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Stream restoration milestones: monitoring scales determine successes and failures

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Abstract

Urban stream restoration is growing globally, but there is much to learn from successes, failures, and evaluating tradeoffs in restoration practices. Significant time and resources have been invested towards restoring the structure and function of urban ecosystems and understanding and slowing the drivers of degradation. However, the rapid pace of urbanization and its effects on urban waters present an ever-growing challenge to environmental managers and restoration practitioners when identifying and prioritizing effective strategies for restoration and monitoring outcomes. Here, we synthesize major findings and papers originating from the 5th Symposium on Urbanization and Stream Ecology (SUSE5) and propose a new concept for monitoring restoration based on lessons learned. Efforts from SUSE5 showed that urban disturbances and restoration activities have strong localized impacts that can be challenging to detect and disentangle across broader watershed scales and longitudinal flowpaths. Most urban stream restoration projects are monitored at only one or a few locations that do not capture significant variability across stream reaches and longer flowpaths. Based on knowledge from SUSE5, we present a new concept called 'restoration milestones.' The restoration milestones concept proposes that the scale of stream monitoring over space and time can influence whether a stream restoration project is considered a success or failure. Therefore, answers to questions regarding restoration effectiveness and durability can be affected by spatial and temporal monitoring scales. Setting realistic restoration milestones involves establishing monitoring strategies that account for spatial and temporal variability. Tracking restoration performance through time across stream reaches along longitudinal flowpaths could aid in more accurately assessing project performance. We explore applications for evaluating restoration milestones along longitudinal stream flowpaths including: (1) identifying target areas of improvement along drainage networks, (2) accurately accounting for tradeoffs in habitat, protection of infrastructure, and water quality along flowpaths, and (3) detecting how far downstream the effects of stream restoration and stormwater management can be propagated. Monitoring across different spatial and temporal scales is an overlooked but critical factor in determining restoration success. Additionally, the scale of the restoration project itself can determine the type and magnitude of improvements. Expectations for what a restoration project can accomplish in terms of water quality improvements should be calibrated to the project's spatial scale and evolution over time. Longitudinal studies of stream restoration help identify successes and failures along flowpaths.

Keywords Urban water quality · Urban flowpaths · Community driven restoration · Longitudinal stream synoptic monitoring · River continuum · Urban watershed continuum

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Introduction

Much time, money, and effort have been expended on understanding urban watersheds and stream restoration from local to global scales (Bernhardt et al. 2005; Craig et al. 2008; Newcomer Johnson et al. 2016), but our knowledge of what contributes to success and failure in urban ecosystem restoration is still growing. Most urban stream restoration occurs at a reach scale, but may be expected to unrealistically address problems related to water quality, habitat, and geomorphic stability across broader watershed spatial scales (Walsh et al. 2005; Roy et al. 2008; Bernhardt and Palmer 2011; Hawley 2018). Stream restoration is implemented a reach at a time in phases due to financial and logistical constraints, and there may be expectations for treating a certain amount of impervious surface cover upstream in the watershed or volume of water passing through the stream restoration and stormwater management project (e.g., Roy et al. 2014, Altland et al. 2020). If we evaluate the ecosystem effects of stream restoration at the watershed scale, we may get different results and interpretations than evaluating results at the stream reach scale; there may be noticeable improvements at small spatial scales that disappear as the spatial scale gets larger (*sensu* Roy et al. 2008). Furthermore, there can be reach scale variability in responses to degradation and restoration due to local factors such as forest riparian cover, hydrologic connectivity with groundwater or impervious surfaces, and diverse pollution inputs (*sensu* Roy et al. 2005, Kaushal et al. 2008, Sivirichi et al. 2011, Kaushal and Belt 2012, Utz et al. 2016). The mismatch in urban stream restoration at the stream-reach scale and expectations of watershed-scale outcomes by scientists, environmental managers, and the public have challenged our ability to ascertain whether urban stream restoration projects succeed or fail (Smith et al. 2016). Interdisciplinary information ranging from empirical case studies, research syntheses and perspectives, and long-term monitoring can improve the next generation of urban watershed management and stream restoration practices.

Given that urbanization causes holistic degradation that evolves from instantaneous to decadal or longer temporal scales, a key question is whether restoration can keep pace with disturbance or if streams may continue to degrade even with restoration efforts. Urban effects in streams get expressed over multiple temporal scales, from instantaneous pulses of chemical cocktails to long-term channel evolution (Kaushal et al. 2014a, b, c, Kaushal et al. 2020). Degradation drivers constantly increase over time in urban ecosystems (e.g., bigger and more intense storms, aging/failing infrastructure, channelization, and ongoing development and redevelopment), which stress restoration infrastructure while existing urban development continues to impact restored stream reaches creating cumulative impacts on stream structure and function (Kaushal et al. 2014a, b, c). In addition, some urban contaminants and stressors are regulated, monitored, and managed (nutrients, metals, fecal coliforms) whereas many classes of unregulated and unmanaged contaminants and multiple stressors continuously emerge (e.g., Ríos-Touma and Ramírez 2019; Masoner et al. 2019; Fork et al. 2021; Kaushal et al. 2022a, b).

In response to multiple stressors, management interventions, selective pressures, and natural factors, the structure, function, and services of urban ecosystems evolve over time (Kaushal et al. 2014a, 2015; Hale 2016, McPhillips et al. 2018). Thus, urban ecosystems evolve towards degradation or restoration based on whether or not they receive appropriate and effective urban management (Hopkins et al. 2014; Kaushal et al. 2014a, 2015). For example, there is continued degradation of streams of different ages with different stormwater management technologies, but new technological approaches to restoration are developed along with repair of infrastructure, monitoring and management of past reach-scale restoration projects (Hale 2016). However, layered on top of these advances in stormwater technology are intensifying storm regimes driven by climate change (Kaushal et al. 2014b), which increasingly stress restoration projects (Hale 2016). Consequently, sustaining ecosystems and associated water quality functions involves maintaining and managing existing restoration projects and constantly adding new ones. Ultimately, an important question lingers about what can be done to get ahead of changing environmental conditions, as opposed to only making minimal or no progress despite constant investments in restoration. The solution to this type of daunting problem can be better informed by lessons from the urban streams research community based on recent synthesis (Fork et al. 2022a).

Here, we synthesize a recent special collection of papers published in *Urban Ecosystems* regarding urban stream ecology (Hawley 2022; Hawley et al. 2022; Fork et al. 2022b; Ríos-Touma 2022; Wood et al. 2022; Mayer et al. 2022; Bixler et al. 2022; Rieck et al. 2022; Hill et al. 2022; Castelar et al. 2022). Specifically, our synthesis provides 10 lessons learned on the emerging state of the science of urban stream restoration and proposes a new concept for evaluating and tracking restoration progress over space and time called 'restoration milestones.' We also propose a new concept tor tracking restoration success called 'restoration milestones' based on this collection of work. The lessons learned were primarily derived from the 5th Symposium on Urbanization and Stream Ecology and selected articles in the special collection of papers in *Urban Ecosystems*; thus, our 'restoration milestones' concept is largely constrained to this context. Nonetheless, we address the realities of urban stream restoration at the reach scale and the effects of setting achievable restoration milestones at appropriate spatiotemporal scales for monitoring and managing heterogeneous and complex stream impairments in urban ecosystems. Collectively, the papers in this special issue highlight the importance of reach scale variability in evaluating stream hydrological, geomorphic, biological, and chemical responses to both urban impacts and stream restoration and stormwater management. Further below, we highlight specific themes and lessons learned from the papers.

This grouping of papers in our synthesis of the special collection of papers on urban stream ecology attempts to place findings into a broader context, and emphasizes their larger importance for evaluating restoration success in urban streams. For example, while it is well known that stream conditions vary over space and time (Schum et al. 1984, Poff et al. 1997), the importance of this spatiotemporal variability in determining whether or not restoration activities were successful is often taken for granted. Using examples from the literature, along with the recent papers from the special collection and SUSE5, we explore how spatiotemporal variability needs to be a primary consideration in evaluating restoration projects.

Advancing urban stream restoration beyond degradation: gathering a community

The collection of papers in this special issue originates from the 5th Symposium on Urbanization and Stream Ecology (SUSE5), which was held in February 2020 in Austin, Texas, USA (https://www.urbanstreamecology.org/suse5.html). The SUSE5 meeting brought together researchers, practitioners, students, stakeholders, and others from diverse regions across the United States (U.S.) and world to advance stream restoration and address "wicked problems" (Fork et al. 2022a). Building on the success of previous SUSE symposia, numerous themes emerged from SUSE5 at the intersection of stream ecology, stormwater planning/engineering, and social equity. New knowledge emerged from plenary contributions from Africa, Australia, the United Kingdom, and the U.S. The event highlighted the spatial and temporal variability of investment in urban stream improvements, responses to natural/human health disasters, and changes in community support. Many of the following papers in this special issue expand on such themes from SUSE5, including social engagement frameworks, trade-offs in ecosystem functions and services, and case studies exploring how approaches to stream restoration and stormwater management attempt to balance environmental and community goals. In this special SUSE5 collection of papers, researchers investigate, identify, and evaluate which factors contribute to successes and failures in watershed and stream restoration outcomes. Knowledge regarding underlying ecological, hydrological, and biogeochemical mechanisms leading to successful restoration can eventually improve urban ecosystem restoration principles and practices (Chesapeake Stormwater Network 2020). We also acknowledge that we may learn more from failures than successes when designing, monitoring, and evaluating urban stream restoration projects (e.g., Roy et al. 2008, Bain et al. 2014, Hawley 2018).

Lessons learned: urban impacts, restoration approaches, and ecosystem responses

In this section, we discuss main lessons learned from the papers in this special SUSE5 collection, and how they highlight the importance of accounting for spatial and temporal variability in accounting for successes, failures, and tradeoffs relevant to urban ecosystem restoration. This special collection of papers can be divided into two broad themes: (1) studies analyzing variability in urban impacts on degradation of stream ecosystems and urban ecosystem processes at a stream reach scale (Ríos-Touma et al. 2022, Castelar et al. 2022; Hill et al. 2022; Fork et al. 2022b) and (2) studies analyzing variability in incentives and ecosystem responses and tradeoffs associated with watershed and stream restoration (Hawley 2022; Hawley et al. 2022; Rieck et al. 2022; Wood et al. 2022; Mayer et al. 2022; Bixler et al. 2022). The top 10 lessons from these papers are summarized below according to implications for advancing our knowledge of more accurately evaluating two main areas of study: (1) reach scale variability in response to degradation and (2) reach scale variability in response to restoration approaches and potential tradeoffs.

Lessons learned: principles and practices that stream restoration could advance by explicitly considering reach scale variability in response to degradation

1. *A lack of riparian preservation and wastewater treatment can lead to degraded stream reaches.*

Urban expansion may lack planning and appropriate infrastructure to protect streams and their ecosystem function and services. For example, more than 80% of people in Latin America live in urban areas (ECLAC, 2022), but lack of wastewater treatment, and the direct discharge of untreated sewage to water bodies can cause water quality issues (Walteros and Ramírez 2020). In addition, some cities around the world have either buried their streams or reduced the channel and riparian areas (Elmore and Kaushal 2008, Roy et al. 2009, Rios-Touma & Ramírez 2019). Some expanding urban areas around the world are located in highly biodiverse areas, and the resulting degradation of these ecosystems is alarmingly high. Rios-Touma et al. (2022, in this series) reports that in Quito, the capital city of Ecuador, streams lose almost 78% of stream insect taxa following watershed urbanization, wastewater inputs to streams, and a lack of riparian preservation. Such losses due to urbanization may be underestimated given that the true historical baseline aquatic biodiversity may be unknown in biodiversity-rich, tropical regions (Rios-Touma 2022). Knowledge about native biodiversity could thus be fundamental for quantifying urban stream degradation, evaluating factors that limit such losses, and, ultimately, structuring urban stream restoration.

2. *Urban inputs of organic matter and nutrients can be spatially and temporally heterogeneous.*

While urban trees provide multiple ecosystem services, they can also contribute excess nutrients and organic matter (which can accumulate on impervious surfaces and in storm drains) that can degrade the water quality in urban streams (Duan et al. 2014, Selbing 2016, Janke et al. 2017, Fork et al. 2018). Hill et al. (2022, in this special collection) shed new light on how the inputs of nutrients and organic matter from the urban forest in Idaho vary among litter types (leaves, blossoms, and fruit), species, and seasons. Urban trees drop greater masses of leaves and fruits compared to blossoms, but the blossoms have much greater capacity to leach nutrients and dissolved organic carbon into stormwater. Because of differences in the amounts and timing of litter produced among the tree species that make up urban forests, the potential contribution to nitrogen, phosphorus, and carbon in stormwater and the timing of the greatest potential contributions varies among tree species. This study highlighted the contribution of all types of litterfall, not just leaves, in calculating the impacts of urban trees on water quality, and has implications for the management of the urban forest to ensure that it provides multiple benefits to residents with minimal negative impacts on stream water quality (Hill et al. 2022).

3. *Urban stormwater disturbances can propagate along stream reaches longitudinally but may be attenuated based on reservoirs along flowpaths.*

Managing flashy pulses of urban stormwater can represent a major problem in urban streams (Walsh et al. 2005, 2016), but there are questions regarding the fate and impacts of runoff pulses as streams enter downstream impoundments. Impoundments are common features along stream networks (Gardner et al. 2019), so significant stormwater from urban development likely enters reservoirs or other impoundments. Fork et al. (2022b, in this special collection) quantified the propagation and impacts of stormwater runoff into large reservoirs for three streams in Tennessee, U.S.A. with variable watershed urban land cover. They found that stormwater from a relatively small urban stream frequently traveled at least 800 m (m) into the reservoir from the stream mouth, disrupting thermal stratification and likely transporting the contaminants well into the impoundment (the exact distance traveled varied across similar ecosystems and is likely based on the size of the watershed, stream, and reservoir). The ratio of total stormwater volume to the volume of water stored in the reservoir predicted the distance that stormwater runoff pulses traveled. Urban stormwater management that promotes infiltration rather than runoff can reduce the total stormwater volume reaching an impoundment and management of water levels in reservoirs can control the volume of stored water. By reducing the amount of precipitation that runs off of urban development, stormwater management can not only protect streams in urban landscapes but also the water quality and ecosystem function of receiving reservoirs (Fork et al. 2022b).

4. *Urban wastewater pollution can propagate along stream reaches longitudinally but may be attenuated based on dilution capacity along flowpaths.*

Casterlar et al. (2022, in this special collection) show that longitudinal patterns in nutrient concentration downstream of wastewater treatment plants may attenuate based on season and types and amounts of pollutants. Although some efforts in urban stream ecology have focused on nutrient uptake in streams, seasonal variability in uptake due to changes in hydrology and wet and dry weather has been less studied. Casterlar et al. (2022) show that streamflow can exert important influences on the capacity of streams to dilute and attenuate nitrate pollution, but phosphorus pollution appears to remain strongly under biological control across streamflow conditions. Overall, this work highlights important longitudinal patterns in water quality beyond a reach scale that emerge as a consequence of hydrologic conditions and management similar to Fork et al. (2022b). Given the emergence of broader longitudinal patterns and spatial and temporal heterogeneity, more evaluations of urban water quality may benefit from a broader watershed and stream network perspective.

Lessons learned: principles and practices that stream restoration could advance by explicitly considering reach scale variability in response to restoration approaches and potential tradeoffs

5. *Hydrologic-based restoration approaches along stream reaches have the potential to exert more ecological uplift along flowpaths and stream networks.*

Hawley (2022, in this special collection) presents the case for using hydrologic restoration to exert more ecological uplift along larger portions of the stream network than portions that are ecologically uplifted by conventional stream restoration alone. In a related paper, 20 years of research on the effectiveness of distributed stormwater control measures in greenfield developments in Maryland suggests that stormwater management can be tailored to maintain baseflows, runoff yields, and peak flows comparable to undeveloped watersheds (Hopkins et al. 2022). Such hydrologic mitigation can help buffer water quality impacts (Jefferson et al. 2017) and minimize macroinvertebrate community impacts relative to pre-developed conditions (Hopkins et al. 2022). By extension, hydrologic-based restoration in impaired watersheds could restore hydrologic processes that can support ecological recovery in greater portions of the stream network than conventional reach-based habitat restoration projects (Booth 2005; Walsh et al. 2016). For example, Hawley et al. (2017) documented how an inexpensive retrofit of a conventional detention basin in Northern Kentucky, U.S.A. was able to reduce peak flows and prolong baseflows in the receiving stream, which subsequently supported enough perennial flow for fish to recolonize pools in a reach that previously went dry ~ 10% of the time (Hawley 2018) as well as concurrent increases in stream habitat scores (Hawley 2022). Hydrologic restoration also has greater potential to improve water quality than conventional in-stream restoration, although projects that combine *both* habitat restoration and stormwater management may show the largest benefits in water quality (Lammers et al. 2020). By extension, Hawley (2022) suggests that even simple habitat restoration strategies such as riparian reforestation, invasive species removal, and hand-placement of in-stream wood (Wheaton et al. 2019; Hawley 2018) could further enhance the geomorphic, habitat, and ecological benefits of hydrologic-based restoration interventions. These hydrological and habitat improvements associated with flow-based restoration can have a monetary value via stream mitigation credits, providing a potential funding source for more comprehensive hydrologic restoration efforts in urban watersheds (Hawley 2022).

6. *Hydrologic-based restoration approaches can restore geomorphic integrity along stream reaches but there can be variability based on local site conditions and flow regimes.*

Hawley et al. (2022, in this special collection) also present a framework that documents how stormwater management can be tailored to preserve geomorphically relevant aspects of the natural flow regime to both maintain geomorphic integrity downstream of greenfield developments and restore geomorphic integrity in previously degraded reaches downstream of stormwater retrofits. Their paper builds on decades of well-established river mechanics science (e.g. Biedenharn et al. 2001, MacRae 1997, Wolman and Miller 1960) and highlights examples where their framework has been used with success to promote trajectories of geomorphic recovery downstream of stormwater retrofits (Hawley et al. 2022). The authors also underscore the roles of the stream's geomorphic condition and time in bearing out such trajectories of geomorphic recovery. For example, streams with coarser streambeds may recover more quickly than fine-grained streams (Hawley and Bledsoe 2013). Additionally, degraded severely entrenched streams (that have yet to substantially widen) may take longer to recover than streams that have already switched to aggradational trajectories (Schumm et al. 1984). Some urban streams also require substantial lateral (floodplain) space given that banks can erode and widen as they switch from trajectories of degradation to aggradation (Hawley et al. 2020) as they reach geomorphic equilibrium, further highlighting the importance of considering areas beyond the stream reach when conducting restoration (Hawley et al. 2022).

7. *Hydrologic-based restoration involving stream-floodplain reconnection can reduce peak stormflows and nitrogen loads, but can degrade over time based on site conditions.*

Reconnecting streams with floodplains is an increasingly popular restoration approach to improve urban water quality. Mayer et al. (2022, in this special collection) present long-term data from Minebank Run (located in Baltimore County, Maryland, USA) on the effectiveness of stream-floodplain reconnection as a means of improving water quality. Long-term data are rare for many stream restoration sites, but have been collected at Minebank Run since around 2003. Previous work at Minebank Run has shown spatial variability in denitrification and nitrogen removal rates associated with different types of stream-floodplain restoration (Kaushal et al. 2008; Mayer et al. 2022) demonstrate reductions in nitrate concentrations and transport per unit runoff following stream-floodplain reconnection in Minebank Run.

However, results also suggest that the effect may deteriorate over time due to erosion and failure of restoration features. Floodplain reconnection and riparian vegetation can also enhance nitrate sources and sinks and contribute to increasing or decreasing nitrate concentrations in restored streams based on seasonality and hydrology (Ledford and Lautz 2015). More work is necessary to investigate the spatial and temporal heterogeneity of stream restoration on water quality using longitudinal synoptic monitoring repeated over time throughout drainage networks similar to a growing number of studies (Sivirichi et al. 2011; Newcomer Johnson et al. 2014; Pennino et al. 2016).

8. *Stream restoration may create water-quality tradeoffs during the construction phase when trees are removed, but there can be recovery after construction disturbance.*

Trees in riparian zones improve key water quality functions that become somewhat limited in urban settings (Roy et al. 2005). Restoration projects often remove riparian trees despite their ecological value and the negative impact of their removal on the recovery trajectory. Wood et al. (2022, in this special collection) investigated the impact of reach-scale riparian tree removal during stream restoration and subsequent recovery (if any) on groundwater quality across restored, degraded, and forested reference sites over 20 years (located in Baltimore County, Maryland, USA). They found that riparian zones could either retain or release nutrients to groundwater based on whether or not trees were cut. Specifically, sites where trees were removed had higher nutrient (nitrogen, potassium, calcium, etc.) concentrations in the groundwater than sites where trees remained. Nutrients and carbon in groundwater were highest immediately following construction during restoration or tree removal, and there were significantly increased concentrations in riparian groundwater for at least 5 years following tree removal (Wood et al. 2022). Previous work demonstrated the effects of riparian forest cover on spatial heterogeneity in responses of urban stream reaches to degradation (Roy et al. 2005). These combined observations highlight both the spatial (stream reach) and temporal variability in restoration trajectories, which are important considerations for setting achievable expectations for urban restoration.

9. *Managing urban stormwater is complex and can benefit from consideration of space and time.*

Rieck et al. (2022, in this special collection) assess the effectiveness of stormwater management in overcoming an array of challenges before implementation, especially in smaller communities. Effective stormwater management policy and urban planning may include consideration of multiple spatiotemporal scales when facilitating stream recoveries and monitoring project outcomes (Rieck et al. 2022). The myth that stormwater management only benefits downstream communities can be a barrier to implementing stormwater policies that can be specifically tailored to benefit a community (Rieck et al. 2022). For example, time for a stream to recover following stormwater construction projects can vary and may be long (maybe several years) in relation to both hydrologic and geomorphic restoration (Hawley 2022; Wooten et al. 2022), re-establishment of riparian forests (Wood et al. 2022), and macroinvertebrate recolonization (Clinton et al. 2022).

10. *Urban stream restoration can benefit from transdisciplinary approaches.*

Sustainable urban stream restoration involves communities and stream professionals during all stages of development, from planning to implementation (Scoggins et al. 2022; Bixler et al. 2022, in this special collection) examine the involvement of community members in multidisciplinary teams investigating how “wicked problems” in urban streams affect team perception of the process and solutions. Transdisciplinary teams placed greater emphasis on social and environmental justice issues compared to single and multi-disciplinary teams of stream scientists who largely focused on instream problems. The broader perspective from transdisciplinary teams resulted in more diverse restoration solutions that were subjectively rated by SUSE5 participants as better than solutions from single and multidisciplinary teams (Bixler et al. 2022). However, differences in social norms, cognitive models, and lack of trust among stakeholders can challenge sustainable solutions (Norström et al. 2020). During the SUSE5 meeting, there was high variability in how individuals within transdisciplinary teams ranked the process (Bixler et al. 2022), with results that emphasized that strategies developed by social scientists can help in developing effective community engagement when addressing urban sustainability challenges.

Restoration milestones concept: tracking longitudinal stream outcomes over time

Overall, the growing body of work from SUSE5 demonstrates considerable variability in degradation and restoration responses among urban streams due to spatial and temporal variability in hydrology, nutrient concentrations, and ecological communities. The concept of restoration milestones explicitly considers temporal and spatial variability along stream reaches for assessing urban stream restoration. Furthermore, the scale of stream monitoring over space and time influences whether a stream restoration project is considered a success or failure. Therefore, answers to questions regarding restoration effectiveness and durability can be strongly influenced by the spatial and temporal monitoring scales. The restoration milestones concept also involves evaluating stream response and condition along longitudinal flowpaths to identify areas of improvement along drainage networks and to determine how far downstream the effects of stream restoration propagate. Finally, we propose to think beyond only individual restoration projects and consider the broader hydrologic networks and flowpaths within a restoration framework. Tracking restoration milestones along a longitudinal gradient allows scientists to better identify the effects of restoration projects from broader impacts of disturbances at the watershed or network scale.

The growing need for a restoration milestones framework and longitudinal studies

Much work has focused on evaluating stream restoration in degraded vs. restored reaches. However, some knowledge gaps and concerns regarding restoration exist because of: (1) the relatively small spatial scales in which we typically monitor or study stream-floodplain restoration projects, (2) the focus on analyzing only one or a few stressors, and (3) the lack of extensive spatial and/or long-term data to provide adequate context to interpret effects of watershed restoration activities. Evaluating restoration at a small reach scale does not provide any information about how far downstream the restoration signals can persist along flowpaths. Do the restoration effects last only a few meters downstream, or do some of these restoration effects persist further down for kilometers? How do different hydrologic conditions affect the persistence of the restoration signals when comparing across sites? There is a great need for monitoring efforts, which adequately capture hydrologic variability over time when quantifying pollutant loading/yields. Infrequent sampling can lead to inaccurate assessment of success/failure of restoration efforts, especially when typical routine monitoring at one fixed site using on a monthly basis can miss flows during hydrologic events (Mayer et al. 2022). Most studies focus on analyzing only one or a few contaminants and miss opportunities for comprehensively understanding how: (1) multiple contaminants are impacted by restoration, (2) water quality tradeoffs can be avoided after narrowly focusing on one process, and (3) opportunities for more efficiently co-managing multiple contaminants can be maximized (Kaushal et al. 2018, 2019, 2020). A restoration milestones framework accounting for transport and transformation of multiple contaminants along stream flowpaths across space and time is needed.

Applying the restoration milestones concept: monitoring scales to match management

Using a milestones approach, restoration performance across stream reaches along urban watershed flowpaths is explicitly considered, benchmarked, and tracked over time (see example study design; Table 1). Urban watersheds encompass a space-time continuum over which the structure, function, and services of streams vary (*sensu* Kaushal and Belt 2012). The four dimensions of the urban watershed continuum are: (1) 'longitudinal' encompassing the flowpath from upstream to downstream along the mainstem, (2) 'lateral' encompassing flowpaths from uplands and riparian zones to streams and tributary inputs, (3) 'vertical' encompassing groundwater-surface water interactions, hyporheic exchange, and stream surface-atmosphere fluxes, and (4) 'time.' For example, there is longitudinal connectivity from upstream to downstream, lateral connectivity from riparian zones and floodplains to stream channels, and vertical connectivity from subsurface groundwater and leaky pipes and infrastructure to surface waters (Kaushal and Belt 2012). In addition there are vertical stream surface-atmosphere fluxes of greenhouse gasses, which are of concern (e.g., methane, nitrous oxide, and carbon dioxide emissions) (Smith et al. 2017). In addition, urban hydrologic flowpaths evolve over time (Kaushal and Belt 2012; Kaushal et al. 2014a,c; 2015) suggesting that a 4-dimensional framework that evaluates longitudinal, lateral, vertical and temporal connectivity of hydrologic flowpaths could be the most comprehensive approach for evaluating urban streams. Yet, evaluations of restoration successes or failures may not monitor these 4 dimensions which could provide a more holistic understanding of and way to improve management of urban streams. Most restoration studies focus on tracking changes in water quality across one dimension, time. There is a need to get a better picture of water quality changes in multiple spatial and temporal dimensions to generate a better picture of water quality changes in response to restoration.

Current monitoring approaches for urban stream restoration may focus on sampling only a few fixed points over time; however, this limited approach can miss important opportunities for identifying which restoration features and stream reaches contribute the most to changes in geomorphic stability, hydrology, water quality, and biotic communities or may not detect how far downstream restoration effects persist. Our restoration milestones approach suggests setting and tracking goals across specific measurable spatial and temporal scales, reflecting the reach scales at which the original restorations were implemented (Table 1, Steps 1–2). As just one simple approach towards more accurately evaluating restoration milestones, more synoptic sampling can be done along stream networks to better assess spatial heterogeneity (Table 1, Steps 3–4). Longitudinal synoptic sampling and sampling across seasons may be increasing in urban stream ecology, which can reveal interesting patterns of successes and failures in reaches along urban stream networks (Sivirichi et al. 2011; Newcomer Johnson et al. 2014; Pennino et al. 2016). Longitudinal sampling points can be designed to capture geomorphic, hydrological, chemical, and biological signals from specific restoration features and/or tributary inputs and/or riparian disturbances (Kaushal and Belt 2012; Kaushal et al. 2014a, c; Gabor et al. 2017). Monitoring of longitudinal outcomes can also illustrate differences in hydrologic connectivity of impervious surfaces (Baruch et al. 2018), help elucidate the importance of groundwater and surface water interactions along draining networks (Cooper et al. 2014; Gabor et al. 2017), and be used to assess the extent of degradation from physical, chemical, and/or biological factors (e.g., Cooper et al. 2014; Fork et al. 2022b, Casterlar et al. 2022). This type of detailed spatial information along reaches may be missing in evaluating current stream restoration projects which could benefit from further work in analyzing hydrological, geomorphic, biological, and chemical changes upstream and downstream of geomorphic elements and specific restoration features.

Our restoration milestones concept fosters tracking spatial changes and improvements along stream reaches over time (Table 1, Step 2). Longitudinal synoptic monitoring can be repeated over time to make comparisons of how water quality changes across seasons and hydrologic events. In some cases, the functionality of stream restoration and recovery in water quality from construction disturbances can improve with time (Wood et al. 2022; Mayer et al. 2022; (Kaushal et al. 2022a). Given natural inter-annual variability, Before/After-Control/Impact (BACI) study designs that examine relationships among parameters of interest for several years both pre- and post-restoration periods can be helpful in detecting responses (Kaushal et al. 2008; Hopkins et al. 2020, 2022; Mayer et al. 2022; Wood et al. 2022; Walsh et al. 2022). Over shorter time scales, seasonal storm event sampling can be used to evaluate restoration milestones for characterizing reach-scale responses to hydrologic events (Mayer et al. 2022) and chemical inputs and outputs along targeted stream restoration features and reaches. Routine sampling of restoration performance and ecosystem functions and services over time can help evaluation of success (Kaushal 2014a,c; 2015; Hopkins et al. 2022). Furthermore, combined analysis and evaluation of multiple biological, chemical, and hydrogeomorphic parameters together across space-time can holistically be important diagnostics of the recovery of the structure and function of urban waters (Table 1, Step 5).

Longitudinal studies of restoration that adequately capture hydrologic variability

Using a longitudinal synoptic approach to monitor restoration milestones over time, we can separate baseflow longitudinal synoptic sampling events and wet weather longitudinal synoptic sampling events in statistical analyses when appropriate. Baseflow synoptic sampling at steady state can measure not only changes in concentrations of multiple chemicals, but also loads of chemical contaminants and how they change downstream along flowpaths (Kaushal et al. 2014c). In most cases, it is more feasible to assess changes in chemical loads (and measure stream discharge) during baseflow at steady state conditions (Kaushal et al. 2014c); this can allow scientists and managers to determine how downstream concentrations and loads of multiple chemicals can change with restoration interventions, land use, and watershed area. However, longitudinal synoptic measurements during wet weather can also be compared to baseflow measurements and allow us to understand how contaminant sources change downstream during wet weather events such as snow events and rainstorms.

Longitudinal synoptic monitoring of ‘chemical cocktails’ to evaluate water quality

A watershed ‘chemical cocktail’ approach suggests the importance of analyzing combinations of elements to infer sources, flowpaths, and mechanisms of chemical transport and transformation in watersheds (Kaushal et al. 2018, 2020, 2022a, b). For example, floodplain and stormwater management BMP sediments can be “hot spots” of denitrification due to low oxygen and redox conditions (Kaushal et al. 2008; Mayer et al. 2010; Harrison et al. 2011, Newcomer Johnson et al. 2014). However, related work has also shown that they can release phosphorus and iron under certain redox conditions at the small reach scale (Duan et al. 2019). Applying a watershed chemical cocktail approach can allow detection of these water quality tradeoffs between multiple chemical elements. In addition, there can be water quality tradeoffs associated with removal of trees and soil disturbances during the construction process leading to significantly elevated concentrations of salt ions, nutrients, and metals in streams, limiting uplift and recovery at the small reach scale (Wood et al. 2022; (Kaushal et al. 2022a, b). Yet, it is unclear whether these tradeoffs only impact small, localized stream reaches near the disturbances or whether there is propagation of unanticipated impacts across multiple elements further downstream along broader watershed scales. There are likely significant differences in the sources and sinks of nutrients, salts, and metals that warrant holistic comparisons. A monitoring approach integrating both space and time and multiple contaminants or 'chemical cocktails' along longitudinal flowpaths can be a more comprehensive way for improving watershed assessments and evaluating restoration of multiple water quality parameters.

Outcomes from longitudinal studies of restoration provide a broader context

A longitudinal flowpath approach provides a broader watershed context for interpreting specific results at the reach scale by identifying unexpected or unique changes within a given reach and determining if there are other factors besides the restoration that drive patterns at a particular reach. For example, a longitudinal synoptic approach can allow us to better understand watershed processing and transport and potential implications for downstream receiving waters for multiple chemicals in urban streams (Kaushal and Belt 2012; (Kaushal et al. 2020, 2022a, b). However, the longitudinal flowpath approach can also be used for more than just chemicals and applied more broadly to evaluating restoration performance (hydrological, geomorphic, chemical, biological) across time and space at both the stream reach scale and whole watershed scale (Table 1).

Table 1 Example of a study design for implementing a stream restoration milestones approach across space and time

Step 1:	Select stream flowpaths and reaches along a watershed experiencing varying degrees of restoration, management, and degradation from headwaters to watershed outflow. Work with environmental managers to establish specific milestones for restoration performance (hydrological, geomorphic, chemical, biological) across time and space at both the stream reach scale and whole watershed scale.
Step 2:	Establish a routine monitoring site at the watershed outlet, which focuses on stream discharge, water quality, and sensor deployments. Data can be collected across hydrologic events, seasons, and years to characterize changes in stream discharge, chemical concentration, loads, and other variables.
Step 3:	Conduct high-resolution synoptic sampling at multiple points along longitudinal stream flowpaths for monitoring changes in discharge, channel cross sections, geomorphic channel stability, chemical concentrations/loads, and/or biological metrics from headwaters to watershed outlets. Sampling multiple times before and after restoration is important to capture seasonal and interannual variability. High-spatial resolution synoptic results can be compared across restored and degraded stream flowpaths and linked to surrounding land use and disturbance history.
Step 4:	Analyze high-resolution spatial sampling results to identify "hot spots" of contaminant transport and transformations and/or significant changes in biodiversity, hydrologic and geomorphic changes along stream reaches. Track changes in stream reach scale performance of ecosystem and hydrologic functions along flowpaths with hydrologic, geomorphic, chemical, and biotic metrics over time. Performance along stream reaches can be ranked and graded based on established milestones over time, and compared to reference conditions.
Step 5:	Analyze temporal monitoring at the watershed outlet to determine cumulative changes in water quality and hydrologic responses and flashiness over time in the watershed related to changes in climate, land use, and management interventions. Evaluate whether changes or trends at the watershed scale are meeting milestones and goals for hydrology, geomorphology, water quality, and stream biology.

Conclusions: tipping the balance between urban degradation and restoration

In this paper, we synthesized a major theme from SUSE5 papers, which is that the scale of monitoring is critical to evaluating urban stream restoration projects. Throughout this paper, we also presented real-world examples about why including spatiotemporal variability is critical to determining urban stream restoration success. Research from SUSE5 highlights the temporal and spatial variability of restoration outcomes along stream reaches and the complexity in prioritizing restoration approaches across stream reaches. From this compilation of papers, we learned that stream restoration at the reach scale cannot realistically mitigate disturbances generated at the watershed scale, but there can be discernible improvement and tradeoffs at the reach scale based on restoration approach and selected response variables. Most importantly, we learned that monitoring across different spatial and temporal scales can influence our evaluations of degradation and restoration responses. A restoration milestones concept suggests that appropriate monitoring scales be matched with relevant management questions and setting achievable restoration goals. Expanding monitoring at broader or more diverse spatiotemporal scales could be used to holistically evaluate whether restorations are successes or failures at spatial scales relevant to the restoration process itself. Overall, this special issue provides an improved understanding of how managing and restoring hydrologic flowpaths (e.g., Fork et al. 2022b; Wood et al. 2022), changing or limiting pollutant sources (Castelar et al. 2022), and improving management along watersheds and streams (e.g., Hawley et al. 2022a,b; Mayer et al. 2022) can influence the quantity, quality, and ecosystem functions and services of urban waters across space and time. New knowledge and emerging insights from this special issue and SUSE5 are intended to help improve monitoring and management efforts toward a more desirable balance between degradation and restoration of urban waters. Given that rates of degradation from urbanization are rapid and identifying recovery can be complex (Roy et al. 2014, Ríos-Touma et al. 2022, Fork et al. 2022b; Hawley et al. 2022; Hopkins et al. 2022), evaluating restoration milestones is an important aspect of urban water protection. A key question from SUSE5 remains: How quickly and accurately we can identify successful outcomes and approaches to help tip the balance between rates of ecosystem degradation and successful evolution of urban stream restoration and recovery in the future?

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Declarations

Competing interests The authors declare no competing interests.

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