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Twenty-six key research questions in urban stream ecology: an assessment of the state of the science

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Abstract. Urban streams have been the focus of much research in recent years, but many questions about the mechanisms driving the urban stream syndrome remain unanswered. Identification of key research questions is an important step toward effective, efficient management of urban streams to meet societal goals. We developed a list of priority research questions by: 1) soliciting input from interested scientists via a listserv and online survey, 2) holding an open discussion on the questions at the Second Symposium on Urbanization and Stream Ecology, and 3) reviewing the literature in the preparation of this paper. We present the resulting list of 26 questions in the context of a review and summary of the present understanding of urban effects on streams. The key questions address major gaps in our understanding of ecosystem structure and function responses (e.g., what are the sublethal impacts of urbanization on biota?), characteristics of urban stream stressors (e.g., can we identify clusters of covarying stressors?), and management strategies (e.g., what are appropriate indicators of ecosystem structure and function to use as management targets?). The identified research needs highlight our limited understanding of mechanisms driving the urban stream syndrome and the variability in characteristics of the effects of urbanization across different biogeoclimatic conditions, stages of development, government policies, and cultural norms. We discuss how to proceed with appropriate management activities given our current incomplete understanding of the urban stream syndrome.

Key words: urbanization, impervious surface, stressors, management, ecosystem function, community structure.

Catchment urbanization sets into motion a cascade of changes to stream ecosystems. These changes, collectively termed the urban stream syndrome (Meyer et al. 2005a, Walsh et al. 2005b), have been the subject of an expanding field of scientific research that has contributed to successful characterization of urban streams in many parts of the world (see reviews by Paul and Meyer 2001, Walsh et al. 2005b). Nevertheless, considerable gaps in our understanding remain. Some areas, such as urban stream processes and sublethal effects on biotic assemblages, are only partially understood (Martí et al. 2004, Smith et al. 2009), and the work of characterizing the variability of the urban stream syndrome under differing government policies, cultural norms, and biogeoclimatic conditions has only just begun. Perhaps the biggest gap in our knowledge concerns the relative importance of different mechanisms driving the urban stream syndrome and the interactions among them. Our ability to make inferences about the relative importance of different stressors is often confounded because the process of urbanization changes multiple stressors at the same time (Paul and Meyer 2001, Walsh et al. 2005b).

Our objective is to advance the pace of research into these difficult problems by identifying some of the most critical unanswered questions in urban stream ecology. We are motivated in part by an interest in developing a body of information useful to urban stream managers. The current lack of mechanistic understanding makes difficult the identification of the specific stressors of concern under different conditions and the most efficient solutions for meeting stream management objectives. Our intention is to identify research areas that will yield insights useful for achieving efficient, effective management of urban stream stressors.

We define *urban* in the broadest possible sense to include the entire landscape developed for residential, commercial, industrial, and transportation purposes, including cities, towns, villages, suburbs, and exurban sprawl that has a density of >1 residential unit/2 ha. We use this encompassing definition because even very low-density development can have measurable negative effects on aquatic ecosystems. We focus on impervious cover (total imperviousness [TI]) as an indicator of urban intensity because, in the absence of deliberate management, TI is highly correlated with stream degradation (Leopold 1968, Schueler 1994, Booth and Jackson 1997). This relationship is captured by the Impervious Cover Model (ICM; Center for Watershed Protection 2003), which takes the form of a wedge-shaped distribution of ecological condition. Streams with low TI can vary widely in condition, from minimally altered to degraded, but as TI increases, the best attainable condition declines until only degraded streams are observed.

The strong relationship between TI and stream ecosystem indicators is driven by the fact that TI affects streams via multiple mechanistic pathways and is closely correlated with other stressors (Brabec et al. 2002, Walsh et al. 2005b). Elevated TI causes an increase in contaminant-laden stormwater runoff that alters stream hydrology at the same time that it alters water chemistry (Fig. 1). This effect is often exacer-

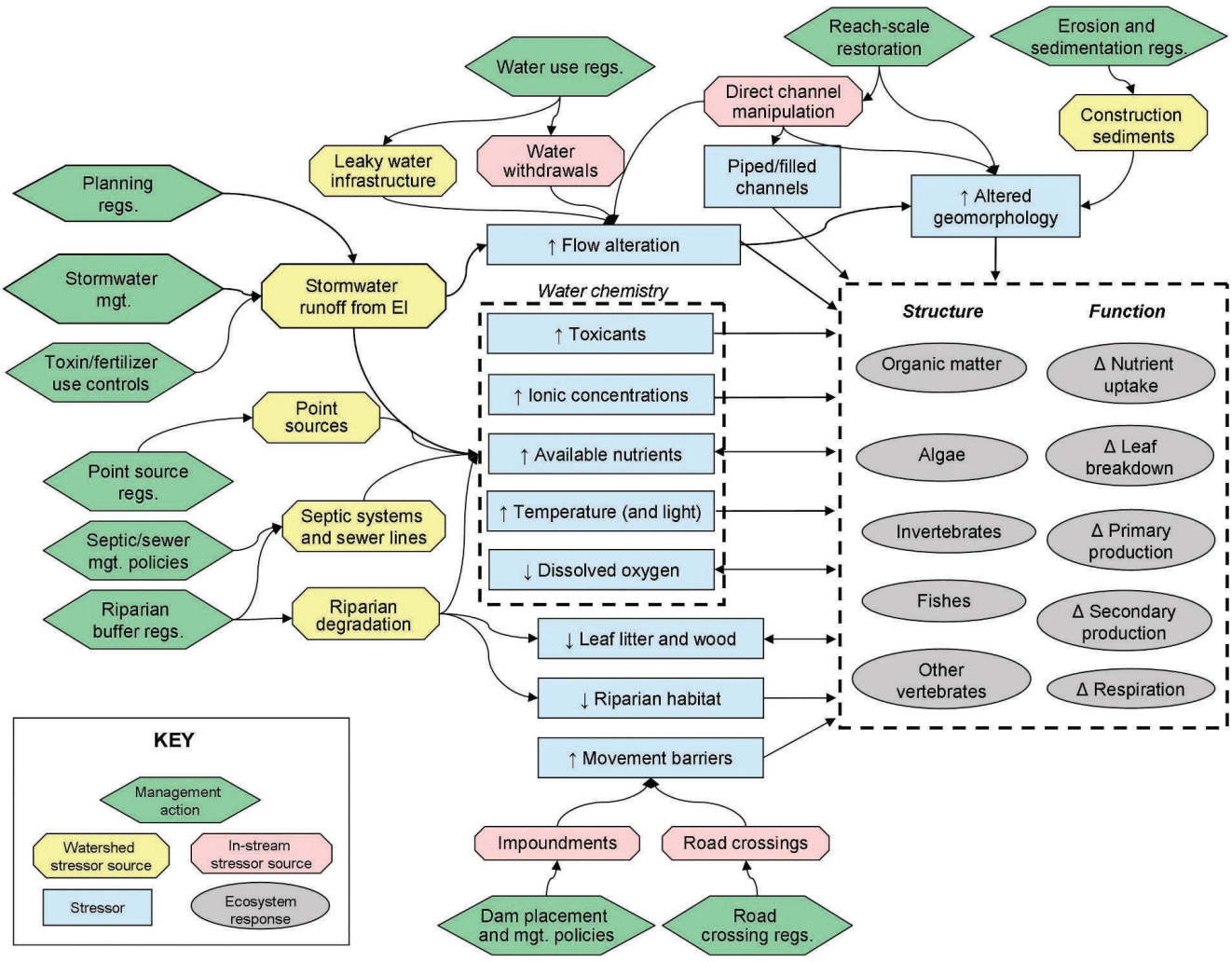

FIG. 1. Conceptual model of urban impacts on streams. Arrows show selected major pathways, but many important pathways are omitted for readability. For example, piped/filled channels affect virtually all other stressors but most of these linkages are not shown. All water-quality variables (grouped within dashed lines in center) are treated as a group for purposes of linkages to instream stressor sources; all stream ecosystem variables (grouped within dashed lines at right) are likewise treated as a group. Pathways among the stream ecosystem variables are not shown for readability. EI = effective impervious, mgt. = management, regs. = regulations.

bated by routing runoff to streams through stormwater drainage pipes. For this reason, such directly connected impervious cover (termed effective imperviousness [EI]) is often a better predictor of stream ecological condition than is TI (e.g., Wang et al. 2001, Hatt et al. 2004; see also review by Brabec et al. 2002). High TI and EI tend to be correlated with sewerage infrastructure, stream piping, and reductions of riparian vegetation, all of which can further degrade water and habitat quality. On the other hand, some urban stressors, such as septic systems and point-source discharges, with weaker correlations with impervious cover might be equally important in driving the urban stream syndrome in some regions of the world. These various stressors and their relationships to sources and responses are shown graphically in Fig. 1. Only selected major causal pathways are shown and much detail, including the complexity of urban stream food webs and functional relationships (grouped in a box at the right of the diagram), is omitted. More detailed diagrams for individual stressors were developed for the US Environmental Protection Agency (EPA) Causal Analysis/Diagnosis Decision Information System (CADDIS) program (www.epa.gov/caddis). We have adopted symbols and terms consistent with CADDIS

TABLE 1. Number of individuals attending the Symposium on Urbanization and Stream Ecology (SUSE2) by affiliation type. The distribution of affiliations of members of the urban stream listserv was similar.

Affiliation type	Attendees
University	75
US federal government	23
Consultant	6
US local or state government	5
Nongovernmental organization	3
Non-US government	3
Private individual	1
Total	116

and consider our diagram to be a collapsed version that aggregates all CADDIS diagrams related to urban stressors. In our paper, we used the organizational framework of ecosystem responses, stressors, and sources to summarize our current understanding of urban stream ecosystems. We identified critical unknown elements, which we list as key research questions. Later, we discuss how urban stream management can proceed with our current level of understanding.

Methods for identifying key questions

We identified key research questions through 3 phases of information gathering: 1) solicitation of questions via a listserv and website survey, 2) breakout sessions during the Second Symposium on Urbanization and Stream Ecology (SUSE2; Salt Lake City, Utah), and 3) drafting of this paper. During winter 2007 to 2008, we solicited candidate research questions from a listserv of >100 ecologists, engineers, and environmental scientists. We removed redundant questions and combined similar ones to produce a list of 47 questions, which were then resubmitted to listserv members for ranking in a website survey. Twenty-eight people responded to the survey. Based on the results, we cut low-ranked questions, combined and split some questions, and added a few new ones to produce a revised list of 38 questions. At the SUSE2 meeting held on 22 to 23 May 2008, 116 attendees (Table 1) were divided into 4 groups to review and refine the proposed questions. Each group produced a new list of questions, many of which were broader in scope than the initial list. This process yielded a total of 19 questions. Our paper is based on the list of questions refined by meeting participants, complemented by some of the questions from the web survey and additional questions added during manuscript preparation. The result is a set of 26 questions that we suggest are among the top research priorities needed to improve our understanding and management of urban streams.

Although urban stream management was a motivation for developing the research questions, the attendees at SUSE2 and the contributors of research questions were mostly academics and government researchers, not watershed managers or planners (Table 1). Therefore, this list represents the opinion of a subset of the research community regarding knowledge gaps that should be filled to develop more informed and effective urban stream management policies and strategies. SUSE2 included a panel of watershed managers to help focus discussions, but the primary goal was not to identify research priorities for meeting existing short-term management goals (although these were considered), but rather to consider what new research was needed to advance the state of the science in ways that will better meet the broader objective of healthy urban streams. We intended this project to be international in scope, but most of the authors of this paper and 91% of participants at SUSE2 were from the US (including 7 from Puerto Rico). The remaining SUSE2 participants were from Australia, Brazil, Canada, China, New Zealand, and Spain. This geopolitical distribution no doubt introduced some bias into the findings.

Stream Ecosystem Responses to Urbanization

Stream community structure responses

Research has repeatedly demonstrated declines in assemblage richness, diversity, and biotic integrity of algae, invertebrates, and fishes with increasing urbanization (reviewed in Paul and Meyer 2001, Walsh et al. 2005b). The disappearance of sensitive species is sometimes accompanied by an increase in tolerant species, many of which might be nonnative. Fewer studies have addressed the responses of herpetofauna, riparian birds, and other vertebrates to urbanization (Fig. 2), but the limited data suggest reduced abundances of taxa in these groups in urban streams (Mattsson and Cooper 2006, Lussier et al. 2006, Miller et al. 2007). Microbial communities in urban streams are not well studied and should be a focus of future research (question 1; Table 2). The general pattern of structural change in response to increasing urbanization is fairly consistent across different biogeoclimatic conditions, but responses of individual taxa might vary in different physiographic regions (Utz et al. 2009). The effects of urbanization also might be exacerbated by climate shifts (Webb and King 2009, Nelson et al. 2009), another area in need of

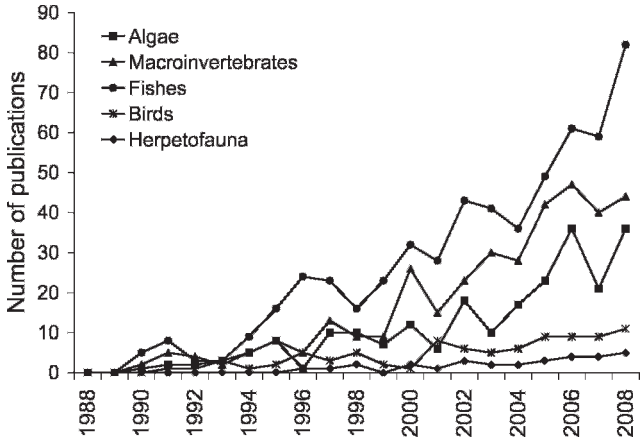

FIG. 2. Number of papers related to effects of urbanization on biological assemblages published in peer-reviewed journals between 1988 and 2008. Search included all articles found in Web of Science using the following search criteria: urban* AND (stream* OR river*) AND algae (alga* OR periphyton OR diatom* OR macrophyte*) AND macroinvertebrates (macroinvertebrate* OR invertebrate* OR insect*), fishes (fish*), birds (bird*) AND herpetofauna (amphibian* OR salamander* OR reptile*).

study (question 2). Urbanization effects often are reduced or confounded when urbanization occurs on land previously used for agriculture (Fitzpatrick et al. 2004, Van Sickle et al. 2004, Heatherly et al. 2007). In their synthesis of research in 9 metropolitan areas across the US, Brown et al. (2009) found no detectable responses of water quality (N and herbicides), algae, and fishes to urbanization of previously agricultural lands. Presumably, this lack of response was observed because sensitive members of these groups already had been eliminated by stressors associated with agricultural activities.

Responses vary by assemblage group, and macroinvertebrates often show the highest sensitivity to urbanization (Brown et al. 2009, Walters et al. 2009). However, this pattern might be a result of the higher diversity of macroinvertebrates than of fishes, and our greater knowledge of invertebrate taxa than of algal taxa. Some studies have demonstrated responses at very low levels of urbanization, such as 4% total urban area (fish; Miltner et al. 2004), 4.4% TI (invertebrates; Ourso and Frenzel 2003), and even 1% EI (diatoms; Walsh et al. 2005a). The spatial arrangement of impervious cover and urban development in a watershed might be a significant determinant of the magnitude of stream ecosystem response (King et al. 2005, Moore and Palmer 2005). Given the range of response patterns and thresholds observed for different taxa and different geographic locations (Walsh et al. 2005b), we argue against attempting to identify a universal threshold of imperviousness or urbanization at which ecosystem responses become significant. Furthermore, evidence indicates that algae, macroinvertebrate, and fish assemblages are influenced by different urban stressors (Brown et al. 2009, Walters et al. 2009). Multiple taxa often are used to assess urban impacts and causal pathways because of the lack of concordance among assemblages and potential differences in response mechanisms (e.g., European Union Water Framework Directive 2000, Walsh and Kunapo 2009).

The structural changes described above might be influenced by trophic and other species interactions, but these mechanistic pathways are not well studied in urban streams. For example, both aquatic macroinvertebrate species and invertivore fish species might decline in urban streams, but whether these responses to stressors are independent or the fish decline is mediated in part by alteration of food resources is not clear. Similarly, loss of sensitive species could result from loss of suitable habitat conditions, or it could reflect a more subtle shift in the competitive environment that favors generalists. More research on foodweb shifts, species interactions, and sublethal responses to urbanization is required (question 3).

Stream functional responses

Stream ecosystem functional responses to urbanization are less studied than are structural responses, but this imbalance is beginning to shift. One frequent finding is that leaf breakdown rates are higher in some urban streams than in nonurban streams, but putative mechanisms differ. Paul et al. (2006) attributed higher breakdown rates to physical abrasion, a result supported by the findings of Swan et al. (2008). However, Imberger et al. (2008) demonstrated that microbial activity, not physical abrasion, was the primary driver. In streams with significant contamination by Zn, Cu, and other metals, leaf decomposition might be reduced as a result of reduced abundances of shredders (Duarte et al. 2008, Roussel et al. 2008). Thus, leaf breakdown rates can show a unimodal response to increasing urbanization in which rates increase with higher nutrients and microbial activity up to some threshold level of urban impact and then decrease in response to high toxicant concentrations at high levels of urban impact (Chadwick et al. 2006). However, Imberger et al. (2008) found increased leaf breakdown despite reduced shredder abundance, perhaps in part because urban riparian zones in some locations are dominated by

TABLE 2. Twenty-six key research questions in urban stream ecology. Questions are organized by the order referenced in the text, not by importance.

Question number	Question
1	What is the relationship between urbanization and the structure and function of microbial communities and their associated services?
2	How will climate change affect structural and functional responses to urbanization?
3	What behavioral and other sublethal life history changes occur to species under urbanization, and how do these affect species interactions?
4	How do transport, retention, removal and transformation of nutrients and C vary among urban streams and compare to less disturbed streams?
5	To what extent do urban-induced changes in lower trophic levels affect upper trophic levels?
6	How do primary and secondary productivity vary among urban streams and compare to less disturbed streams?
7	How do hydrologic budgets and stream hydrologic regimes vary based on density of urbanization, stormwater mitigations, application of low-impact development principles, riparian and forest retention policies, age of infrastructure, climate, and soil conditions?
8	What is the contribution of aging infrastructure (e.g., leaking sewer and water lines) to stream flow, nutrient levels, and toxin levels?
9	What are channel geomorphic responses at different stages of urbanization, are the responses predictable, and do urban streams eventually reach a new stable state?
10	What are the characteristics of structure and function within piped and concrete-lined streams, especially with regard to biogeochemical processing?
11	How do piped and concrete-lined streams affect ecosystem structure and function in downstream reaches?
12	To what degree has elevated temperature contributed to biotic assemblage shifts in urban streams across various regions?
13	Does elevated temperature in urban streams contribute to increases in metabolic rates?
14	Which toxicants have significant effects on urban stream ecosystem structure and function and at what concentrations?
15	Do urban toxicants alter the community or functional composition of microbial communities, thereby affecting critical ecosystem functions?
16	Does alteration of terrestrial inputs have significant effects on urban stream ecosystems, and under what circumstances?
17	How does urbanization affect movement of aquatic organisms and populations both within and beyond urban areas?
18	How can we best identify clusters of covarying stressors (e.g., by causal pathway analysis, management approach, etc.) to minimize the effort required for evaluating individual stressors? How do clusters of covarying stressors vary based on region, type of development, and stage of development?
19	What are the interactions and synergies among multiple stressors and multiple responses?
20	Can retrofitted, dispersed stormwater treatment measures in existing urban areas mimic some of the important ecological and hydrological processes previously performed by headwater streams that are now buried?
21	What are urban stream management strategies that provide both stream ecosystem improvements and other societal benefits?
22	Which management actions are likely to achieve improved ecological condition under different levels of impervious cover and different current stream conditions?
23	What are cost-effective restoration strategies for different stream conditions and different stressors, and when and how should they be applied?
24	What are appropriate indicators of ecosystem structure and function to use as management targets under different circumstances?
25	How do structure and function in urban streams combine to produce ecosystem goods and services, and how do those services map to those desired by the public and decision makers?
26	How can we improve communications between scientists, managers, planners, engineers and stakeholders?

exotic species with more labile leaves than native species. We have seen no published studies of woody debris breakdown rates in urban streams.

N processing in urban streams is an area of active research, and some patterns are emerging (reviewed by Bernhardt et al. 2008). Urban streams tend to transport elevated N loads (Groffman et al. 2004, Lewis and Grimm 2007, Kaushal et al. 2008b), and the biotic capacity of these streams for attenuating increased N loads might become diminished or saturated compared with biotic capacity in streams draining natural landscapes (e.g., Martí et al. 2004, Grimm et al. 2005, Gibson and Meyer 2007, Klocker et al. 2009). In some cases, the capacity of streams to assimilate N decreases at even low levels of suburban development (Kaushal et al. 2006). Denitrification might be substantial and

spatially variable in many urban streams (e.g., Baker et al. 2001, Groffman et al. 2005), and denitrification rates increase with increasing NO_3^- concentrations, albeit not enough to keep pace; i.e., efficiency declines with increasing concentrations (Mulholland et al. 2008). Where channel incision lowers floodplain water tables, denitrification in the riparian zone might be reduced because of a lack of saturated, anoxic riparian soils or decreased hydrologic connectivity between the stream channel and hyporheic zone (Groffman et al. 2003, Kaushal et al. 2008a). Conversely, nitrification might be elevated in urban streams, particularly those receiving wastewater effluent (Merseberger et al. 2005), unless dissolved O_2 is severely depressed. Elucidating the relative importance of different environmental variables influencing N retention and removal in urban streams is still a central area of research (question 4). Moreover, an emerging picture is that unless all species of N are tracked, what appear to be reductions or losses might simply be conversion to other forms.

Studies of stream ecosystem respiration and metabolism have not yielded a clear trend with urbanization (Meyer et al. 2005a, Iwata et al. 2007, von Schiller et al. 2008). However, streams receiving untreated or partially treated wastewater discharges—a category that includes many urban streams in the developing world, and even in Europe and North America—have high respiration rates because of inputs of high-quality C and nutrients (Ometto et al. 2004, Izagirre et al. 2008). Mechanisms affecting metabolism are not always straightforward. For example, bed sediment instability, which can result from increased stormwater runoff in urban areas, reduces both primary production and community respiration (Uehlinger et al. 2002). Metabolism is linked to light, temperature, nutrient availability, organic matter, and channel dynamics, so responses vary among streams depending on how urbanization has affected each of those factors.

Some urban streams have higher algal biomass relative to less disturbed streams (e.g., Taylor et al. 2004, Catford et al. 2007), and might have higher primary production. In some cases, nutrient and C concentrations in urban streams stimulate sufficient periphyton growth to alter fundamentally the structure of the benthic habitat (Murdock et al. 2004). These changes to primary productivity might have cascading effects on higher trophic levels (question 5). However, use of algal standing crops to infer primary productivity is especially problematic in urban streams because frequent high flows can scour and remove algal accumulations. In a Texas stream where wastewater effluent comprised ~70% of baseflow, high nutrient and C levels contributed to rapid algal growth, but algae were regularly removed by frequent flow events generated by as little as 1.3 cm of rainfall (Murdock et al. 2004). High algal biomass in urban streams has been variously explained by increased nutrients (Catford et al. 2007) and increased light (e.g., Roy et al. 2005a). Conversely, high levels of toxicants are associated with reduced algal biomass (Hill et al. 1997), so algal biomass and primary production might follow the same unimodal relationship with urbanization as leaf breakdown rates. Many questions about the effects of urbanization on stream metabolism remain unanswered (e.g., question 6).

Urban Stream Stressors

The stressors reviewed in this section are loosely organized to proceed from physical to chemical and biological in nature. This organization reflects the concept that changes to the physical environment are often fundamental and affect many other stressors, but does not mean that physical stressors are always the most important drivers of changes to biota and function.

Hydrologic alteration

Impervious surfaces increase surface runoff, which alters stream hydrology by increasing the frequency and magnitude of high-flow events (e.g., Leopold 1968, Schueler 1994, Booth and Jackson 1997). The result is often a profound change to the disturbance regime of urban streams. The degree to which the disturbance regime changes depends heavily on the nature of stormwater management systems (Booth and Jackson 1997, Walsh et al. 2005a), including whether stormwater is collected and routed directly to streams, is routed into sewer lines in a combined wastewater system, is temporarily detained in ponds or other structures, or is infiltrated onsite. Base flows sometimes are reduced with urbanization because of lack of groundwater recharge, although lawn watering, septic effluent, point-source discharges, leaking water and sewer lines, and deforestation associated with urbanization might augment base flows (Lerner 2002, Konrad and Booth 2005, Roy et al. 2009). In other regions, flows can be reduced locally by groundwater and surface-water withdrawals (Konrad and Booth 2005). Some of the mechanisms by which urban-induced hydrologic alteration affects stream ecosystems were reviewed by Konrad and Booth (2005). Significant among these mechanisms are increased scour of algal assemblages, rapid export of nutrients and organic matter (i.e., decreased retentiveness), and direct physical washout of fauna. Hydrologic alter-

ation influences channel geomorphology and water quality and indirectly affects biotic communities and ecosystem processes. Climate change might further exacerbate hydrologic alteration, especially in regions where storms increase in frequency and severity. Issues related to hydrologic budgets and hydrologic alteration are fundamental drivers of many of the changes shown in Fig. 1 (questions 7 and 8).

Altered geomorphology

As a result of hydrologic alteration and changes in sediment supply, urban stream channels typically have increased bed and bank erosion that leads to increased widths and cross-sectional areas compared to nonurban streams unless artificially constrained (Leopold 1968, Booth and Jackson 1997, Hession et al. 2003, Chin 2006). A long-standing paradigm is that urban stream channels first undergo a period of sedimentation from construction, subsequently experience channel enlargement from increased storm flows, and eventually stabilize (Wolman 1967, Chin 2006). Significant urban stream channel enlargement has been documented, but numerous studies have been unable to find a relationship between degree of urbanization and indicators of enlargement (Doyle et al. 2000, Cianfrani et al. 2006, Yagow et al. 2008). Eventual stabilization of enlarged urban streams also has been described (Finkenbine et al. 2000, Henshaw and Booth 2000), but stabilization might be rare, and much work needs to be done to determine under what conditions a new stable form might occur (question 9). Channel enlargement (where it occurs) can affect stream ecosystems by several mechanisms. Expanding channels can be a major source of sediment (Trimble 1997); unstable channels can provide poor habitat for some organisms (Schiff and Benoit 2007); and channel incision can lower the water table below microbially active soil zones (Groffman et al. 2003).

Urban stream geomorphology also can be affected by direct channel modification and by large inputs of sediment. Direct modification often takes the form of placing a stream in a concrete-lined channel to prevent it from migrating or enlarging. This practice causes extreme habitat simplification, and although it will stabilize the local reach, it will tend to exacerbate hydrologic and geomorphic impacts downstream. Moreover, concrete channels separate the stream from the floodplain and the hyporheic zone and eliminate important locations of microbial processing and other biological activity. Many urban streams also have elevated suspended sediment levels compared to streams in undeveloped watersheds (e.g., Walters et al. 2003, Grimm et al. 2005), although this trait is not universal (Burcher and Benfield 2006). High levels of suspended and bed sediment have multiple deleterious effects on aquatic ecosystems (reviewed by Newcombe and MacDonald 1991, Waters 1995, Wood and Armitage 1997).

Piping and filling channels

Piping and filling of streams (i.e., stream burial) is an extreme form of modification that is common in highly urbanized areas, especially where stormwater is routed into combined sewer–stormwater overflow systems. The proportion of buried streams can be quite high; in Baltimore City, ⅔ of all stream reaches have been buried (Elmore and Kaushal 2008). The degree of burial has not been assessed in most urban areas, but in many regions, most buried reaches are ephemeral or intermittent headwater streams (Roy et al. 2009), which are areas of high biological activity in undisturbed systems (Meyer and Wallace 2001). Piping of headwaters causes downstream impacts via increased flow velocities, altered C and nutrient inputs, and amplified N transport; these effects can be exacerbated by increased climatic variability (Kaushal et al. 2008b). In the US, interest in understanding how headwater degradation affects downstream waters is particularly strong because of important ramifications for regulation under the US Clean Water Act (Leibowitz et al. 2008). Questions 10 and 11 relate to stream burial.

Increased temperature and light

Urban streams often have higher summer baseflow water temperatures than do nonurban streams because of the urban heat island effect (increased air temperatures in urban cores), release of stored water from shallow detention ponds, point discharges from wastewater treatment plants, and increased insolation from removal of riparian vegetation. In some climates, urban streams also suffer pulses of high temperatures because runoff from heated impervious surfaces can result in highly variable temperatures over short time scales (Van Buren et al. 2000, Nelson and Palmer 2007). Increased insolation also can lead to increased algal production (see *Stream functional responses* above). Elevated water temperatures can exceed tolerances of cold-water species or favor species metabolically adapted to higher temperatures, thereby altering assemblage structure (Krause et al. 2004, Nelson et al. 2009). Elevated water temperatures also can affect whole-reach metabolism, especially respiration. However, controls on stream temperature are numerous and complex (LeBlanc et al. 1997, Burkholder et al. 2008). Most research has focused on

developing predictive models from small- or medium-scale data sets (e.g., Van Buren et al. 2000, Nelson and Palmer 2007), but research is needed to address questions related to the broad-scale patterns of temperature effects and whether elevated temperatures are contributing to higher metabolic rates (questions 12 and 13). Answers to these questions will contribute to our understanding of the interactive effects of climate change and urbanization on aquatic communities and ecosystem functions.

Increased toxicants

We use *toxicants* broadly to mean chemical contaminants that cause lethal and sublethal effects on aquatic organisms. Our definition includes what are commonly called emerging contaminants (potentially harmful but traditionally unmonitored compounds) and regulated trace metals and organic contaminants. Detrimental effects on ecosystem structure and function from toxicants has been well documented (reviewed by Paul and Meyer 2001), but determining which toxicants are of most concern is usually difficult. Toxicants common in urban streams include heavy metals (particularly Cd, Cr, Cu, Pb, and Zn), polycyclic aromatic hydrocarbons (PAHs), and a range of pesticides (Bannerman et al. 1993, Beasley and Kneale 2002, Gilliom et al. 2006). In US National Water Quality Assessment (NAWQA) surveys conducted between 1992 and 2001, 83% of urban water samples and 70% of urban bed sediment samples exceeded aquatic life benchmarks for ≥ 1 pesticides (Gilliom et al. 2006). Many other potential toxicants can be present in urban streams, especially streams that receive point-source wastewater discharges (Kolpin et al. 2002). Interactions among compounds can have synergistic or antagonistic effects that further complicate our ability to predict the consequences of these substances for stream structure and function, although some of these issues are being addressed as part of the NAWQA program (Belden et al. 2007).

Toxicity tests of urban runoff on aquatic biota have shown mixed results, with some studies reporting high toxicity (e.g., Skinner et al. 1999) and others showing low biotic responses to relatively high contaminant concentrations (Maltby et al. 1995). Sensitivity to toxins varies greatly among taxa (reviewed by Beasley and Kneale 2002), so the choice of study organism in such tests is critical. In addition, many contaminants are present at much higher concentrations in sediments than in the water column, and sediment suspension during high flows can greatly increase toxicity (Christensen et al. 2006). Despite an increasing volume of research, many questions about the importance of toxicants in urban streams remain unanswered (questions 14 and 15).

Dissolved O_2

In urban streams that receive insufficiently treated wastewater, biological and chemical O_2 demand can be elevated and can lead to O_2 deficits (reviewed in Paul and Meyer 2001). O_2 deficits also can occur in urban streams with reduced baseflows or elevated organic matter (e.g., Mallin et al. 2006, Pellerin et al. 2006), and in areas where increased sedimentation leads to stagnant, anaerobic pools. Most lotic macroinvertebrates and fishes are adapted to well-oxygenated environments, so low dissolved O_2 can reduce biotic integrity. However, anaerobic microbial processes, such as denitrification, can be enhanced under these conditions.

Increased ionic concentrations

Stormwater runoff, deicing salt, point-source discharges, leaking sewer lines, and improperly functioning septic systems can increase concentrations of dissolved solutes and conductivity in urban streams. Conductivity values vary naturally among streams with different underlying geology, but conductivity consistently increases along gradients of urbanization. Elevated salinity can be a stressor to freshwater organisms, particularly mayflies (Kefford et al. 2003, Kaushal et al. 2005). In high-latitude locations where salt is used as a deicer, salinity and Cl^- concentrations reach toxic levels for many organisms and can have numerous secondary effects, including acidification and mobilization of metals (Kaushal et al. 2005, Daley et al. 2009). Urban streams in lower latitudes also have elevated conductivities (e.g., Rose 2007), but salinities are generally at least an order of magnitude lower than toxic levels. Nevertheless, conductivity is a useful and inexpensive indicator of certain aspects of urban disturbance, especially wastewater inputs (Wang and Yin 1997).

Increased available nutrients

According to US NAWQA data from 1992 to 2001, inorganic nutrient levels are higher in urban than in forested streams and are similar between urban and agricultural streams, although NO_3^- and total N are highest in agricultural streams (Mueller and Spahr 2006). This pattern is less likely in many developing countries where fertilizer use is low and discharges of untreated wastewater in urban streams are high. NH_4^+ concentrations tend to be highest in urban streams (von Schiller et al. 2008), especially those

receiving inputs from wastewater treatment plants (Martí et al. 2004). In a recent review of N dynamics in urban watersheds, Bernhardt et al. (2008) found that, in many cities, the original source of most N is food, with significant additional contributions from fertilizer, drinking water, and atmospheric deposition, especially highly local deposition of combustion-derived N produced by automobiles. In urban areas with effective wastewater treatment systems, most of this N is exported to terrestrial systems as sludge, but in areas with limited wastewater management much N is discharged into streams and rivers (Bernhardt et al. 2008). Even where effective treatment systems exist, significant quantities of nutrients enter streams via leaking sewer and septic systems (Kaushal et al. 2006, Walsh and Kunapo 2009) and stormwater runoff delivered to streams through stormwater drainage systems (Hatt et al. 2004, Bernhardt et al. 2008). The actual contributions of various sources are often unclear (e.g., see question 10). Elevated nutrients and shifts in relative proportions of different nutrients (e.g., N to P) or of forms of N (e.g., NO_3^- to NH_4^+) can alter stream processes, including nutrient uptake, leaf breakdown rates, and primary production.

Altered terrestrial inputs

Reduced riparian cover and burying of streams in urban areas can reduce inputs of leaves, wood, and terrestrial invertebrates. However, leaves that fall onto roads in many urban areas ultimately wash into streams via the storm drainage network. Thus, leaf inputs can be much higher in urban than in undeveloped watersheds (Miller and Boulton 2005, Carroll and Jackson 2009). Alteration of riparian vegetation in urban areas can significantly change the composition and timing of leaf inputs. For example, deciduous leaf inputs (and thus, N inputs) are higher in urban than in nonurban areas in the northwestern US, and timing of inputs differs between urban and nonurban areas (Roberts and Bilby 2009). However, terrestrial inputs are more important in some systems than others. For example, Amazonian stream ecosystems depend heavily on allochthonous inputs, and decreased riparian cover and loss of terrestrial input are important factors in the decline of macroinvertebrates in urban streams in Brazil (Couceiro et al. 2007). Large wood inputs tend to be lower in urban than in forested streams (Finkenbine et al. 2000, Elosegi and Johnson 2003), and wood is sometimes removed to prevent flooding and damage to bridges. The lack of wood can affect stream habitat and biological assemblages (reviewed by Gurnell et al. 1995, Díez et al. 2000). Even when present, the functions of wood can be compromised in urban streams (Larson et al. 2001). The degree to which terrestrial inputs are altered and the extent to which this alteration drives observed ecosystem changes are unclear (question 16).

Increased barriers to movement

Streams in urban areas tend to have high densities of instream obstructions that prevent movement of fish and other aquatic organisms. Road crossings, particularly culverts with extreme slopes, velocities, pool sizes, or vertical drops, can prevent small organisms from passing upstream or downstream (Warren and Pardew 1998, Schaefer et al. 2003). Culverts also can be barriers to upstream dispersal of adult aquatic insects (Blakely et al. 2006), and absence of forested areas can prevent among-stream dispersal of adults (Smith et al. 2009). Even small channel modifications can interrupt movement. For example, road crossings that divide discharge into multiple sections can be unsurpassable barriers for neritid snails that rely on complex hydrologic cues for upstream migration (Blanco and Scatena 2006). Movement barriers are of particular concern to migratory species, which include temperate anadromous species, such as salmon and eels, and a large proportion of tropical fish, shrimp, and snail species (Ramírez et al. 2009). Thus, coastal cities that sit astride major rivers can affect aquatic communities far inland. However, the overall importance of urban movement barriers has not been well studied (question 17).

Evaluating multiple stressors

Each of the stressors described above has been observed in at least some urban streams, and each can significantly affect ecosystem structure and function under certain circumstances. However, multiple stressors occur in most cases. This tendency for co-occurrences interferes with our ability to connect observed structural or functional changes to a single stressor, and herein lies the crux of the difficulty in understanding the urban stream syndrome. It might be that only a few stressors (e.g., certain toxicants) are the proximal causes for most of ecosystem structural changes, but teasing these stressors apart from those that are relatively unimportant will require an extensive series of reductionist studies. Therefore, we suggest that examining stressors that consistently covary also would be a useful way to elucidate mechanisms (question 18). Furthermore, many stressors interact to produce nonadditive and synergistic effects, in which case management for single stressors could cause unanticipated effects. Thus, stressor interaction is an important area for study (question 19).

Urban Stream Management

Stressor sources and management tools

Many potential stressors are produced by a few key sources, which in theory can be managed by a relatively small suite of tools. This principle is illustrated in Table 3, which links the symptoms of the urban stream syndrome with their specific causes or sources and the prescriptions or management practices used to address them. Here, we discuss the most widespread and significant stressor sources and describe management tools used to control those sources.

Overall, the most significant stressor source in most urban streams in developed countries is stormwater runoff (Walsh et al. 2005b). Researchers have long recognized that increased stormwater runoff from impervious cover is a key indicator of urban impact on aquatic systems (e.g., Leopold 1968, Schueler 1994, Booth and Jackson 1997). Many of the stressors described above are products of efficient delivery of contaminant-laden stormwater runoff from impervious surfaces to streams via the storm drainage systems (measured by EI; Brabec et al. 2002). Stormwater runoff effects can be managed by planning/zoning regulations that reduce EI, stormwater management ordinances that require control or treatment of runoff with engineering or design solutions, and good housekeeping controls on the use and storage of toxicants, fertilizers, and other contaminants. Stormwater controls might even be able to compensate for the loss of some of the ecosystem services provided by headwater streams (question 20). In some cases, control measures could have additional societal benefits. Stormwater harvesting provides a substantial low-energy water resource to cities (Fletcher et al. 2007), and biofiltration systems have the potential to cool urban microclimates that are affected by the urban heat island effect (Endreny 2008). Identifying such win–win management strategies is another important area for future research (question 21).

Riparian degradation is another source of multiple stressors, or is a contributing factor that affects multiple stressors. Intact, naturally vegetated riparian zones have functions, such as trapping and processing nutrients and toxicants, moderating temperatures, and contributing organic matter, that are important for maintaining natural stream function and structure (for reviews see Wenger 1999, Broadmeadow and Nisbet 2004, Mayer et al. 2006). Urban streams commonly have reduced and altered riparian zones. Even intact urban riparian zones have limited opportunities to function because much stormwater runoff is routed directly into streams via the stormwater conveyance network, which bypasses the riparian buffer (Roy et al. 2005b, 2006). Overall, the importance of riparian degradation as an urban stressor is highly variable. In some regions, such as the Amazon, loss of riparian forests might be a major driver of stream ecosystem changes (Couceiro et al. 2007), whereas in many more developed regions, loss of riparian forests is likely to be less important than stormwater runoff (e.g., Walsh et al. 2007). Riparian degradation can be reduced by effective implementation and enforcement of planning/zoning regulations and riparian buffer ordinances.

Direct channel modification, resulting in buried or concrete-lined streams, is a major stressor source in many urbanizing areas. Direct regulation of stream burial is rare, but the practice sometimes is managed indirectly via riparian buffer ordinances and stream protection laws, such as the US Clean Water Act. Sometimes reach-scale restoration is used to return buried streams to the surface, but the restored stream might still be degraded (Purcell et al. 2002).

In most developed countries, point sources have been regulated for many decades, and management emphasis has shifted to nonpoint sources. Nevertheless, in many urban areas, point sources remain significant sources of labile C and nutrients and a host of poorly studied toxicants that might be of ecological importance, especially during baseflow conditions (Kolpin et al. 2002). In less developed countries, the level of point-source management varies widely, and direct discharges of untreated waste is common in many cities (Bernhardt et al. 2008). In such areas, point sources might be the most significant stressor sources.

Of the remaining stressor sources, construction-site erosion is ubiquitous and one of the most obvious, and for these reasons, it commonly is regulated to some degree. Water withdrawals and impoundments are very significant stressor sources in some regions. However, their effects and potential management often transcend urban boundaries because withdrawals and impoundments are not strictly urban phenomena and often are not managed at the scale of the city. Leaking septic systems, leaking sewer lines, and road crossings are stressor sources that are often of secondary importance but have potentially high local importance (see Fig. 1, Table 3 for management strategies). Much research is needed to determine which management strategies are most effective for controlling stressors under varying levels of impervious cover and differing biogeoclimatic conditions (question 22).

Managing urban streams based on incomplete knowledge

Answering the questions listed above will improve management of urban streams by enabling us to

TABLE 3. Symptoms, causes, and mitigation for the urban stream syndrome.

Symptom	Cause	Mitigation
Hydrologic alteration Increased peak flow magnitude Increased frequency of large flows Increased volume of storm flows Altered low flows (reduced or increased)	Reduced infiltration rates (through compaction, covering by impervious surfaces, and piping of ephemeral channels) Reduced evapotranspiration through loss of vegetation Groundwater withdrawals Imported water	Disconnecting and minimizing impervious surfaces Infiltration practices Bioretention practices to promote evapotranspiration Stormwater harvesting Forest cover Infrastructure improvements to reduce leakage
Altered geomorphology Higher bed mobility Reduced bank stability Channel simplification Increased fine sediment inputs Increased embeddedness	Increased peak flows Riparian disturbance Reduced channel roughness Channelization Construction sediments Road runoff Landscaping and ground disturbance Channel incision and streambank retreat	Riparian buffers Instream channel restoration Stream engineering regulations Improved site design to minimize stream disturbance Zoning and planning Erosion and sediment control (see mitigation of hydrologic alteration)
Direct channel manipulation	Straightening channels Lining with concrete and rip-rap Piping streams Filling streams	Regulations preventing direct manipulations Change in perception of stream appearance Restoration of floodplains to allow reconnection Bring piped streams to the surface
Water chemistry changes Increased nutrients Increased pesticides Increased metals Increased petroleum byproducts Elevated bacteria Increased conductivity Pharmaceuticals	Point-source discharges Fertilization Pesticide application Contaminants from roads Roofing materials Pet waste Leaky wastewater pipes Septic tanks (many of the above transmitted to streams via storm drains)	Regulations or other incentives to minimize fertilizer and pesticide use Water quality treatment of wastewater and stormwater (see mitigation of hydrologic alteration) Constructed wetlands Reduced sewer leakage Elimination of combined sewer overflows Improved septic performance
Increased water temperature and light	Riparian disturbance Runoff from impervious surfaces Discharges from ponds and treatment plants Urban heat island effect	Riparian buffers (canopy cover) Stormwater retention practices (see mitigation of hydrologic alteration)
Altered terrestrial inputs Reduced habitat complexity	Riparian disturbance Wood removal High flows (flushing) Road drainage	Riparian buffers Behavioral modification via homeowner education (see mitigation of hydrologic alteration)
Movement barriers	Road culverts blocking passage Geomorphic alteration Water quality changes	Use of bridges rather than culverts Better culvert design and placement
Lost riparian habitat	Riparian disturbance Exotic species Channel incision	Riparian buffers (see mitigation of hydrologic alteration and channel modification)

target the causes of degradation with appropriate strategies and regulations. However, some of these questions might never be answered fully from a scientific perspective, and streams nevertheless must be managed now. How might urban stream management proceed with existing knowledge? We suggest 3 simple steps (modified from Palmer et al. 2005):

1) Identify the desired stream ecosystem state.—Potential states of urban streams can be categorized into 3 groups: a) *minimally altered* streams in which near-

natural ecosystem structure and function is preserved or restored; b) *moderately altered streams* with significantly modified ecosystem structure and function, but that still provide multiple ecosystem services (usually the largest category of urban streams outside of dense urban cores); c) *severely altered* streams that have lost all but the most tolerant species and provide few ecosystem services (often in concrete channels and managed purely for stormwater drainage and dilution of contaminants).

This categorization scheme is essentially a simplified version of the Biological Condition Gradient (Davies and Jackson 2006) that is used by the US EPA. Currently, most urban stream management proceeds without conscious declaration of goals, and streams arrive at one of these states (usually moderately or severely altered) haphazardly. We argue that explicit identification of the desired end state of an urban stream is a necessary first step in its management to minimize misallocation of resources. Each of these 3 states might be an appropriate choice, depending on the situation. In a newly developing watershed where imperiled fish species are present, minimally altered would be the appropriate goal for most streams. In a heavily urbanized watershed with important downstream resources (say, a bay with a productive fishery), moderately altered might be reasonable, with a focus on minimized downstream nutrient and contaminant transport rather than on maintaining local biotic integrity. In a heavily urbanized city in a developing nation with few resources, the paramount objective could be to provide improved drainage for public health purposes, and severely altered might be an acceptable state. However, such a decision should not be made lightly. In many cases, developing cities might be able to avoid the mistakes of the developed world and implement new stormwater management strategies that provide multiple environmental and social benefits, sometimes at lower financial cost than conventional drainage practices (Bernhardt et al. 2008, Roy et al. 2008).

The choice of desired end state is one for society to make, perhaps through a public participation process involving residents and stakeholders of each stream's catchment or region. Scientists can inform this decision by communicating the costs and benefits of setting different goals in terms of supplied ecosystem services. The existing state of the stream is a key issue, and scientists have the critical roles of assessing the existing condition and the factors that led to it (step 2, below) and advising decision makers on the kind of improvement that is possible, given ecological, economic, and political constraints. The question of what is possible is often difficult to answer, and additional research is needed to find practical, inexpensive, and effective stream management tools (questions 20–22).

2) Identify major stressors or stressor sources and select appropriate management actions.—The 2nd task is to identify stressors that might prevent the stream from being in the desired end state. In some cases, the major stressors will be apparent, and in others, causal assessment tools, such as CADDIS, could be used to identify the stressors of concern. However, in many cases, the available evidence will not indicate clearly which stressors are critical. In such cases management can proceed on the basis of our understanding of strong links between overarching stressor sources and ecosystem responses even when the intermediate mechanisms and specific stressors are poorly understood. For example, using low-impact design techniques to infiltrate stormwater can manage stressors ranging from hydrologic alteration to toxicants (Walsh et al. 2005a, Ladson et al. 2006, Murakami et al. 2008).

We wish to emphasize 2 basic principles for selecting management approaches. First, a tool that addresses stressors and their underlying sources is more likely to have long-term success than a tool that treats symptoms. Second, preventative approaches that implement regulations in advance of development are more cost-effective than retrofitting or restoring developed watersheds. Therefore, we recommend that reach-scale stream restoration be used judiciously because it might not achieve desired goals unless implemented as part of a broader management strategy that controls the critical underlying stressors (Bernhardt and Palmer 2007). Stream restoration is a multibillion dollar business, but most restoration projects are not held to criteria for success (Palmer et al. 2005) or monitored (Bernhardt et al. 2005), although notable exceptions exist (e.g., Kaushal et al. 2008a). In general, restoration of urban streams has relied far too heavily on structural approaches, such as channel reconfiguration or bank armoring, rather than process-based approaches, such as restoration of natural flow and reestablishment of features, such as floodplain wetlands and infiltration areas, that protect infrastructure *and* promote desired ecosystem services (Kaushal et al. 2008a, Craig et al. 2008, Palmer 2009, Klocker et al. 2009). In other words, restoration has focused on addressing reach-scale symptoms rather than considering the underlying dynamics of the watershed as a whole (Palmer 2009). More research is needed on how to design truly effective restoration strategies and how to integrate restoration of streams with upland stormwater management (question 23).

3) Identify appropriate monitoring indicators and manage adaptively.—As with any type of management activity, the degree to which goals are being met must be monitored, and a system is needed for adjusting management approaches that are not delivering intended results. A discussion of these issues is beyond the scope of our paper, but we note 2 key points. First, selection of indicators is not trivial (question 24). Sometimes the choice of indicators is driven by government mandates, such as the total maximum daily loads of the US Clean Water Act, but mandated metrics are not necessarily useful surrogates for other ecosystem services of interest. The European Union Water Framework Directive (2000) has made identification of indicators a high priority, although to date, the emphasis has been more on structural than functional indicators. Second, adaptive management (Walters and Hilborn 1978) should be considered from the outset. This management strategy is challenging in urban systems, where management decisions affect numerous stakeholders and might be controversial. Decision makers should be prepared from the beginning for the possibility that management policies might have to be revisited. A clear monitoring and assessment plan with *triggers*—thresholds of monitoring results that require action—should be established early in the management process and communicated to all involved parties.

The Need for Better Communication among Scientists, Managers, and Decision-Makers

Even complete scientific understanding will not benefit urban streams if the understanding is not communicated effectively to planners, managers, and decision makers. One of the major themes of the SUSE2 meeting was the need to convey existing scientific knowledge to on-the-ground practitioners. A particular example is the need to describe the ecosystem services provided by urban streams, especially those of greatest societal value (question 25). A more fundamental question is how to establish better multiway communications among all parties with an interest in urban stream function and management (question 26). Considerable time at the SUSE2 meeting was devoted to seeking answers to question 26. Ideas included fact sheets, workshops and training sessions, and cooperative programs to test scientific questions with on-the-ground management actions that include effective monitoring. Many existing government agencies, educational institutions, and nongovernmental organizations work actively in this arena, and the need for multidisciplinary, integrative approaches to urban ecology is well recognized (e.g., Pickett et al. 2008). However, discussions at the SUSE2 meeting revealed that scientists still have work to do to ensure we are contributing our share to effective communication.

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