Global perspectives on the urban stream syndrome

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Abstract: Urban streams commonly express degraded physical, chemical, and biological conditions that have been collectively termed the "urban stream syndrome". The description of the syndrome highlights the broad similarities among these streams relative to their less-impaired counterparts. Awareness of these commonalities has fostered rapid improvements in the management of urban stormwater for the protection of downstream watercourses, but the focus on the similarities among urban streams has obscured meaningful differences among them. Key drivers of stream responses to urbanization can vary greatly among climatological and physiographic regions of the globe, and the differences can be manifested in individual stream channels even through the homogenizing veneer of urban development. We provide examples of differences in natural hydrologic and geologic settings (within similar regions) that can result in different mechanisms of stream ecosystem response to urbanization and, as such, should lead to different management approaches. The idea that all urban streams can be cured using the same treatment is simplistic, but overemphasizing the tremendous differences among natural (or human-altered) systems also can paralyze management. Thoughtful integration of work that recognizes the commonalities of the urban stream syndrome across the globe has benefitted urban stream management. Now we call for a more nuanced understanding of the regional, subregional, and local attributes of any given urban stream and its watershed to advance the physical, chemical, and ecological recovery of these systems.
Key words: urban streams, development, regional, restoration, ecosystem

The literature on urban streams is striking in describing their uniformity. Leopold (1968, pp. 2–3), writing almost a half-century ago of his observations on primarily eastern USA urban streams, found them with "unstable and unvegetated banks, scoured or muddy channel beds, and unusual debris accumulations". Twenty-three years later, Booth (1991, pp. 107–108) described suburban streams on the western side of the North American continent as " . . . hav[ing] a characteristic 'look' to them. Their beds are uniform, with few pools or developed riffles to break up the planar surface. Channel banks are raw and near-vertical, with incisions of one to many feet. The erosion of adjacent steep banks is constantly adding new sediment. Woody debris is small and sparse, and it is either suspended above the level of the flow or is only weakly anchored in the bed. Finally, the aquatic organisms that thickly populate equivalent drainages in undeveloped settings are nearly absent . . ." Walsh et al. (2005), drawing examples from all over the world, also described consistent responses of urban streams that include increased channel width, pool depth, and scour; high pollutant loads; reduced channel complexity; and an overall loss of sensitive taxa.

The authors of papers in this *BRIDGES* cluster have followed the historical precedent of these and other authors and use the term 'urban streams' to include the wide variety of free-flowing channels that are influenced by runoff from urban land uses—roads, houses, commercial buildings, and parking lots. The term is sometimes restricted to streams or stream segments as they flow through urban centers, but we use it more broadly to include any stream

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affected by urban, suburban, or exurban development in its contributing watershed.

Urban streams are prevalent throughout the world, and the altered ecosystem structure and the reduction in services provided by these systems has led to an exponential increase in research on urban streams in recent years (Wenger et al. 2009, Smucker and Detenbeck 2014) and to multiple descriptions of the suite of typical physical and ecological responses to urbanization, collectively termed the urban stream syndrome (Meyer et al. 2005, Walsh et al. 2005). The urban stream syndrome provides a conceptual framework for considering common responses to watershed urbanization across the globe. In the medical profession, a syndrome comprises characteristic symptoms that consistently occur together. Urban streams also are strikingly uniform across widely disparate locations, despite the global diversity of climate, geology, physiology, and biota, and the variety of development patterns and stormwater infrastructure. The urban stream syndrome is of great concern because ecosystem functions and services can be profoundly diminished where in-stream conditions diverge from the range of conditions typical of natural streams.

The form and function of urban streams are consistently more homogeneous than those of their less-disturbed counterparts (Fig. 1A–D), but the extreme variety of environmental and social factors influencing urban streams across the globe results in important differences in the expression of the urban stream syndrome. Variations across regions, watersheds, and localities arise particularly from differences in climate (Hale et al. 2016), urban infrastructure (Parr et al. 2016), and resources available to urban centers in less-developed countries (Capps et al. 2016).

Despite the diversity of watershed characteristics and the variety of urban development, synthesis efforts of the last decade have been focused primarily on describing and analyzing commonalities among urban streams (Paul

Figure 1. Paired views of undisturbed (A, C) and urbanized (B, D) streams. A and B show upstream and downstream reaches of East Fork Issaquah Creek in western Washington state (city of Issaquah), a humid region with relatively uniform hydrographs, glacially derived sediment, and abundant channel–vegetation interactions. C and D show upstream and downstream reaches of Mission Creek in southern California (city of Santa Barbara), a semi-arid region with flashy hydrographs, active sediment delivery from the rapidly uplifting Transverse Ranges, and limited riparian vegetation.

and Meyer 2001, Walsh et al. 2005, Wenger et al. 2009). This approach has left a continuing need to explore critical differences in the expression of the urban stream syndrome, and in turn, the choice of effective management approaches to alleviating its symptoms. The purpose of our introduction to this *BRIDGES* cluster is to explore the interplay of these countervailing forces—the diversifying influence of watershed context and the homogenization imposed by urbanization—from both regional and global perspectives, to better understand the commonalities and differences among those watersheds and their associated urban streams. First, we synthesize key studies that highlight differences in expressions of the urban stream syndrome, and then we describe differences in the hydrologic and geomorphic drivers of responses to urbanization across watersheds. Last, we describe how understanding the commonalities and the differences in responses can help guide management of urban streams and how social and political context can influence management. Our hope is that a more nuanced appreciation of these interactions can guide environmental managers to identify appropriate ecological endpoints and the most effective strategies to reach those goals in any urban stream.

HETEROGENEITY IN URBAN STREAMS

Several cross-regional studies of urban streams have been conducted over the past decade. The best known of these in North America is the US Geological Survey (USGS) National Water-Quality Assessment Program (NAWQA). The investigators who conducted the study, which was an assessment of stream responses to urbanization in 9 metropolitan US cities, concluded that urbanization results in different effects on hydrology, physical habitat, water quality, and biota in different metropolitan areas (Brown et al. 2009). They found relatively consistent (but not universal) increases in several types of variables, including hydrology (specifically, the frequency and magnitude of high-flow events), geomorphology (increases in channel cross-section), and water quality (particularly conductance and insecticides). Biological responses to urbanization, notably declines in fish and benthic macroinvertebrates, generally were consistent within a given metropolitan region (i.e., more urbanized streams showed more impaired biological assemblages) but difficult to generalize from one region to another (Brown et al. 2009). NAWQA results demonstrated that broad regional differences in undisturbed environmental conditions and in responses to urbanization do exist, but that more immediate, watershed-scale dependence on previous or upstream land use (particularly large-scale agriculture) can be even more influential than regional environmental differences in determining the present status of any given urban stream (Cuffney et al. 2011). The results also highlighted that not every urban stream "looks" the same.

Other investigators have reported stream responses to urbanization inconsistent with the uniformity often implied by the urban stream syndrome. Konrad and Booth (2005) compared the hydrologic responses to urbanization in 8 gaged watersheds situated primarily on the eastern and western coasts of the USA. In a comparison of hydrographs from 2 periods separated by 23 y of rapid urbanization, they found no hydrologic metric that showed statistically significant change in all 8 watersheds, and only in 1 watershed did they find significant change to all of the 4 hydrologic metrics commonly associated with urbanization that they evaluated (high-flow frequency, baseflow/peak-flow distribution, flashiness, and low-flow magnitude). In the arid and semi-arid southwestern USA, exotic species require the more uniform (rather than the naturally intermittent) flow regime of urban streams (Cooper et al. 2013). In tropical Puerto Rico, urbanization did not further affect the flashiness of naturally flashy streams, and fish assemblages did not exhibit declines typically associated with urbanization because they were dominated by diadromous species that were strongly affected by connectivity rather than land use in the watershed (Ramírez et al. 2009). These examples underscore some differences among urban streams but not the underlying mechanisms that can drive the differences. Below, we offer some examples of potential underlying causes of differential ecological response to urbanization.

DIFFERENCES IN THE CAUSES OF URBAN STREAM RESPONSES

Difference in climate is a major driver of differential response of streams to urbanization (Hale et al. 2016). At one end of the strong climatological gradient along the western coast of the USA, urban lowlands of the Pacific Northwest receive low-to-moderate rainfall throughout most of the year (annual totals generally <1000 mm, 2-y 1-h intensities ≈ 8 mm/h). In contrast, urban coastal areas of southern California, 1500 km to the south, receive average annual rainfall totaling <~⅓ of that received by the Pacific Northwest, but the peak intensities are about doubled (US Department of Commerce 1964). Regional and watershed-specific hydrologic growth curves (i.e., graphs showing the proportional increases in discharge with increasing flood recurrence) reflect this strong disparity in rainfall intensities. Curves from the Pacific Northwest rise gradually (with 100-y peak discharges typically <5× the 2-y peaks), whereas curves from southern California display order(s) of magnitude increases across the same range of flood frequencies (Fig. 2). Similar differences can be found on a global scale. For example, the hydrologic growth curves compiled from multiple data sources (fig. 2 by Farquharson et al. 1992) indicate close similarity between frequency of flood recurrence in Great Britain and in the Pacific Northwest, whereas hydrologic growth curves for South Africa, Queensland,

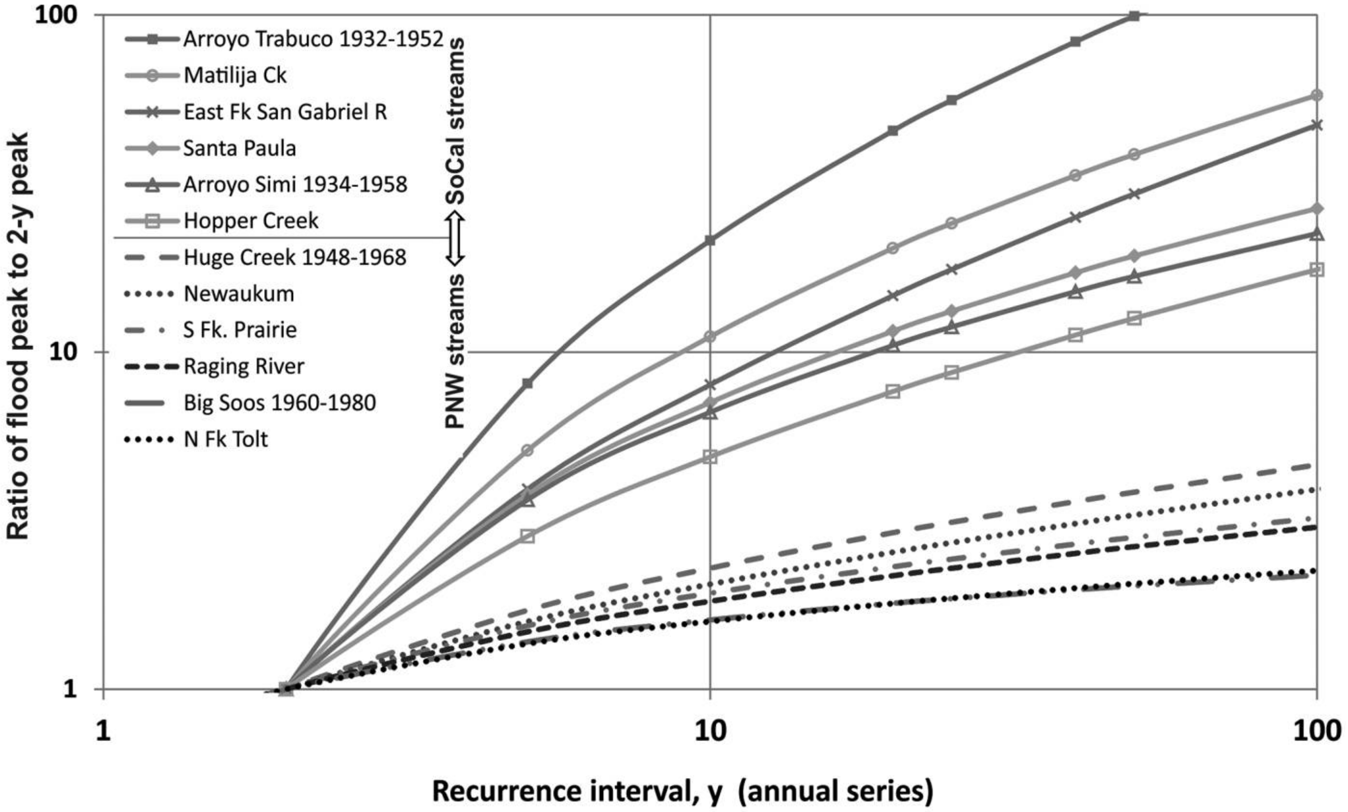

Figure 2. Hydrologic growth curves for rural streams with >20-y records from southern California (SoCal) and the Pacific Northwest (PNW). Recurrence intervals were calculated for full gage record or specified period (Bulletin 17B procedures implemented through www.erams.com).

and "all arid basins" climb >3× as steeply (see also fig. 16.6 by Lewin 1989 for other global compilations showing similar variability across regions).

Typical urbanization-induced increases in peak flow magnitudes can result in very different changes to flood frequencies in different regions. For example, 2-y peak flows are widely reported as being 2 to 5× greater in urban than in rural streams (e.g., Hollis 1975, Booth 1991, Hawley and Bledsoe 2011). In the Pacific Northwest, this increase results in posturban discharges that exceed multidecadal (or greater) preurban recurrences generated from storms that once would have produced only modest annual peak floods. However, in southern California streams, such a storm event generally would yield a posturban discharge at or below the preurban 10-y discharge. Thus, changes to flow regime can differ strongly among regions. In regions with consistent climate conditions (e.g., the Pacific Northwest), urbanization is a radical alteration of frequency–magnitude–duration relationships in stream discharge, and large ecological changes are well-documented in response to urban-induced hydrologic alteration (e.g., Roy et al. 2005, Kennen et al. 2010). In contrast, in regions with infrequent but large storms with long intervening periods of quiescence, flow recurrences will be more affected by the magnitude of decadal-scale storms than by the amount of urban land cover (Fig. 3A, B).

Increased delivery of water from a developed landscape commonly is accompanied by reduced delivery of sediment from armored streambanks and stabilized hillslopes (after the initial land-clearing stage has passed). Landscapes of the Pacific Northwest yield relatively little sediment under natural conditions, so a posturban decrease in sediment delivery does not represent a major change. However, landscapes of southern California yield high sediment loads under natural conditions, so decreased posturban sediment delivery may affect channel morphology as strongly as increased discharge (Bledsoe et al. 2012, Booth and Fischenich 2015). As a further complication, direct modification of channels is far more widespread in southern California than in the Pacific Northwest. Channel modification limits the geomorphic work that can be accomplished locally by increased flows but potentially amplifies these effects elsewhere along the channel network.

Regional differences in urban infrastructure, age and timing of development, and historical land cover can also affect stream responses to urbanization (Parr et al. 2016). Such regional and even local differences highlight the complex, interconnected influence of urban development

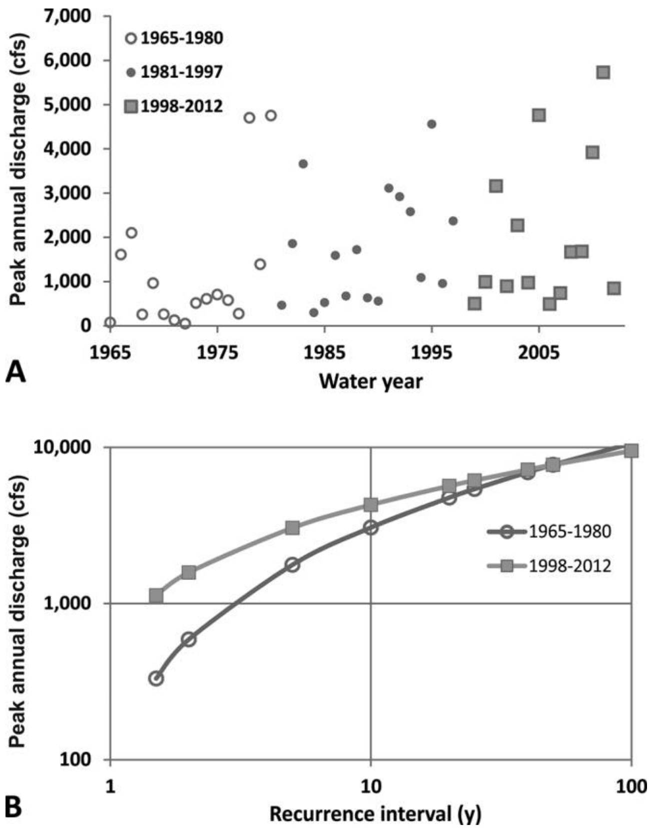

Figure 3. A.—Peak annual discharges for Los Penasquitos Creek in southern California at US Geological Survey gage 11023340. 1965–1980 was a period of limited urban development, 1981–1997 was a period of rapid urbanization, and 1998–2012 was a period when the area was largely urbanized (20.1% impervious surface) (Hawley and Bledsoe 2011). B.—Flood-frequency analysis for the limited development and largely urban periods. Discharge reported in original units (cubic feet per second; 100 cfs = 2.83 m^3/s; 7000 cfs = 198 m^3/s).

on urban streams and suggest why prior efforts to characterize these relationships have generally been most successful when restricted to specific case studies without trying to invoke universal applicability.

SIMILARITIES AND DIFFERENCES IN URBAN STREAM MANAGEMENT

Efforts to manage and rehabilitate urban streams have grown commensurately with our understanding of the urban stream syndrome. Restoration and rehabilitation of urban streams is now big business; efforts range from small-scale (Bernhardt et al. 2005) to large-scale, multimillion dollar (e.g., Whalen et al. 2002, Brooks and Lake 2007) projects. Collectively, cost estimates range from >100 million AU$/y in a single state of Australia (Victoria) to over a billion US$/y in the USA. In Europe, management and improvement of urban streams is now explicitly incorporated into legislation under the Water Framework Directive (ec.europa.eu/environment/water/water-framework). Given this investment in urban streams, understanding regional similarities and differences in the urban stream syndrome is critical to guide effective management.

Recognized commonalities among urban streams enable transfer of management approaches from watershed to watershed. If pathways of degradation and the biophysical context are similar, then an approach that succeeded in one location should work in another similar situation. For example, increased stormflow associated with increased impervious surfaces has been recognized as the primary driver of stream impairment in many places around the world (Konrad and Booth 2005, Walsh et al. 2005). This knowledge has led to widespread calls for redesign of urban infrastructure by disconnecting impervious surfaces from streams and stormwater management approaches that maximize infiltration and harvesting within watersheds (Walsh 2004, Ladson et al. 2006, Burns et al. 2012) and rapid expansion of designs and tests of these practices. The success of watershed-scale implementation of these approaches has been tested only a few times (e.g., in Cincinnati: Mayer et al. 2012, Roy et al. 2014; in Melbourne: Fletcher et al. 2011, Walsh et al. 2015), but these advances in stormwater management have been possible only because increased stormwater runoff is recognized as a critical, virtually universal stressor of urban streams.

However, transferability has limits. For example, infiltration- and retention-promoting stormwater practices, such as green roofs and rain gardens, have varying effectiveness depending on regional storm characteristics (e.g., Dussaillant et al. 2005, Li and Babcock 2014) and can induce perennial flows in previously intermittent streams (Hawley et al. 2012). Approaches that emphasize harvesting of increased runoff volumes are more likely to be widely applicable (Walsh et al. 2016). Moreover, biological characteristics may confer different degrees of susceptibility or resilience to urbanization (Utz et al. 2016), so understanding the differences among urban streams is vital for setting realistic management goals, which requires an understanding of the interplay between watershed and urbanization attributes, the regional ecological assemblage, and the social and economic feasibility of management approaches. Given the differences in physiographic conditions, degradation pathways, and manifestation of urban responses, management requires a systematic understanding of location-appropriate endpoints before appropriate conservation and restoration tools can be identified. As with human health, any treatment of urban streams should address the underlying causes of symptoms (i.e., the stressors) rather than the symptoms themselves (Beechie et al. 2010), and these stressors can be as varied as their watersheds.

Different restoration issues for urban streams in London, UK, illustrate the importance of place-specific analyses and management responses, even at sites separated by short distances. Analysis of the ecological condition of the

River Wandle, a groundwater-fed chalk stream in south London, identified contaminated fine sediments as a major constraint on fish populations in stretches of the river that otherwise have good water quality (Wandle Trust 2014). Installation of hydrodynamic vortex silt traps and monitoring to assess effectiveness were identified as the preferred management option. However, input of untreated sewage remains the major stressor for several other urban tributaries of the River Thames in London (Smith and Chadwick 2014). For these streams, diffuse pollution is a significant issue, but any path to ecological recovery must first address acute water-quality problems. The problem of raw sewage input is more common in less-developed countries lacking basic infrastructure. Capps et al. (2016) highlighted the need to adopt management strategies that first address primary water-quality stressors.

SOCIAL HETEROGENEITY INFLUENCES URBAN STREAM RESTORATION

Even where urban streams have been degraded in similar ways, the socioeconomic, institutional, and legislative context can determine the kind of management that is ultimately adopted. The interplay between the public perception of rivers (as hazards vs environmental assets), the level at which the power lies to make decisions regarding rivers (e.g., national environmental agency, regional government, municipal government), and investment priorities can lead to very different models for managing rivers. These factors determine the restoration goals that are set for urban streams (e.g., Karvonen and Yocom 2011) and the management approaches that are adopted. Understanding the transferability of different techniques tells us what might work in a particular physical watershed context, but understanding what might work in a particular social context also is crucial. This dynamic also works in reverse. Developing appropriate objectives for urban stream management, even if these are modest to start with, can promote increased community engagement with the stream that can subsequently support longer-term environmental goals, particularly if care is taken to include social as well as ecological objectives (Findlay and Taylor 2006, Smith et al. 2016).

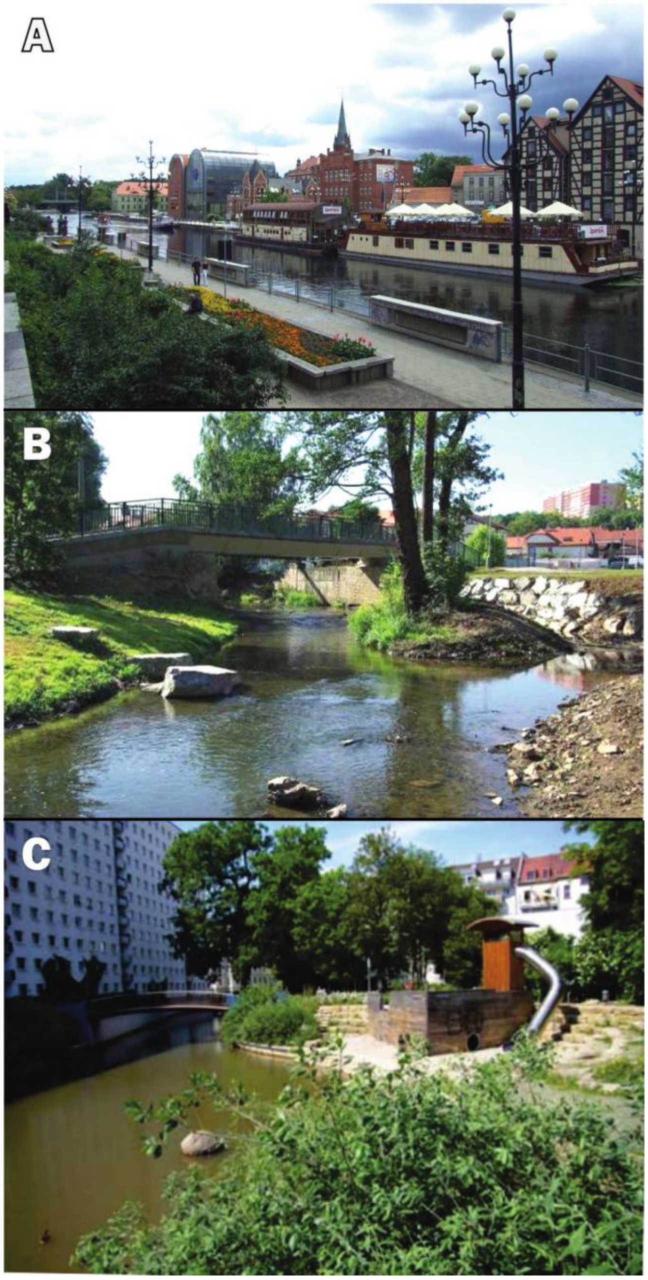

Figure 4. Urban streams in Poland (A), the Czech Republic (B), and Germany (C) where socioeconomic differences led to different management approaches for urban streams.

A comparison of urban stream management and restoration in Poland, Germany, and the Czech Republic illustrates these points (Fig. 4A–C). The urban streams in the 3 countries are similar in their physical and ecological attributes, and all exhibit clear symptoms of the urban stream syndrome, such as channelization, decreased lateral and longitudinal connectivity, and poor water quality (REURIS 2012). However, different socioeconomic and institutional contexts significantly alter the management of these systems. In Poland, the focus is on aesthetic and recreational improvement, and funding for river restoration in urban areas does not include activities for ecological improvement. In the Czech Republic, flood protection is the overriding objective, with limited scope for the application of more natural approaches to stream restoration. In Germany, approaches vary depending on municipality, but most projects integrate ecological and social objectives (REURIS 2012). For urban waterbodies in Europe, the legislative requirement of the Water Framework Directive to meet "good ecological potential" may systematically shift management toward more ecological goals, but socioeconomic and institutional differences clearly will continue to shape approaches to urban stream management.

The importance of social context and constraints is most important in less-developed countries (Capps et al. 2016). Where people lack basic sanitation, human health issues are paramount. Improved sanitation and sewage treatment have dual benefits for human health and the aquatic environment, and they can set the stage for further improvement of rivers and streams. Alternative stormwater management approaches in less-developed countries might prevent some of the ecosystem-damaging mistakes of the last century (mistakes that are now being corrected at great cost), but the overarching social drivers of development may require following certain aspects of the traditional development trajectory (e.g., combined sewer and stormwater pipes and centralized sanitation) despite their long-lived ecological consequences.

CONCLUSIONS

This synoptic overview of research and experience with the urban stream syndrome highlights the widespread commonalities and some significant differences between streams in urbanized watersheds around the world. The most noteworthy feature of these streams, as a whole, is how much more similar they are to each other than to their less-impacted counterparts: the urban stream syndrome is real. The commonality of expression and of the typical attributes of urban development in industrialized societies that give rise to homogenous urban streams has fostered increasingly rapid advances in the management of urban stormwater. However, the striking degree of similarity among urban streams has obscured meaningful differences among them. These differences merit deeper examination and ultimately should motivate management approaches tailored to each stream's physical and social context.

Therefore, we have introduced this *BRIDGES* cluster by threading a path between the dangerously simplistic belief that all urban streams can be cured by the same treatment and the paralysis that can arise from recognizing the many differences between any 2 such systems. Our efforts to recover the physical and ecological health of urban streams have benefitted greatly from the thoughtful consideration of work across the globe. We look to a new era of urban stream research that will provide more nuanced understanding of the regional, subregional, and local attributes of any given urban stream and its watershed to aid further recovery of these key elements of the natural and social landscape.

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