Urbanization and stream ecology: Moving the bar on multidisciplinary solutions to wicked urban stream problems

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Abstract: Decades of research on the effects of urbanization on stream ecology have shown that urban stream problems are inherently wicked. These problems are wicked in the sense that they are difficult to solve because information is incomplete, changing, or conflicting and because finding potential solutions often requires input from stakeholders who can have conflicting and competing values. The 5th Symposium on Urbanization and Stream Ecology (SUSE5) in February 2020 brought together diverse perspectives from scientists, managers, practitioners, and local communities. Participants at SUSE5 discussed the state of the science in urban stream ecology and worked through in-depth case studies in teams to tackle complex real-world problems in urban stream management. The papers in this special series on urbanization and stream ecology include empirical research studies and synthesis papers sparked by discussions at SUSE5 and advance multidisciplinary solutions to wicked urban stream problems.
Key words: urban stream ecology, urbanization, sustainable water management, restoration, transdisciplinary

Managing and restoring streams in urbanized watersheds is more important than ever because the rate of expansion of urban lands is accelerating worldwide (Liu et al. 2020) and >½ of the global population now lives in cities (United Nations et al. 2019). People also likely interact with urban streams more frequently than streams in more rural settings because of their proximity. In addition, we depend on urban streams for services like drainage of stormwater, flood control, recreation, aesthetic beauty, plant and animal habitat, and sometimes even drinking water (Palmer et al. 2014, Yocom 2014). However, urban streams are subject to pressures that can limit their capacity to provide these services, such as flashy runoff from impervious surfaces, increased water temperature, removal or degradation of vegetated buffers, pollution by nutrients and other contaminants, and others (Walsh et al. 2005). Urban stream restoration offers the potential to mitigate pressures and increase the ecological function and services of urban streams.

Managers have attempted to restore many urban streams, but recovery is rarely documented in the empirical literature (Rubin et al. 2017). This may be in part because the information that is needed to identify, evaluate, and solve urban

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stream problems is incomplete and because stakeholders can have competing goals and contradicting values (Smith et al. 2016, Lintern et al. 2020). Because of these characteristics, urban stream restoration may be considered a wicked problem (i.e., a problem without a clear, optimal solution; Bixler et al. 2022). There is increasing recognition that environmental problems are also social problems and that effective solutions to both social and environmental problems will likely focus on recovering critical components of ecosystems (Palmer and Stewart 2020). Further, social forces may often influence the type of restoration efforts implemented (Lave 2016). The path forward for restoration may be one that promotes equitable opportunities for people to interact with and manage the environment while recognizing dynamic power relations among stakeholders (Osborne et al. 2021). These calls for interdisciplinary thinking and consideration of power dynamics and equity influenced the framing of the most recent Symposium on Urbanization and Stream Ecology (SUSE) and, subsequently, the papers included in this special series.

SUSE

The goal of the SUSE is to advance understanding of how urbanization alters and degrades aquatic ecosystems and the effectiveness of management interventions at improving stream ecosystems across the world. The themes of SUSE meetings have evolved and built upon previous symposia: synthesizing the urban stream syndrome (SUSE1, 2003, Melbourne, Australia; *Freshwater Science* 2005 24[3]), identifying key research questions for urban streams (SUSE2, 2008, Salt Lake City, Utah, USA; *Freshwater Science* 2009 28[4]), summarizing global dissimilarities in urban streams (SUSE3, 2014, Portland, Oregon, USA; *Freshwater Science* 2016 35[1]), developing strategies to overcome barriers to catchment-scale rehabilitation (SUSE4, 2017, Browns Summit, North Carolina, USA), and developing multidisciplinary solutions to wicked urban stream problems (SUSE5, 2022, Austin, Texas, USA; *Freshwater Science* 2022 41[3]). Participants at SUSE meetings have diversified through time from primarily scientists from Australia and North America representing a few disciplines to an array of global participants from Latin America, Africa, Europe, Australia, New Zealand, and the United States representing environmental, social, and political sciences, stream restoration and management practitioners, nonprofit community groups, and local community members.

SUSE5 included many activities (plenary talks, posters, breakout groups) and topics (ecology, restoration) like the first 4 SUSE meetings, but it uniquely incorporated place-based issues through case studies that facilitated discussions of creative, collaborative solutions to wicked urban stream problems. Importantly, local voices were included in some of the case-study groups, which provided novel perspectives that are often not incorporated into urban stream restoration (Scoggins et al. 2022). For example, explicit incorporation of ecology, engineering, and social equity goals challenged participants to identify solutions that addressed broad urban sustainability challenges (Bixler et al. 2022). These case studies underscored the historic inequities in stormwater infrastructure investments in traditionally underserved communities, which contribute to disproportionate stream degradation in the neighborhoods where these communities live (SUSE5 2020, Moulds et al. 2021). In Austin, the stakeholder-inclusive process that SUSE5 participants experienced not only led to a more comprehensive understanding of the problems at local case study sites, but it also revealed positive feedbacks in community support, political will, and funding opportunities when stream problems are placed within the context of neighborhood needs (Scoggins et al. 2022). Expanding beyond the Austin experience, SUSE5 revealed the importance of meeting urban stream stakeholders (e.g., neighborhood residents, regulators, funding sources, etc.) wherever they are (Smith et al. 2014, Bice et al. 2019). This interactive approach broadens discussions to include how desired ecosystem services fit into the context of community values (Pahl-Wostl 2006).

Papers in this special series

The papers in this special series on urbanization and stream ecology include empirical research studies and synthesis papers sparked by discussions at SUSE5. Papers are grouped into 2 general themes: emerging challenges in urbanized watersheds and stream ecosystem response to stormwater management and restoration. The special series also includes a *BRIDGES* cluster that addresses the difficulties of effectively engaging all stakeholders toward developing urban stream restoration projects that are equitable and informed by community values. Publications in the journal *Urban Ecology* (across multiple issues in Volume 25) highlight additional research and conceptual advances that were sparked by SUSE5.

Theme 1: Emerging challenges in urbanized watersheds

The first 3 papers in this special series present emerging perspectives on the interacting social and environmental context in which urban stream restoration problems are embedded. Specifically, these papers focus on strategies for forming the multistakeholder collaborations that are critical for restoring both the ecological systems in urban streams and the social systems in communities living around them (Scoggins et al. 2022), and the management challenges associated with interacting contaminants in urban streams (Guasch et al. 2022, Kaushal et al. 2022).

Despite awareness that meaningful collaboration with stakeholders and local communities is valuable throughout the process of restoring urban streams, communication with local community stakeholders often comes after plans and designs have been made, if at all (e.g., Smith et al. 2016, da Cruz e Sousa and Ríos-Touma 2018, Moran et al. 2019). Two papers in this special series (Kaushal et al. 2022, Scoggins et al. 2022) demonstrate the need and value of early, meaningful stakeholder engagement in restoring urban streams and mitigating stream degradation. Scoggins et al. (2022) build on both the experiences of organizers, facilitators, and participants in the place-based case studies of the SUSE5 meeting and the authors' years of professional experiences to articulate a vision for how we can elevate the role of community stakeholders in urban stream restorations. Importantly, their vision involves working to concurrently restore the ecological integrity of the stream ecosystem and repair racial and socio-economic inequities suffered by communities living around the stream. Scoggins et al. (2022) contend that this path, which necessarily involves meaningful transdisciplinary collaboration, is the most direct way to restore the stream ecosystem and repair current and historical inequities suffered by the local community. Kaushal et al. (2022) also describe how stakeholders were involved in the process of identifying research needs to help drive future research on freshwater salinization, an emerging concern in urban streams. The themes of community engagement and equity with respect to urban stream restoration are further explored in the *BRIDGES* cluster (see below).

Contaminants carried to streams in storm runoff are among the major causes of stream degradation in urban landscapes. The ways in which individual contaminants interact with one another, naturally occurring chemicals, and the biota in urban landscapes to influence contaminant fate and transport are poorly understood. Kaushal et al. (2022) describe how co-occurring management of precipitation and runoff in urban areas contributes to and interacts with the freshwater salinization syndrome. Increasing concentrations of salts (from road deicers, fertilizers, infrastructure weathering products, etc.) have been measured in runoff and stream water (Kaushal et al. 2005, 2017, Moore et al. 2020). As these salts move along urban flow paths and through landscapes modified in accordance with best management practices such as those with green stormwater infrastructure, they interact with other contaminants, often with unknown consequences for the mobilization of chemical cocktails and their effects on biota in urban streams. Guasch et al. (2022) describe interactions between microplastics, a common contaminant in urban streams, and biofilms. Urban streams typically receive excess light and nutrients (Walsh et al. 2005) as well as plastic pollution (Hoellein et al. 2014, Mani et al. 2015, Khan et al. 2018, Donoso and Ríos-Touma 2020). The excess light and nutrients produce thick biofilms that likely enhance the trapping and transient storage of microplastics by biofilms with unknown ecosystem consequences. Both Guasch et al. (2022) and Kaushal et al. (2022) describe interactions of pollutants in urban environments that lead to complex and unknown ecosystem-level effects.

Theme 2: Stream ecosystem response to stormwater management and restoration

Four papers in this special series focus on approaches to stream restoration and stormwater management including a review of the current state of knowledge on macroinvertebrate reintroductions (Clinton et al. 2022), a new approach to optimize design standards for stormwater management based on critical discharge (Wooten et al. 2022), monitoring of threshold discharge for sediment mobilization and its departure from conventional calculations in urban streams (Hawley et al. 2022a), and a synthesis of long-term monitoring of the effects suburban development with distributed stormwater management on a suite of stream functions (Hopkins et al. 2022). These studies identify some of the limitations of conventional stormwater management policies and approaches and the utility of adaptive management approaches that learn from, and improve upon, the failure of traditional approaches. They also highlight novel ways to retrofit detention ponds in existing urban development (Wooten et al. 2022) and use distributed stormwater control at the watershed scale in new suburban development (Hopkins et al. 2022).

Stormwater management and stream restoration are beneficial in numerous ways, but papers in this special series also provide examples of the unintended consequences associated with management efforts. For example, macroinvertebrate reintroductions may be able to jump start recovery following restoration, but the risk of such reintroductions to both the donor and receiving assemblages from factors such as disease and genetic homogenization should be considered (Clinton et al. 2022). Kaushal et al. (2022) describe how best management practices intended to reduce peak flows may exacerbate or even create new water quality problems by mobilizing contaminants or changing the temporal patterns of their transport to streams. Hopkins et al. (2022) emphasize that distributed stormwater control can improve some water-quality constituents like nitrate concentrations but increase specific conductance and have little effect on overall baseflow nitrate export (because baseflow volumes increase).

The special series highlights how empirical approaches can be used to improve urban water management decision making. For example, Clinton et al. (2022) synthesize studies of macroinvertebrate reintroductions to provide guidance on determining whether species reintroductions are appropriate for a given site. Wooten et al. (2022) describe a science-based approach to setting stormwater management design targets in Sanitation District No. 1 of Northern Kentucky, USA. Their approach uses a locally calibrated stormwater design standard based on critical discharge (Q_c) rather than a theoretical design standard. Q_c identifies the flow rate threshold that induces sediment transport, rather than commonly used design storms based on the 2-y, 24-h storm, which has been assumed to represent bankfull discharge but rarely coincides with the threshold for sediment movement. Hawley et al. (2022a) expand on this approach by comparing theoretical and empirical Q_c across both a range of watershed urbanization and different geographic settings. Their research shows that the discharge that causes sediment mobilization is more likely to differ from theoretical calculations in more urbanized streams, with sediment mobilization in urban streams often requiring higher flow rates than would be predicted by theoretical calculations. This departure has important implications for management of erosion, channel geomorphology, and the biological assemblages in urban streams. Wooten et al. (2022) provide a prioritization scheme for detention basin retrofits that uses volume-to-drainage area ratios to identify basins with the highest retrofit potential in their Sanitation District No. 1 study area.

BRIDGES cluster

Both scientists and practitioners have learned the importance of gaining local community buy-in to improve the success of stream restoration efforts. This understanding is especially true in urban environments, where the success of restoration projects may hinge on community participation. The field of urban stream restoration has recently shifted to prioritize local community engagement on projects with the growing awareness that restoration efforts have a disproportionately large effect on the surrounding communities (Kondolf and Yang 2008, Dhakal and Chevalier 2016, Smith et al. 2016). However, engaging local communities in urban stream restoration has proven challenging for researchers, and there is still uncertainty on how to do it effectively (Crawford et al. 2017).

Each of the 3 papers in the *BRIDGES* cluster discusses the difficulties and limitations of effectively engaging local communities to develop equitable stream restoration projects driven by community values. These 3 papers highlight the importance and challenges of equitable participation by local communities and the need to recognize, consider, and include community values when addressing the wicked problems associated with urban stream restoration. Cross and Chappell (2022) begin the series by discussing the potential pitfalls to community engagement from a social perspective when developing restoration plans for urban streams. Their paper highlights the assumptions that scientists and practitioners make when attempting to engage the community, which sets the stage for a discussion on equitable engagement when planning and carrying out urban stream restoration. Díaz-Pascacio et al. (2022) describe how equitable community engagement can promote maximum community support in urban stream restoration projects. Murphy et al. (2022), the final paper in the cluster, apply a gap analysis to a series of case studies and demonstrate how diverse values and perspectives can complicate objective setting. Murphy et al. (2022) suggest a framework that guides those involved in urban stream restoration projects through an assessment of the values that may inform stakeholders' objectives. They go on to suggest how to balance tradeoffs among diverse stakeholders and achieve the dual goals of community engagement and stream restoration.

The *BRIDGES* cluster moves the ongoing discussion of effective community engagement in urban stream restoration forward, illustrating the historical and current shortcomings in project approaches and highlighting the importance of community conversations to provide an equitable solution. The cluster also demonstrates how equitable, values-based community engagement provides maximum long-term sustainability of urban stream restoration projects. Although implementing effective community engagement has limitations and challenges, especially for researchers and practitioners lacking social science training, these articles offer guidance regarding the actions needed to achieve successful engagement for urban stream restoration projects.

Future directions in urban stream science

The products of the SUSE5 meeting (this special series, Bixler et al. 2022, Castelar et al. 2022, Fork et al. 2022, Hawley 2022, Hawley et al. 2022b, Hill et al. 2022, Mayer et al. 2022, Rieck et al. 2022, Ríos-Touma et al. 2022, Wood et al. 2022) demonstrate the progress that has been made in urban stream science since the last SUSE meeting in 2016. Further, this collection of work has identified future research needs as well as current and future approaches to effective and equitable planning and management of urban stream restoration activities. As a community of researchers and practitioners, we have advanced understanding of complex interactions in urban streams (e.g., among contaminants, among stakeholders, among goals, etc.) and identified strategies for using data and case studies in the pursuit of restoration goals. Still, gaps in our knowledge and the potential for further development of urban stream science remain and are highlighted in several of the papers in this special series. Part of the wickedness of urban stream problems is their setting and context dependence, but cross-site syntheses of both process and outcomes can expand and enrich the portfolio of potential approaches to urban watershed management and restoration. In particular, the papers in this special series highlight the continued need for multi- and transdisciplinary teamwork in defining, developing, and implementing urban watershed management and restoration activities.

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LITERATURE CITED

Bice, S., K. Neely, and C. Einfeld. 2019. Next generation engagement: Setting a research agenda for community engagement in Australia's infrastructure sector. Australian Journal of Public Administration 78:290–310.

Bixler, R. P., J. A. Belaire, K. M. Faust, M. Scoggins, and A. González. 2022. Exploring the connection between transdisciplinary coproduction and urban sustainability solutions: A case study at an urban stream management symposium. Urban Ecosystems 25.

Castelar, S., S. Bernal, M. Ribot, S. N. Merbt, M. Tobella, F. Sabater, J. L. Ledesma, H. Guasch, A. Lupon, E. Gacia, and J. D. Drummond. 2022. Wastewater treatment plant effluent inputs influence the temporal variability of nutrient uptake in an intermittent stream. Urban Ecosystems 25.

Clinton, S. M., J. Hartman, K. H. Macneale, and A. H. Roy. 2022. Stream macroinvertebrate reintroductions: A cautionary approach for restored urban streams. Freshwater Science 41: 507–520.

Crawford, B. A., R. A. Katz, and S. K. McKay. 2017. Engaging stakeholders in natural resource decision making. ERDC/TN EMRRP-SR-83. United States Environmental Laboratory and Engineer Research and Development Center, Vicksburg, Mississippi.

Cross, D., and J. Chappell. 2022. Highlighting assumptions of community engagement in urban stream restoration. Freshwater Science 41:532–538.

da Cruz e Sousa, R., and Ríos-Touma, B. 2018. Stream restoration in Andean cities: Learning from contrasting restoration approaches. Urban ecosystems 21:281–290.

Dhakal, K. P., and L. R. Chevalier. 2016. Urban stormwater governance: The need for a paradigm shift. Environmental Management 57:1112–1124.

Díaz-Pascacio, E., M. M. Castillo, and N. O. Jelks. 2022. Including equity in urban stream restoration: From historical wrongs to new paradigms. Freshwater Science 41:539–547.

Donoso, J. M., and B. Ríos-Touma. 2020. Microplastics in tropical Andean rivers: A perspective from a highly populated Ecuadorian basin without wastewater treatment. Heliyon 6:e04302.

Fork, M. L., R. A. McManamay, and J. B. Heffernan. 2022. Propagation of inflowing urban stormwater pulses through reservoir embayments. Urban Ecosystems 25.

Guasch, H., S. Bernal, D. Bruno, B. C. Almroth, J. Cochero, N. Corcoll, D. Cornejo, E. Gacia, A. Kroll, I. Lavoie, J. L. J. Ledesma, A. Lupón, H. Margenat, S. Morin, E. Navarro, M. Ribot, T. Riis, M. Schmitt-Jansen, A. Tlili, and E. Martí. 2022. Interactions between microplastics and benthic biofilms in fluvial ecosystems: Knowledge gaps and future trends. Freshwater Science 41:442–458.

Hawley, R. J. 2022. Expanding catchment-scale hydrologic restoration in suburban watersheds via stream mitigation crediting—A Northern Kentucky (USA) case study. Urban Ecosystems 25: 133–147.

Hawley, R. J., K. L. Russell, and L. J. Olinde. 2022a. Q_c threshold departs from theoretical Q_c in urban watersheds: The role of streambed mobility data in managing the urban disturbance regime. Freshwater Science 41:489–506.

Hawley, R. J., K. Russell, and K. Taniguchi-Quan. 2022b. Restoring geomorphic integrity in urban streams via mechanistically-based storm water management: Minimizing excess sediment transport capacity. Urban Ecosystems 25.

Hill, S. K., R. L. Hale, J. B. Grinath, B. T. Folk, R. Nielson, and K. Reinhardt. 2022. Looking beyond leaves: Variation in nutrient leaching potential of seasonal litterfall among different species within an urban forest. Urban Ecosystems 25.

Hoellein, T., M. Rojas, A. Pink, J. Gasior, and J. Kelly. 2014. Anthropogenic litter in urban freshwater ecosystems: Distribution and microbial interactions. PloS ONE 9:e98485.

Hopkins, K. G., S. A. Woznicki, B. M. Williams, C. C. Stillwell, E. Naibert, M. J. Metes, D. K. Jones, D. M. Hogan, N. C. Hall, R. M. Fanelli, and A. S. Bhaskar. 2022. Lessons learned from 20 y of monitoring suburban development with distributed stormwater management in Clarksburg, Maryland, USA. Freshwater Science 41:459–476.

Kaushal, S. S., S. Duan, T. R. Doody, S. Haq, R. M. Smith, T. A. Newcomer Johnson, K. D. Newcomb, J. Gorman, N. Bowman, P. M. Mayer, K. L. Wood, K. T. Belt, and W. P. Stack. 2017. Human-accelerated weathering increases salinization, major ions, and alkalinization in fresh water across land use. Applied Geochemistry 83:121–135.

Kaushal, S. S., P. M. Groffman, G. E. Likens, K. T. Belt, W. P. Stack, V. R. Kelly, L. E. Band, and G. T. Fisher. 2005. Increased salinization of fresh water in the northeastern United States. Proceedings of the National Academy of Sciences 102:13,517–13,520.

Kaushal, S. S., J. E. Reimer, P. M. Mayer, R. R. Shatkay, C. M. Maas, W. D. Nguyen, W. L. Boger, A. M. Yaculak, T. R. Doody, M. J. Pennino, N. W. Bailey, J. G. Galella, A. Weingrad, D. C. Collison, K. L. Wood, S. Haq, T. A. Newcomer-Johnson, S. Duan, and K. T. Belt. 2022. Freshwater salinization syndrome alters retention and release of chemical cocktails along flowpaths: From stormwater management to urban streams. Freshwater Science 41:420–441.

Khan, F. R., B. S. Mayoma, F. J. Biginagwa, and K. Syberg. 2018. Microplastics in inland African waters: Presence, sources, and fate. Pages 101–124 *in* M. Wagner and S. Lambert (editors). Freshwater microplastics: Emerging environmental contaminants? Springer, Cham, Switzerland.

Kondolf, G. M., and C.-N. Yang. 2008. Planning river restoration projects: Social and cultural dimensions. Pages 43–60 *in* S. Darby and D. Sear (editors). River restoration: Managing the uncertainty in restoring physical habitat. John Wiley & Sons, Hoboken, New Jersey.

Lave, R. 2016. Stream restoration and the surprisingly social dynamics of science. Wiley Interdisciplinary Reviews: Water 3: 75–81.

Lintern, A., L. McPhillips, B. Winfrey, J. Duncan, and C. Grady. 2020. Best management practices for diffuse nutrient pollution: Wicked problems across urban and agricultural watersheds. Environmental Science & Technology 54:9159–9174.

Liu, X., Y. Huang, X. Xu, X. Li, X. Li, P. Ciais, P. Lin, K. Gong, A. D. Ziegler, A. Chen, P. Gong, J. Chen, G. Hu, Y, Chen, S. Wang, Q. Wu, K. Huang, L. Estes, and Z. Zeng. 2020. High-spatiotemporal-resolution mapping of global urban change from 1985 to 2015. Nature Sustainability 3:564–570.

Mani, T., A. Hauk, U. Walter, and P. Burkhardt-Holm. 2015. Microplastics profile along the Rhine River. Scientific Reports 5:17988.

Mayer, P., M. J. Pennino, T. A. Newcomer-Johnson, and S. S. Kaushal. 2022. Long-term assessment of floodplain reconnection as a stream restoration approach for managing nitrogen in groundwater and surface waters. Urban Ecosystems 25:879–907.

Moore, J., R. M. Fanelli, and A. J. Sekellick. 2020. High-frequency data reveal deicing salts drive elevated specific conductance and chloride along with pervasive and frequent exceedances of the US Environmental Protection Agency aquatic life criteria for chloride in urban streams. Environmental Science & Technology 54:778–789.

Moran, S., M. Perreault, and R. Smardon. 2019. Finding our way: A case study of urban waterway restoration and participatory process. Landscape and Urban Planning 191:102982.

Moulds, S., W. Buytaert, M. R. Templeton, and I. Kanu. 2021. Modeling the impacts of urban flood risk management on social inequality. Water Resources Research 57:WR029024.

Murphy, B. M., K. L. Russell, C. C. Stillwell, R. Hawley, M. Scoggins, K. G. Hopkins, M. J. Burns, K. T. Taniguchi-Quan, K. H. Macneale, and R. F. Smith. 2022. Closing the gap on wicked urban stream restoration problems: A framework to integrate science and community values. Freshwater Science 41:521–530.

Osborne, T., S. Brock, R. Chazdon, S. Chomba, E. Garen, V. Gutierrez, R. Lave, M. Lefevre, and J. Sundberg. 2021. The political ecology playbook for ecosystem restoration: Principles for effective, equitable, and transformative landscapes. Global Environmental Change 70:102320.

Pahl-Wostl, C. 2006. The importance of social learning in restoring the multifunctionality of rivers and floodplains. Ecology and Society 11:10.

Palmer, M. A., S. Filoso, and R. M. Fanelli. 2014. From ecosystems to ecosystem services: Stream restoration as ecological engineering. Ecological Engineering 65:62–70.

Palmer, M. A., and G. A. Stewart. 2020. Ecosystem restoration is risky . . . but we can change that. One Earth 3:661–664.

Rieck, L., C. Carson, R. J. Hawley, M. Heller, M. Paul, M. Scoggins, M. Zimmerman, and R. F. Smith. 2022. Phase II MS4 challenges: Moving toward effective stormwater management for small municipalities. Urban Ecosystems 25:657–672.

Ríos-Touma, B., C. Villamarín, G. Jijón, J. Checa, G. Granda-Albuja, E. Bonifaz, and L. Guerrero-Latorre. 2022. Aquatic biodiversity loss in Andean urban streams. Urban Ecosystems 25.

Rubin, Z., G. M. Kondolf, and B. Ríos-Touma. 2017. Evaluating stream restoration projects: What do we learn from monitoring? Water 9:174.

Scoggins, M., D. B. Booth, T. Fletcher, M. L. Fork, A. Gonzalez, R. L. Hale, R. J. Hawley, A. H. Roy, E. E. Bilger, N. Bond, M. J. Burns, K. G. Hopkins, K. H. Macneale, E. Martí, S. K. McKay, M. W. Neale, M. J. Paul, B. Ríos-Touma, K. L. Russell, R. F. Smith, S. Wagner, and S. Wenger. 2022. Community-powered urban stream restoration: A vision for sustainable and resilient urban ecosystems. Freshwater Science 41:404–419.

Smith, B., N. J. Clifford, and J. Mant. 2014. The changing nature of river restoration. Wiley Interdisciplinary Reviews: Water 1:249–261.

Smith, R. F., R. J. Hawley, M. W. Neale, G. J. Vietz, E. Díaz-Pascacio, J. Herrmann, A. Lovell, C. Prescott, B. Ríos-Touma, B. Smith, and R. M. Utz. 2016. Urban stream renovation: Incorporating societal objectives to achieve ecological improvements. Freshwater Science 35:364–379.

SUSE5 (5th Symposium on Urbanization and Stream Ecology). 2020. SUSE5 program book. 5th Symposium on Urbanization and Stream Ecology, Austin, Texas. (Available from: urban-streamecology.org/suse5-program—agenda.html)

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan II. 2005. The urban stream syndrome: Current knowledge and the search for a cure. Freshwater Science 24:706–723.

Wood, K. L., S. S. Kaushal, P. G. Vidon, P. M. Mayer, and J. G. Galella. 2022. Tree trade-offs in stream restoration: Impacts on riparian groundwater quality. Urban Ecosystems 25.

Wooten, M. S., R. J. Hawley, and C. Rust. 2022. Optimizing stormwater management to facilitate urban stream restoration via a science-based approach. Freshwater Science 41:477–488.

United Nations, Department of Economic and Social Affairs, and Population Division. 2019. World urbanization prospects: The 2018 revision. ST/ESA/SER.A/420. United Nations, New York, New York.

Yocom, K. 2014. Building watershed narratives: An approach for broadening the scope of success in urban stream restoration. Landscape Research 39:698–714.