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Review

Urban Evolution: The Role of Water

Sujay S. Kaushal [1,*], William H. McDowell [2], Wilfred M. Wollheim [2], Tamara A. Newcomer Johnson [1], Paul M. Mayer [3], Kenneth T. Belt [4] and Michael J. Pennino [5]

[1] Department of Geology & Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 21201, USA; E-Mail: tammy.a.newcomer@gmail.com

[2] Department of Natural Resources and the Environment, University of New Hampshire, Durham, NH 03824, USA; E-Mails: bill.mcdowell@unh.edu (W.H.M.); wil.wollheim@unh.edu (W.M.W.)

[3] US Environmental Protection Agency, National Health and Environmental Effects Research Lab, Western Ecology Division, Corvallis, OR 97333, USA; E-Mail: Mayer.Paul@epa.gov

[4] United States Department of Agriculture Forest Service, Northern Research Station, Baltimore, MD 21228, USA; E-Mail: kbelt@fs.fed.us

[5] Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA; E-Mail: michael.pennino@gmail.com

* Author to whom correspondence should be addressed; E-Mail: skaushal@umd.edu; Tel.: +1-301-405-7048.

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Abstract: The structure, function, and services of urban ecosystems evolve over time scales from seconds to centuries as Earth's population grows, infrastructure ages, and sociopolitical values alter them. In order to systematically study changes over time, the concept of "urban evolution" was proposed. It allows urban planning, management, and restoration to move beyond reactive management to predictive management based on past observations of consistent patterns. Here, we define and review a glossary of core concepts for studying urban evolution, which includes the mechanisms of urban selective pressure and urban adaptation. Urban selective pressure is an environmental or societal driver contributing to urban adaptation. Urban adaptation is the sequential process by which an urban structure, function, or services becomes more fitted to its changing environment or human choices. The role of water is vital to driving urban evolution as demonstrated by historical changes in drainage, sewage flows, hydrologic pulses, and long-term chemistry. In the current paper, we show how hydrologic traits evolve across successive generations of urban ecosystems via shifts in selective pressures and adaptations over time. We explore multiple empirical examples including evolving: (1) urban drainage from stream burial to stormwater management; (2) sewage flows and water quality in response to wastewater treatment; (3) amplification of hydrologic pulses due to the interaction between urbanization and climate variability; and (4) salinization and alkalinization of fresh water due to human inputs and accelerated weathering. Finally, we propose a new conceptual model for the evolution of urban waters from the Industrial Revolution to the present day based on empirical trends and historical information. Ultimately, we propose that water itself is a critical driver of urban evolution that forces urban adaptation, which transforms the structure, function, and services of urban landscapes, waterways, and civilizations over time.

Keywords: urban watershed continuum; urban karst; urban succession; urban adaptation; transitional ecosystems; convergent urban evolution; urban calcium cycle

1. Introduction

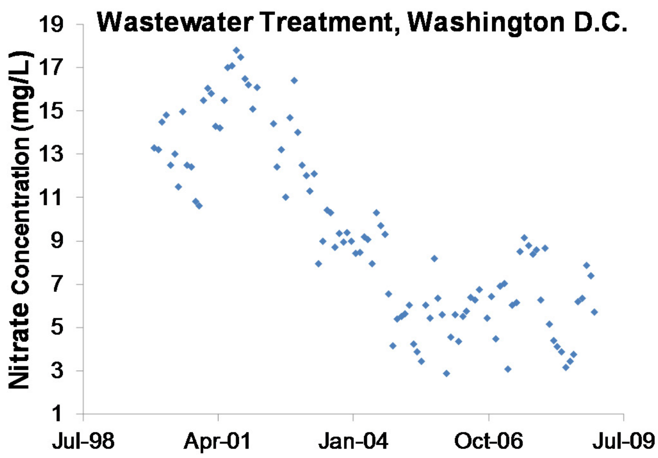
Over half of the Earth's population currently lives in urban areas and this number is projected to increase in the future [1]. Given that Earth is rapidly urbanizing, there is an evolving demand for water resources by expanding cities and suburban areas globally [2–4]. Adaptation to environmental changes including water scarcity and floods have been recognized as critical for the survival of human settlements over time [5,6]. For example, recorded history has been characterized by the rise and fall of empires such as Rome due to periods of rapid urbanization and water and food shortages for urban populations [6–8]. Understanding the evolution of how humans have interacted with urban waters is important for guiding innovations for future water management [9]. It is also important for improving our scientific understanding of how urban water systems evolve over time scales from seconds to centuries as Earth's population grows, infrastructure ages, and sociopolitical values alter them. It has been proposed that the built environment often changes quickly in response to human activities, thus contributing to an "urban evolution" of structure, function, and services of human settlements over time [10]. In this paper, we define and review core concepts relevant to studying urban evolution, and we propose a new conceptual model for the evolution of urban waters from the Industrial Revolution to present day.

Over recorded history, water has driven evolution of the structure, function, and services of cities [6,7,11,12]. For example, most industrial cities were originally located near water for transportation, power, and trade [11,13]. The "Industrial City" was characterized by factories where production of commodities primarily took place, and point and nonpoint source pollution to urban waters was dominated by manufacturing and industrial processes [11–13]. Later, a transition in the structure, function, and services from the Industrial City to the "Sanitary City" was driven by the need for clean drinking water and centralized sewage infrastructure [14]. More recently, there has been interest in transitioning from the Sanitary City to the "Sustainable City," which has focused on green infrastructure and ecosystem restoration [15–17]. Many cities are now implementing sustainability plans along with new regulations (e.g., Total Maximum Daily Loads in the U.S.) and economic, social, and environmental benefits [17,18]. Urban sustainability plans can include sewer upgrades, innovative stormwater management, and watershed, stream, and river restoration [16,17,19–23].

In this paper, we define key concepts for studying urban evolution and illustrate how urban waters evolve in watershed drainage, hydrology, sewage flows, and long-term chemistry over time (Figures 1–4). Our overall objective is to provide a conceptual and predictive framework for characterizing stages, transitions, and mechanisms related to urban evolution. Currently, we have few conceptual and predictive frameworks for understanding trajectories of ecosystem development in urban ecosystems as compared to natural ecosystems (e.g., succession, climax communities, dynamic equilibrium, *etc.*). Urban evolution allows us to anticipate and compare changes under varying environmental conditions and minimize unintended consequences due to *ex post facto* reactive management. The concept of urban evolution can be useful in informing discussions and debates regarding the manner, rates, and extent to which ecosystem management and restoration should be done. Furthermore, we suggest that the concept of urban evolution is critical for elucidating the role of urbanization during the Anthopocene, an epoch when human activities have had a significant global impact on the Earth's ecosystems including water [24,25].

Evolving Wastewater Treatment

(a)



(b)

Figure 1. Blue Plains is among the largest advanced wastewater treatment plants in the world, and it treats sewage from Washington, DC, USA (Photo Courtesy: S. Kaushal) (**a**); Blue Plains discharges treated effluent to the Potomac River. There has been a long-term decline in nitrate concentrations in wastewater effluent as denitrification technology has improved over time (**b**) (Data courtesy of Dr. Sudhir Murthy and Blue Plains).

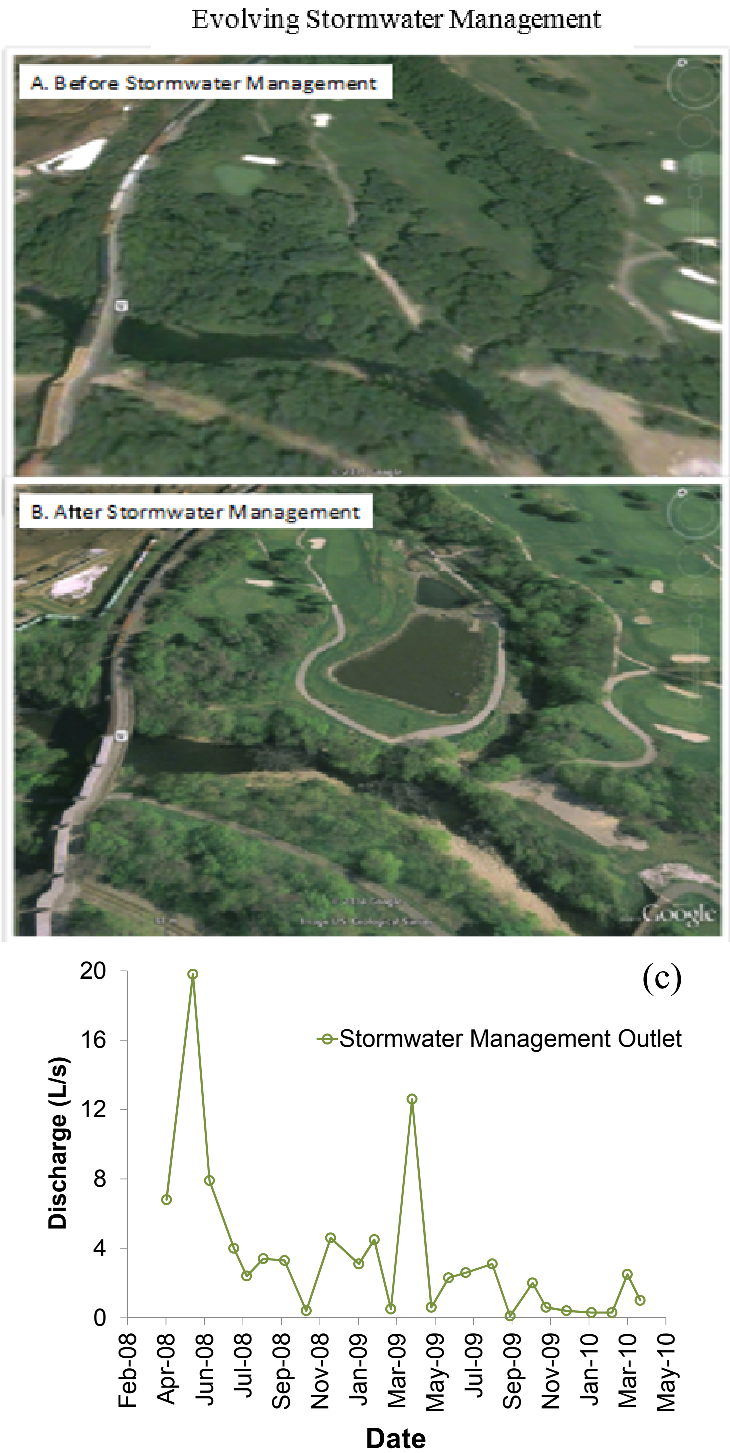


Figure 2. Aerial photography from Google Earth showing (**A**) before and (**B**) after the addition of stormwater management in the Gwynns Run watershed in Baltimore, MD, USA; There has been a decline in discharge from stormwater management over time due to growth of macrophytes, accumulation of trash at the inlet, and sedimentation in the stormwater management controls [10] (**C**).

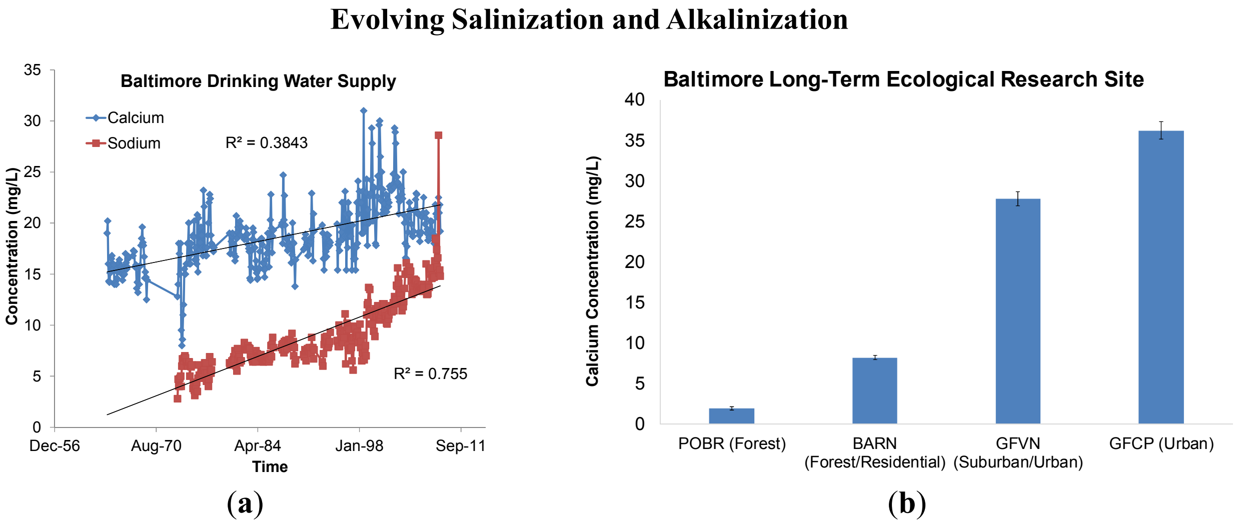


Figure 3. Long-term increasing trends in calcium and sodium concentrations in the drinking water supply of Baltimore, MD, USA (**a**) (data courtesy of Bill Stack, Baltimore City Department of Public Works). Increased seasonal mean calcium concentrations in streams across a gradient of urbanization at the Baltimore Long-Term Ecological Research (LTER) site during 2009 (POBR is a forested stream, BARN is a stream draining forest/residential land use, GFVN is a stream draining suburban/urban land use, and GFCP drains urban land use); error bars denote standard error (**b**).

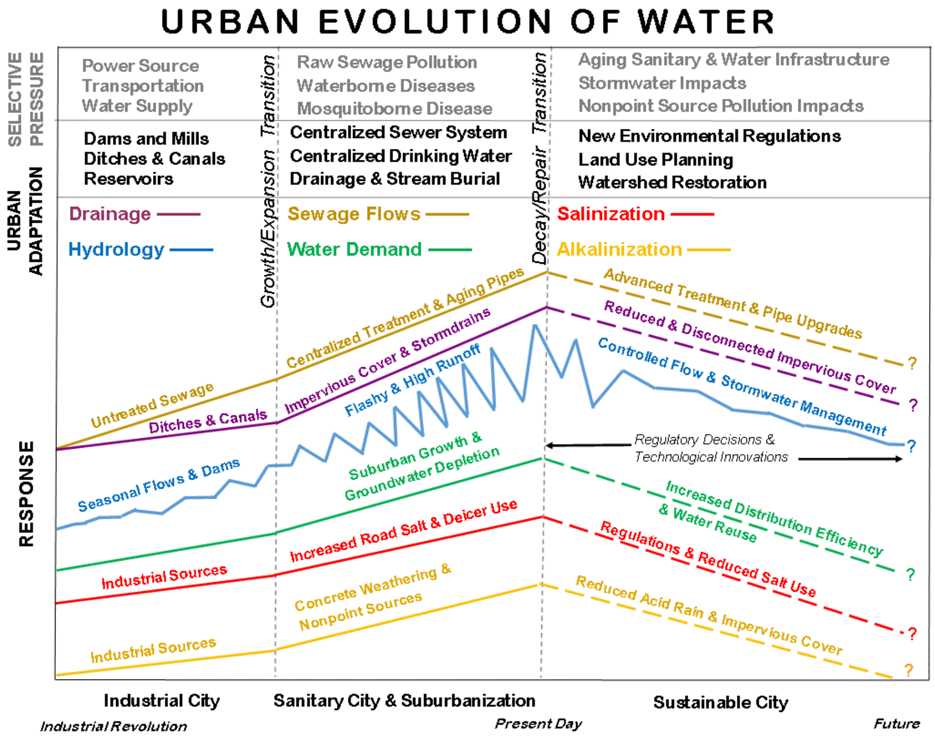


Figure 4. Urban evolution of water from the Industrial Revolution to the present. Hydrologic traits evolve across successive generations of urban ecosystems via shifts in selective pressures and adaptations over time. Urban evolution can occur across distinct stages and transitions where the adaptations of previous generations lead to urban selective pressures forcing the next generation of urban adaptations.

2. Urban Waters: From Syndrome to Continuum

Previous work has documented and reviewed the impacts of urbanization on landscapes and waterways [16,26–28]. A growing body of research has clearly demonstrated that urbanization contributes to a "syndrome" of impacts in streams and rivers including flashy hydrology, channel incision, reduced biodiversity, and increased transport of contaminants [29–32]. The drivers of urban water impairments were recognized decades ago to include increasing coverage by impervious surfaces and enhanced hydrologic connectivity between terrestrial and aquatic environments *via* storm drains and channelization [33,34]. A major contribution of the urban stream syndrome concept was that it directly linked the effects of watershed impervious surface cover to a suite of hydrologic, biological, and chemical impacts in streams [31]. A lesson from the urban stream syndrome concept was that effective restoration of urban streams over longer time scales is not likely without reducing hydrologic connectivity of impervious surfaces within the watershed upstream [35,36].

Although the effects of urbanization on water quantity and quality were comprehensively described as part of the urban stream syndrome, unanswered questions remained regarding the extent to which natural and engineered waterways could both be considered integral components of the urban ecosystem [37–40]. For example, there were questions regarding the biogeochemical impacts of engineered waterways at a watershed scale [41,42]. As urban watershed concepts further developed, it was suggested that engineered waterways should explicitly be considered as integral components of the urban ecosystem due to their immense spatial distribution and importance in watersheds and drainage networks [43–45]. In many cities, engineered waterways have actually surpassed "natural streams" in spatial extent and watershed drainage area [41,44,46]. Thus, there is a need to better detect changes in ecosystem structure, function, and services along both natural and engineered hydrologic flowpaths, from roof tops to ground water, as an entire urban ecosystem evolving across space and time [4,43–45,47].

Consequently, more studies now fully acknowledge engineered waterways as an integral component of the urban ecosystem. For example, research has characterized ecosystem functions such as nitrogen uptake, denitrification, and ecosystem metabolism in buried streams, storm drains, and stormwater management controls [37,42,48–50]. Other work has investigated broader spatial patterns in transport and transformation of materials along natural and engineered hydrologic flowpaths of the urban watershed continuum [45,51,52]. Finally, recent work has also proposed that the urban watershed continuum can be a useful tool for guiding watershed management and ecosystem restoration by recognizing a distinct hydrology and ecology along urban hydrologic flowpaths [50,53]. The growing recognition that water chemistry and ecosystem functions evolve along a space-time continuum underscores the need to use predictive frameworks that include the concept of urban evolution.

3. Defining and Reviewing Core Concepts for Tracking Urban Evolution

The concept of urban evolution was defined to facilitate an understanding of how urban ecosystems change over time and to enable systematic cross-site comparisons across local, regional, and global scales [10]. Although there are important differences and many nuances among urban ecosystems [27,54], urban ecosystems can evolve in surprisingly similar ways regardless of local environmental factors. For example, there can be certain distinct stages of urban evolution including growth/expansion and decay/repair transitions across cities globally (Figure 4). This can present as sequential stages in: development of water drainage structures, stream burial and channelization, streamwater chemistry, stormwater management, and restoration over time. In some cases and regions, these sequential stages include: (1) the Industrial City primarily characterized by the use of water for manufacturing and importance of industrial discharges; (2) the Sanitary City characterized by separate centralized sanitary sewer and drinking water distribution systems; and (3) the Sustainable City characterized by various green infrastructure and watershed restoration strategies. In other cases, urban evolution can follow the trajectory from undeveloped and agricultural lands to low residential or suburban development [4,55,56].

Human population growth, aging infrastructure, natural disasters, and shifting socioeconomic structures and values are universal drivers of how urban ecosystems evolve over time [4,10,27,57]. Associated supply and demand of ecosystem services related to water also evolve with urbanization [4]. Given that urban ecosystems grow and change in both systematic and stochastic ways [58–61], core concepts for studying urban evolution need to be developed and assessed to study urban evolution across local, regional, and global scales.

First, it is important to recognize that the concept of urban evolution crosses interdisciplinary boundaries and integrates core concepts across various disciplines. Specifically, the concept of urban evolution integrates insights from evolutionary biology, earth sciences, engineering, and social sciences to help understand ecosystem processes in urban environments. For example, evolutionary biology contributes to concepts related to selective pressures and adaptations of cities within their environmental setting [62]. Earth sciences contribute to concepts describing how cities create their own distinct geology and hydrology over time [33,63]. Urban evolution was initially controlled by underlying geologic and overlying geomorphic frameworks, in addition to climate [64]. In most cities, some combination of the geology and geomorphology, hydrology, and soils influenced where people settled, built homes and roadways, farmed, and eventually built water supply and wastewater conveyance systems [7,65,66]. As engineering and construction advanced, these geologic and geomorphic frameworks became significantly altered or less constraining over time [7,65,66]. In addition to earth sciences, engineering can contribute to urban evolutionary concepts related to technological innovation and how ecosystem services and functions evolve across the life cycle of urban infrastructure [67]. Social sciences can contribute to urban evolutionary concepts regarding the role of human decisions (and lack of decisions) in influencing evolving ecosystem structure, function, and services of human settlements over time [17,27,68].

Because urban evolution crosses interdisciplinary boundaries, it is useful to have common core concepts with clear definitions so that they can be used properly and consistently. These core concepts lay a foundation for studying urban evolution and may change as further knowledge about urban ecosystems is gained. Below, we present a glossary of core concepts, which provides an interdisciplinary framework for studying the patterns and processes of urban evolution.

3.1. Ecology and Evolutionary Biology Related Concepts

Urban Evolution: The built environment often changes quickly in response to human activities, thus contributing to an urban evolution that affects structure, function, and ecosystem services of human settlements over time (e.g., Figures 1–4). It may be useful to acknowledge that urban evolution can lead to both ecosystem services and disservices in the built environment. Depending upon city growth, design, and management, these changes can be associated with either rapid losses of ecosystem functions/services or progress towards restoration [10]. For example, urban evolution can track stages and transitions from: (1) a previously undeveloped land, agricultural land, or Industrial City; (2) a Sanitary City with buried/channelized streams; and (3) a Sustainable city with innovative stormwater infrastructure and stream restoration (Figure 4).

Urban Adaptation: Urban adaptation is the sequential process by which an urban ecosystem and its structure, function, or ecosystem services becomes more fitted to its changing environment or human choices over time (e.g., increased water demand, flooding, droughts, higher nutrient loads, environmental stressors) (please also see definition for urban selective pressure below). However, unintended consequences often accompany many urban adaptations. For example, storm drains were an early urban adaptation to quickly drain urban landscapes, but then created a myriad of other water related problems such as erosion, channel incision, and reduced nutrient uptake. These unintended consequences led to subsequent generations of urban adaptations more fitted to the changing environment and human choices (e.g., stormwater management and stream restoration). Urban adaptation occurs constantly because it is difficult to develop effective plans during the origin of cities and even more difficult to envision the future needs. During urban evolution, there are foundational imperfections in urban development and management as it is constrained by what is possible at a particular time (politically, financially, *etc.*) rather than what is actually necessary. As knowledge regarding urban watershed management grows, management plans developed in the past under different conditions may no longer be desirable or adaptive for current and future conditions [17,69]. Thus, humans can choose to improve upon past urban designs and purposely modify their environments to be more efficient, accommodate changes in runoff regimes, and/or manage environmental impacts [22,70]. For example, culverts sized for lower precipitation/flood events are no longer adequate and will either be destroyed during storms and/or need to be redesigned/replaced to accommodate increasing impervious surface runoff, climate variability, and flooding.

Urban Selective Pressure: Urban selective pressure is an environmental or societal driver contributing to urban adaptation. An example of environmental urban selective pressure is an increase in flooding leading to the urban adaptations of levees, stormwater management, and improved land use planning. Examples of societal urban selective pressures are human choices for convenient water supply and improved sanitation leading to the urban adaptations of centralized potable water and sewer systems [11]. In some cases, urban selective pressures can optimize urban adaptations where "the best infrastructure and management survive the longest." In other cases, urban selective pressures don't contribute to optimized adaptations to their environment; they can lead to neutral changes or even maladaptations (e.g., humans choosing managed lawns instead of natural vegetative cover based on urban selective pressures including socioeconomic status) [71–73].

Convergent Urban Evolution: A process where cities in different geographic regions and/or experiencing different sociopolitical structures evolve similar traits in structure, function, and ecosystem services in response to environmental conditions and/or socioecological decisions. The "urban convergence hypothesis" originally proposed that ecosystem responses to urbanization should converge relative to native ecosystems being replaced leading to similarity in physical, chemical and biological characteristics in urban ecosystems [74]. Urban convergence can contribute to ecological homogenization of urban ecosystems across lawns, neighborhoods, cities, and at continental scales [59,61]. More work is necessary to compare and predict historical trajectories of convergent urban evolution across cities over time within the context of environmental and socioecological drivers such as urban adaptation and urban selective pressure.

Urban Biotic Succession: Urban biotic succession can be defined as sequential patterns in changes of biological species and community composition over time in the built environment [10]. Urban biotic succession can also represent a dynamic equilibrium based on changes (e.g., disturbances) in the environment as opposed to a definite trajectory [70]. For example, natural variance and stochastic disturbances can drive change over time. Disturbances can be urban land development or ecosystem restoration activities. Dynamic equilibrium and state changes are important to consider when describing and designing urban ecosystems (particularly given the role of unintended consequences in urban ecosystem development over time). Humans can introduce pioneering species based on the aims of the project, costs, *etc.*, or urban biotic succession can be influenced by other environmental vectors like downstream transport of propagules, birds, animals, *etc*. One example of urban biotic succession is the development of "climax" communities of macrophytes in stormwater management ponds, which often develop into wetlands over time. Another example of urban biotic succession is the change in microbial community composition that occurs over time in response to biological adaptation to nutrient inputs and contaminants in urban streams [75,76]. For example, microbial communities in urban streams can become better fitted to survival in their environment by developing resistance to antimicrobial compounds and contaminants through both urban adaptation and urban biotic succession [76,77].

Transitional Urban Ecosystems: Transitional urban ecosystems are unstable stages of urbanizing ecosystems that are in between distinct stages of urban evolution characterized by dominant land uses, watershed management, or infrastructure practices (e.g., undeveloped lands, residential/suburban development, Industrial City, Sanitary City, Sustainable City). Transitions can be triggered by growth, decay, repair, and crises in urban environments (crises can be economic collapse or natural disasters) (please see Figure 4) [17]. Transitional urban ecosystems can exhibit characteristics of different stages of urban evolution or they can show increased variability in ecosystem structure, functions, and services before shifting to a more stable urban regime. For example, there can be transitions from Industrial Cities to Sanitary Cities to Sustainable Cities or other permutations [17] (Figure 4). As an alternative example, a transitional urban ecosystem (formerly forest land use, which is becoming residential/suburban) can begin to exhibit some key characteristics of urban watersheds at key times (e.g., storm nutrient pulses) but retain natural characteristics at others (e.g., during baseflow) [78].

Novel Urban Ecosystems: Here, we quote the definition from Morse *et al.* [79]: "A novel ecosystem is a unique assemblage of biota and environmental conditions that is the direct result of intentional or unintentional alteration by humans, *i.e.*, human agency, sufficient to cross an ecological threshold that facilitates a new ecosystem trajectory and inhibits its return to a previous trajectory regardless of additional human intervention. The resulting ecosystem must also be self-sustaining in terms of species composition, structure, biogeochemistry, and ecosystem services. A defining characteristic of a novel ecosystem is a change in species composition relative to ecosystems present in the same biome prior to crossing a threshold."

3.2. Earth Sciences and Engineering Related Concepts

Urban Watershed Continuum: The urban watershed continuum (UWC) is a conceptual framework recognizing a continuum of engineered and natural hydrologic flow paths, which expands urban drainage networks by increasing hydrologic connectivity. Subsequently, transport and transformation of matter and energy increases across spatial (*i.e.*, longitudinal, lateral, and vertical connectivity with ground water) and temporal dimensions [43].

Urban Karst: The underground infrastructure of a city creates its own distinct hydrology and geology [43,80]. Urban karst is defined as the three dimensional, largely hidden, and dense system of urban water networks that includes buried headwater streams. Urban karst gives rise to a highly connected network in which groundwater flows are interspersed with surface water flows, resembling a natural karst hydrologic system [43,80]. The definition of urban karst was later expanded to also encompass chemical weathering and dissolution of construction materials and urban lithology in the built environment, which also resembles natural karst lithology [10].

3.3. Socioecological Related Concepts

Industrial City: The Industrial City was characterized by expanding commerce and built infrastructure, where production of commodities took place primarily in factories, and point and nonpoint source pollution to urban waters was dominated by manufacturing and industrial processes [11–13].

Sanitary City: Sanitary cities attempt to segregate wastes and other hazards from human populations by using zoning and highly engineered systems that can be energy intensive. Management is organized into separate sectors related to water, transportation, and public health. Local governments are the active decision making and funding entity [14,81]. An example of how cities went through this transition in earlier times can also be found in Tarr *et al.* [82].

Sustainable City: The Sustainable City is characterized by consumption of fewer natural, economic, and human resources from outside its boundaries and more efficient use of resources and people existing within its boundaries. Therefore, the Sustainable City also represents a directional goal for minimizing inflow of energy, water, and any form of resources from outside but maximizing self-sufficiency inside the city and cities globally. Water, materials, energy, and people (residents) are cycled back into the city; this is in contrast to simply being either consumed (*i.e.*, water, materials, energy) or "lost" (*i.e.*, people moving away) from urban ecosystems over time. When local capacity cannot meet demand for ecosystem services related to water, food, and building materials (sand, gravel, lumber), cities must expand their urban "footprint" and look further from their boundaries for necessary resources [4,83]. Over time, even if resources are used efficiently, there will likely need to be increasing connection to surrounding, less impacted areas.

Urban Metabolism: Here, we quote the definition from Kennedy *et al.* [84]: "The sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste".

A glossary of core concepts allows us to better study urban evolution, particularly tracking distinct stages, transitions, and patterns across cities. Some discussion and examples of tracking urban evolution with a focus on water is below. Although we focus on the evolution of urban waters, urban evolutionary concepts can be applied to studying any aspect of the structure, ecosystem function, and services of cities over time.

4. Tracking Stages of Urban Evolution: Hydrological and Water Quality Drivers

It is critical to understand stages and transitions of urban evolution and hydrologic drivers to move from reactive management to predictive management (Figure 4). By tracking the evolution of urban waters, we can anticipate the future based on understanding changes in urban adaptations and selective pressures. Tracking urban evolution allows us to avoid unintended consequences of urbanization over time, particularly in areas undergoing new urban development and redevelopment phases [10].

Collectively, an urban ecosystem can be viewed holistically as a dynamic system that grows, ages, and changes its metabolism over time. Urban ecosystems respond to changes in water movement and chemistry in ways that are somewhat analogous to living systems in organisms [85]. The concept of urban metabolism, in which the inputs and outputs of materials and energy are quantified at the scale of a city, was proposed decades ago by Wolman [85]. In the present paper, we suggest that the metabolism of urban systems evolves over time in response to urban selective pressures through the process of urban adaptation (Figure 4). It is important to emphasize that urban metabolism is just one component that can be considered within the broader concept of urban evolution related to ecosystem structure, function, and services. For example, previous work found that many other properties of cities related to infrastructure and economy scale predictably with population size [58]. Other work has identified convergent urban evolution in the size, shape, and connectivity of urban water bodies with urban development [61], which may be related to urban selective pressure and urban adaptation over time. Thus, a city may evolve over time [34], and water plays an explicit role in the evolution of urban ecosystem structure, function, and services. Below, we discuss evidence illustrating sequential changes in urban ecosystems over time, with an emphasis on water as a driver.

4.1. Sewage Flows: An Evolving Urban Excretory System

Wastewater treatment has undergone significant technological advancements [82]. A dominant form of pollution to urban waterways in industrial cities was from industrial discharges [12]. In the Industrial City, there were no centralized sewer systems and human waste was typically either recycled to nearby agricultural fields and/or directly added to cesspools with no treatment [11]. The expansion of centralized sewers and drinking water infrastructure in the Sanitary City followed a growth and expansion transition (Figure 4). For example, there were urban selective pressures for sanitation and convenient household water in London and Paris [11,86]. Furthermore, local production capacity of drinking water exceeded demand by residents and led to expansion of water supplies and piped infrastructure [11]. In the Sanitary City, expansion of sanitary sewer systems happened over relatively short time scales in response to concern over domestic waste disposal and spillage onto streets (e.g., there was an increase of 570 to 1240 km of sewer network in Paris from 1877 to 1914) [11].

In the Sustainable City, both centralized and distributed wastewater treatment have been continually evolving, including advanced septic systems for enhancing denitrification. In addition, wastewater treatment plant upgrades now include nutrient removal technologies [23,42,87] (Figure 1). Much work has focused on primary, secondary, and tertiary wastewater treatment and is discussed extensively elsewhere [82,88]. Currently, there is interest in advanced wastewater treatment for the Sustainable City, particularly when discharging to receiving waters that are sensitive to nitrogen and phosphorus pollution. For example, studies in the Chesapeake Bay watershed on the East Coast of the U.S. have shown that advanced wastewater treatment can reduce point sources of nitrogen and phosphorus to major rivers (Figure 1) [87,89]. These long-term changes in reductions of nutrient pollution have contributed to ecosystem restoration and recovery over time [87,89]. As another example, the Great Bay in New Hampshire also on the East Coast of the U.S. has been classified as nitrogen impaired by the Environmental Protection Agency and, as a result, wastewater treatment plants are being upgraded to more advanced treatment. The high degree of connectivity between wastewater treatment plants and rivers creates "coupled human-natural ecosystems," which adapt and evolve in response to changing policy and management over time (e.g., U.S. Clean Water Act, Total Maximum Daily Loads, *etc.*). Thus, urban evolution can be driven by technological advances in wastewater treatment, which alter the ecosystem restoration and recovery of urban waterways.

4.2. Evolving Drainage: An Expanding Urban Circulatory System

Since the Industrial Revolution, there has been evolution of watershed drainage networks, both for surface and subsurface flows (Figure 4). Drinking water and stormwater networks expanded during urban growth/expansion transitions (transition periods are indicated in Figure 4) and have aged over time following decay/repair transitions [4,44,90]. This expanding vascular infrastructure across all stages of urban evolution includes ditches, storm drains, leaking water and sewer pipes, roofs, and gutters. Collectively, all of these engineered hydrologic flow paths comprise the urban watershed continuum along with "natural" streams and ground water [43]. Circulation (movement) of water into and out of the city is critical for drinking water and wastewater treatment. As a result, conservation, management, and engineering interventions must be made over the course of urban evolution to maintain function and foster ecosystem restoration (Figure 2). For example, leakage into and from ground water from both water supply, wastewater, and stormdrain pipes creates an engineered "urban karst" that needs to be considered in understanding hydrologic drivers of urban evolution [80,91,92].

4.3. Evolving Hydrology: An Amplified Urban Hydrologic Pulse

Since the Industrial Revolution, there has been an evolution of urban hydrology towards more "pulsed" ecosystems over time primarily due to expanding drainage networks. Urban watersheds evolve towards ecosystems that are characterized by the pulsing of streamflow and contaminant fluxes. It is well known that urban hydrologic systems become flashier in response to increasing watershed development [33]. The interaction between climate variability and urbanization can amplify hydrologic pulses and the export of carbon, nutrients, and contaminants in many urban waterways [79,93–96].

Hydrologic pulses rapidly change water chemistry and environmental conditions in ways that alter patterns in adaptation from the scale of individual species to whole ecosystems. In the Sanitary City, the amplified hydrologic pulse of urban watersheds can contribute to heterogeneity in species-specific adaptations across physiographic gradients in streams [97,98]. The amplified hydrologic pulse of urban watersheds can also contribute to decoupling of streams and riparian zones due to channel incision [31]. This decreased hydrologic connectivity due to channel incision contributes to decreased potential for denitrification and N retention in streams at the ecosystem scale [30,50]. From an engineering perspective, an amplified hydrologic pulse can also drive urban evolution of infrastructure and buildings by necessitating altered designs as society adapts to this increasingly pulsed environment (e.g., road culverts that are no longer large enough for high flows). Finally, urban adaptation to increasingly pulsed water quantity and quality is an ongoing engineering challenge for transitioning to the Sustainable City. For example, the urban adaptation of green infrastructure to enhance infiltration (e.g., bioswales, rain gardens) may control pulses more effectively than traditional gray infrastructure [19,22,23]. However, it may also create unintended consequences due to greater fluxes of water and contaminants to ground water.

4.4. Evolving Stream Restoration: From Syndrome to Urban Adaptation

Although streams are typically not thought of as infrastructure, urban evolution of their basic physical and organizational (*i.e.*, stream and river network) structure is vital to the function of cities. We have previously argued that infrastructure should be considered as an integral part of the urban ecosystem itself [43], and also suggest here that even highly degraded and engineered urban streams may need to be protected, restored, and valued as urban infrastructure. Use of various stream restoration strategies can be considered urban adaptations to increased watershed impairments. Attempts range from extensive channel manipulation (e.g., daylighting of buried streams and removal of concrete lined channels) to floodplain reconnection, innovative stormwater management, and riparian vegetation strategies [20,21,99] (Figure 2) (discussed further below).

From the perspective of urban selective pressure, environmental and societal drivers related to structure, function and services of streams is driving a billion-dollar stream restoration industry [100]. Urban stream restoration is still a relatively young discipline, and there is much knowledge that remains to be learned regarding successes and failures of different adaptive practices for transitioning to the Sustainable City [101,102]. Initially, urban stream restoration projects were a form of urban adaptation attempting to remedy specific problems including species restoration, bank protection/stabilization, grade control, infrastructure protection, and streamflow deflection [99]. Urban stream restoration techniques started with many "hard" structural approaches and techniques have evolved to include "softer" approaches including hydrologic reconnection of streams and floodplains [20,50]. Likewise, there has been a shift in many areas to consider stream restoration in a watershed context and to develop integrated watershed management plans.

More recently, stream restoration has been considered as an urban adaptation to influence ecosystem functions like the cycling of nutrients and organic matter instead of only focusing on structural attributes like habitat and biotic species composition [103,104]. There has been an increase in the number of studies that monitor restoration projects [20,50,105–108]. However, there is still a need for more research to identify patterns and trajectories of stream restoration as an urban adaptation in response to watershed impairments and characterize its role in the transition from the Sanitary City to the Sustainable City.

4.5. Evolving Salinization of Water: Impervious Surfaces and Salt Diets

There has been urban evolution of salinization of water due to land development and this likely started to increase significantly following the Industrial Revolution (Figure 4). Some of the longest records of increased salinization of urban waters span over a century in Europe [109], and there are similar patterns globally [10]. Urbanization has increased salinization of fresh water via inputs of road salt, wastewater inputs, and industrial discharges (Figure 3). Road salt has been recognized as an important agent of salinization of fresh water in colder regions [110–113]. Dietary salt may also be an important salt input for some watersheds in warmer climates [45]. Although food has been recognized as a major watershed nitrogen input [32,114], food can also be a major input of sodium and chloride, which enters urban water from sewage leaks, septic systems, and municipal wastewater [51]. More work needs to be done to unravel urban salt budgets in cities that span gradients of climate and topography [10]. Urban water across many regions will experience increased salinization over time [45,110,111,113]. The long-term effects of salinization of fresh water on ecological communities, infrastructure/property degradation and costs, and drinking water represents a research frontier and looming economic concern for transitioning to the Sustainable City (Figure 3).

4.6. Evolving Alkalinization of Water: Watershed Antacids and Calcium Cycle

There has also been an urban evolution of watershed alkalinization due to acid rain, sewage, and accelerated weathering of building materials in urban areas (Figure 4). Increased alkalinization of urban water (in addition to other dominant land uses) has been documented at numerous sites over decades in the U.S. [115–117]. The chemistry of streams and rivers draining urban areas can be influenced by the dissolution of concrete and other building materials [116,118,119] (Figure 3). For example, cement can contain limestone, gypsum, and other constituents that weather quickly when exposed to acidic water [120]. Rain water is naturally slightly acidic due to the formation of carbonic acid from atmospheric CO_2. The acidity of rain may be increased significantly when fossil fuel combustion releases sulphur and nitrogen to the atmosphere, which combines with water to make sulphuric and nitric acids [121]. Dissolution and degradation of concrete also increases when it is subjected to frequent exposure to road salt [122]. As urban karst weathers and dissolves [10,43], calcium and carbonate are released into urban waters influencing alkalinity, water hardness, and pH [118–120,123] (Figure 3). Additionally, decomposition of labile organic matter (e.g., sewage) in urban watersheds can also increase inorganic carbon concentrations and bicarbonate alkalinity in urban watersheds [124]. Thus, synergistic interactions between geochemical and biological processes and human inputs can contribute to increased alkalinization of urban waters [116]. More work is needed to evaluate the relative importance of geochemical *vs.* biological controls on alkalinization of urban watersheds across gradients of land use, precipitation, and lithology [116,117,125]. The effects of stream and river alkalinization on urban water quality, coastal acidification, and biota is a research frontier for transitioning from the Sanitary to Sustainable City.

5. The Future of Urban Evolution

The concept of urban evolution allows us to move beyond a focus on managing current problems towards systematically tracking trajectories and anticipating future water problems during the Anthropocene [24,25]. Scientists and watershed managers can work together to learn from the past and predict and prepare for the changing future of water using the concept of urban evolution. Given a predictable coherence in the patterns of urban evolution across a range of sites [10], we have defined and reviewed several core concepts for studying urban evolution. These core concepts can be applied across human settlements varying in age, population density, size, and infrastructure. Urban selective pressures and adaptations are universal drivers of urban evolution. From suburban areas to densely populated cities, it is critical to study human settlements as holistic biotic and abiotic systems that evolve over time. Urban ecosystems evolve in response to water issues that include their drainage, sewage flows, hydrology, and long-term chemistry. Urban evolution is occurring globally, and tracking the trajectory of water and biogeochemical cycles in rapidly developing countries *vs.* other developed countries offers a major research opportunity [126,127].

The core concepts, transitions, traits, and stages of urban evolution can be applied across cities, regions, and at a global scale. For example, the amplified hydrologic pulse of urban ecosystems is expected to change due to the interactive effects of land use and climate change across different areas of the U.S. and elsewhere [79,93–96], and this may trigger urban adaptation and evolution of ecosystem structure and function of urban drainage [44,90]. As another example, the number and concentrations of pharmaceutical and personal care products (PPCPs) in the chemical diet of urban watersheds can be expected to increase in the future, and there are questions regarding urban adaptation from individual organisms and ecosystem responses to environmental regulations globally [128–131]. Additionally, there has been a rise in novel urban hydrologic systems during the Anthropocene era in response to urban adaptations of green roofs, rain gardens, and artificial lakes in cities from humid to arid regions [19,61,132,133].

There are evolving socioecological feedbacks across cities, which drive urban evolution including urban adaptations to changes in water supply and quality [4,27,90,134]. The study of urban socioecological systems has been recognized to be important [16,135], and the shifting history of human interactions with water in cities can offer further insight into urban evolution [7,134,136]. During the Anthropocene, humans are increasingly becoming ecological engineers making choices regarding the structure of urban waters (e.g., green infrastructure and stormwater management) [79], which influence ecosystem functions and evolving hydrologic pathways for water and contaminants [22,23]. Furthermore, there can be socioecological shifts from bottom up to top down controls on urban evolution of water due to new regulatory structures implemented in the U.S. and elsewhere. For example, urban evolution is now being driven in response to direct regulations and performance targets such as: (1) the U.S. Total Maximum Daily Loads (TMDL) requirements in the U.S. for reducing mass transport of targeted pollutants from watersheds to receiving waters); (2) the European Directive for Energy Related Products, which requires reducing energy and water consumption; (3) the Horizon 2020 European Union Research and Innovation Program, which fosters industrial research for tackling societal problems related to water and the urban environment (e.g., [137–139]).

Urban evolution may also be driven by technological advancements in the future. Water scarcity in the past was an obstacle to urban development, particularly in arid and semi-arid regions. New technologies, like desalinization, irrigation by deep underground water pumping *via* photovoltaic energy, and strategies for capturing drinking water from air humidity can drive urban evolution of structure, function, and ecosystem services. New technological advancements enhancing urban sustainability may include: leakage control in pipes and energy dissipation *via* micro-hydro power [140–143]. The water, energy, and food nexus is now a primary factor for ensuring urban sustainability. Similarly, adequate water supply with a low energy cost will be a major factor influencing urban evolution in the future.

6. Conclusions

The concept of urban evolution is intended to facilitate the development of a theoretical framework for studying and predicting urban adaptation over time. It is a misconception that evolution always implies a process that works towards some goal. Evolution can also be a stochastic process that can be complex. Over history, there have been many unanticipated consequences of urbanization and management related to impervious surfaces, headwater stream burial, and stormwater management. These unintended consequences have driven different generations of urban adaptations in response to changing environmental conditions and human choices. The study of urban evolution requires thoughtful, long-term research underpinned by experimental approaches to harness it, particularly if we want to try to manage it and avoid unintended consequences. Management and policy changes to protect water quantity and quality will be more effective if considered in the context of urban evolution. It is increasingly important to recognize that cities change and adapt in sequential patterns based on urban selective pressures. Overall, urban evolution allows urban planning, management, and restoration to move beyond reactive management to predict changes based on past observations of sequential patterns over time.

In conclusion, the role of water is vital to driving urban evolution as demonstrated by historical changes in drainage, sewage flows, hydrologic pulses, and long-term chemistry. In the current paper, we illustrated how hydrologic traits evolve across successive generations of urban ecosystems via shifts in selective pressures and adaptations over time. Water is critical for sustaining life in urban areas, and the importance of urban water issues will likely increase into the future. Furthermore, urban evolution towards the Sustainable City will involve increasing interactions and connectivity of components both within cities and interactions between cities at a larger scale. Ultimately, water itself is an important driver of urban evolution that alters biological, and geophysical systems and transforms ecosystem structure, function, and services over time.

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

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