustainable (Frissell and Nawa 1992, Booth 2005).

The relative importance of terrestrial processes in the upland and riparian parts of the catchment compared to instream processes is a critical area of urban stream research, inextricably linked to the way stormwater is managed. Traditionally, stormwater management has largely been aimed at preventing floods, trapping sediment, and reducing erosion potential of runoff. Stormwater managers are increasingly aiming to minimize pollutant loads, particularly N, which is commonly an important threat to downstream coastal water bodies (Vitousek et al. 1997). The studies of nutrient uptake in our series (Grimm et al. 2005, Groffman et al. 2005, Meyer et al. 2005) all suggest an important feedback between streamwater nutrient inputs and nutrient uptake by instream processes. A critical question for urban water management, therefore, is whether N loads can be more effectively managed by maximizing processes that increase N retention in the catchment, the stream, or both (Grimm et al. 2005, Groffman et al. 2005).

It is almost certain that reversal of the consistently observed symptoms of the urban stream syndrome of a flashier hydrograph, elevated nutrients and contaminant concentrations, altered channel geomorphology and stability, and re-

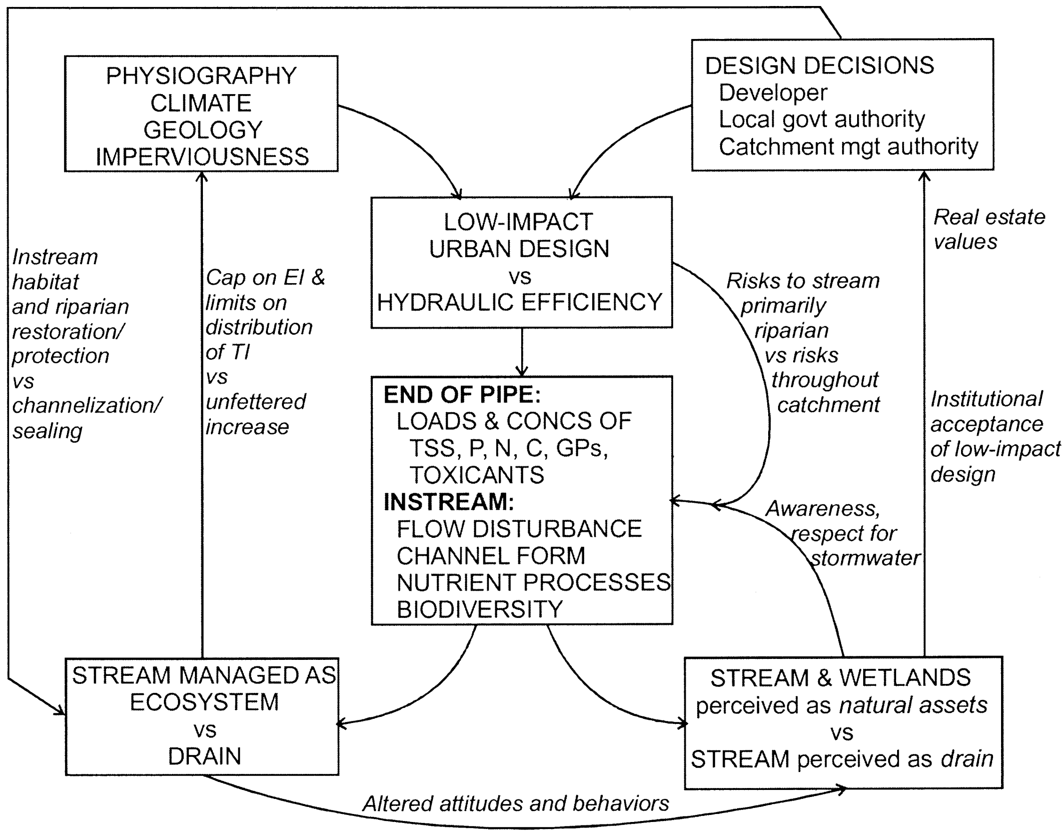


FIG. 3. A conceptual model of stormwater management in relation to stream ecology and urban ecology (after Grimm et al. 2000). EI = effective imperviousness, TI = total imperviousness, GPs = gross pollutants, TSS = total suspended solids.

duced biotic richness and increased dominance of tolerant species requires catchment-scale solutions. A primary requirement of reversing the urban stream syndrome is the management of wastewater effluent and legacy pollutants. In many parts of the developing world, such stressors present significant barriers to achievement of waterways that protect human health, let alone ecological health. In many cities of the developed world, these pollutants are now well managed, although streams remain in poor ecological condition, primarily because of stormwater impacts.

The extent to which stormwater impacts can be managed through innovative approaches to drainage design remains to be tested. However, we believe such approaches may offer the best opportunity for ecologically successful urban stream restoration. Such catchment-scale reductions in stormwater drainage connection may create an ecosystem that is more self-sustaining and resilient to perturbation, thus fulfilling important criteria for ecological improvement of streams (Palmer et al. 2005). Riparian revegetation and instream habitat enhancement also may be necessary, although these more traditional restoration approaches are unlikely to be sufficient by themselves in most urbanized catchments (Table 2). In many urban areas, the prospect of restoration of waterways to more naturally functioning streams may be so remote that urban communities may need to rethink restoration objectives. In such cases, the task may become one of designing ecosystems to maximize attainable ecosystem services (Grimm et al. 2005).

Stream ecology and urban ecology

Human populations are one of the central defining elements of urban areas, and future investigations of urban stream ecology must consider the interaction between social and ecological variables (Pickett et al. 1997, Meyer et al. 2005). The success of any attempt to improve the ecological condition of streams in urban areas will largely depend on human attitudes and behaviors within the catchments, and there may be inherent conflicts between appreciation of urban streams and their protection (Booth 2005). However, integrated social and ecological studies may help to maximize social and ecological outcomes. We end the paper with an example of a conceptual framework for an integrated understanding of social and ecological elements of a developing suburb.

Low-impact urban design (LID) has been identified as an approach with great potential to achieve ecological improvements in urban streams (Booth 2005, Walsh et al. 2005). However, this potential remains untested, because LID has not yet been adopted widely or strategically enough to assess its effects on receiving streams. Many institutional and social impediments to its widespread adoption remain in many regions. Fig. 3 (after Grimm et al. 2000) places the adoption of LID into a conceptual framework for understanding urban ecological systems. Treatment techniques used in LID are primarily applied in the catchment, rather than instream, and largely involve reduction of the hydraulic connection between urban impervious surfaces and the receiving stream.

Stormwater management tools (e.g., Cooperative Research Centre for Catchment Hydrology 2003) use large-scale variables such as climate, physiography, soil characteristics, and imperviousness to predict the concentrations and loads of selected pollutants exported from catchments. The framework (Fig. 3) broadens conventional stormwater management to include the stream and its biological components and processes, requiring predictive models of instream ecological response to stormwater management.

The framework also includes social attributes, which are intrinsic and thus critical elements of any urban ecological study. Human behavior will interact with ecological impacts of stormwater because attitudes and behavior regarding stormwater drainage will have a direct bearing on potential loads of pollutants delivered to the stormwater system. These attitudes are likely to be altered by changes in the condition of receiving waters resulting from the application of LID. Moreover, application of LID also reduces the risks associated with human behaviors (e.g., spills of pollutants onto impervious surfaces in the catchment) by reducing the direct connection between dispersed upland parts of the catchment and the stream. Changes in public attitudes and amenity of the neighborhood and its waterways are likely to result in tangible economic benefits, such as increased real estate values, which in turn, if coupled with educational programs designed to increase public awareness about the social and ecological advantages, are likely to increase and reinforce acceptance of LID by management authorities (Fig. 3).

Thus, the challenge for stream ecologists in furthering our understanding of streams in urban areas is to not only better understand interactions between catchments and stream processes, but to integrate this work with social, economic, and political drivers of the urban environment. The advancement of stream ecology in urban areas and the conservation and restoration of urban streams will require stream ecologists to embrace the approaches of urban ecology (e.g., Grimm et al. 2000) in its integration of ecological, social, behavioural, and economic research.

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