"Accidental" urban wetlands: ecosystem functions in unexpected places

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"Accidental" urban wetlands are formed not through deliberate restoration or management activity, but as a product of land use and water infrastructure decisions by municipalities. Often formed in abandoned industrial, residential, or low-lying commercial areas, where overland flows from storms and municipal water use accumulate, these ecosystems support wetland soils and plant communities. Research that we have conducted in the northeastern and southwestern US suggests that accidental wetlands are capable of counteracting anthropogenic eutrophication, providing habitats for important ecological communities, fostering biodiversity, and mitigating heat. Because the factors contributing to their formation are ubiquitous, accidental wetland systems are likely pervasive in urban landscapes, accounting for a substantial portion of aquatic habitat extent and influencing nutrient and water cycles within cities. They also provide ecosystem services at a fraction of the cost associated with more traditional environmental management efforts.

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Urban areas support many aquatic environments, including remnant or modified versions of aquatic systems that existed prior to human settlement, and systems deliberately created or designed to serve a specific purpose (Steele *et al.* 2014). In contrast, "accidental" urban wetlands are not the result of deliberate construction, nor are they remnant and/or modified environments that existed before human development. Instead, they form as the unplanned result of human activity in the landscape. As with created or remnant systems, accidental ecosystems have many structural elements (organismal, hydrological, soil-related) that mimic natural, unaltered aquatic ecosystems. They may therefore be capable of providing functions (and associated services) similar to natural environments. Here we argue that accidental wetlands, although highly understudied, are likely widespread and important habitats in urban landscapes. Furthermore, because they are not designed and are largely unmanaged, accidental wetlands represent a potential low-cost means of mitigating urban pollution and providing habitat for ecological communities and desirable species. This paper explores the current knowledge of the extent, characteristics, and functions of accidental urban wetlands, based primarily on work in the southwestern and northeastern US, and outlines important research needs associated with these ecosystems.

In a nutshell:

- Accidental urban wetlands are ecosystems that have formed unintentionally, as a result of human activity in the landscape
- They are widespread in urban landscapes, contributing to the extent of aquatic habitat and influencing nutrient and water cycles within cities
- Estimating their extent and function is a challenge because their existence goes largely unnoticed or undocumented, and is sometimes unwanted due to the disadvantages associated with wetlands, including standing water, nuisance species, and regulatory issues
- Accidental wetlands provide ecosystem services such as habitat for wildlife, nutrient removal, carbon sequestration, water storage, and social benefits for people while requiring less monetary input or regulatory effort than traditional wetland creation and restoration activities

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The concept of ecosystem services has emerged as a means of assessing, managing, or designing environments to maximize ecosystem processes that support human well-being. Despite extensive documentation of urbanization impacts on wetlands (Paul and Meyer 2001; Walsh *et al.* 2005; Wenger *et al.* 2009), many studies indicate that remnant and/or modified urban aquatic systems are still capable of performing useful functions (ie those serving key ecosystem services) at relatively high rates or capacities (Ehrenfeld 2004). These functions include nutrient processing and removal (Grimm *et al.* 2005; Ehrenfeld *et al.* 2011; Roach and Grimm 2011), provision of habitat for key organisms (Arena *et al.* 2011; Holzer 2014), carbon sequestration (Lawrence and Zedler 2013), and hydrologic functions such as cooling and groundwater recharge (McLaughlin and Cohen 2013).

Ecosystems such as created wetlands, canals, and artificial lakes, which are deliberately constructed to provide specific services, typically include structural characteristics that mimic those of natural systems. These characteristics facilitate the services that these environments were designed to provide (eg flood control, water storage, and water delivery). Structural components of constructed systems are often highly managed to maintain

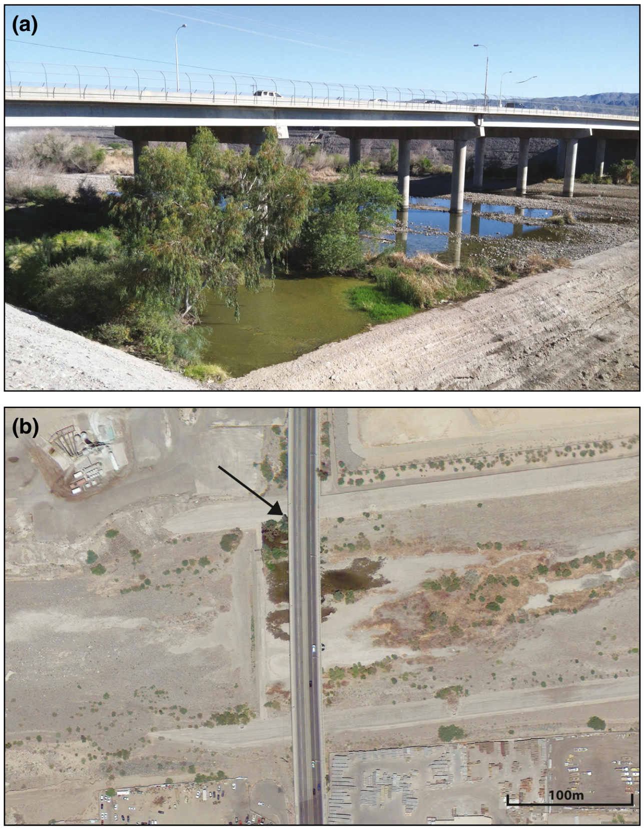

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Figure 1. *One of many fluvial freshwater wetlands formed unintentionally on the formerly dry bed of the Salt River, in Phoenix, AZ. The river has been impounded upstream of the city for over 100 years. Wetlands have formed on the riverbed from water exiting a stormwater outfall. One such outfall (hidden from view) is near the foreground of the photo in (a), and its position is indicated with an arrow in the aerial photo in (b).*

desired services. Interestingly, recent work has also identified inadvertent or unanticipated services and disservices in these systems. We argue, however, that accidental wetlands may provide more services than designed environments because the latter are commonly overdesigned for a limited set of specific functions. For example, the Los Angeles River (California) was straightened, deepened, armored, and reinforced with concrete to prevent property damage and reduce risk to human populations by conveying stormwater to the ocean. This narrowly purposed infrastructure has prevented groundwater recharge, wetland development, and colonization/use by most wildlife in the concretized sections of the channel (Gumprecht 2001). Designed systems with "green" elements may hold the most potential for accidental services. Urban green spaces (including reservoirs, parks, and gardens) provide multiple ecosystem services, whereas built structures and impervious surfaces provide few or no services (Holt *et al.* 2015). In the sections below, we compare accidental wetlands to those with higher levels of intervention (ie restoration or construction) in terms of their potential to provide ecosystem services.

Formation and extent

Wetland boundaries are defined jurisdictionally by management agencies using the presence of hydric soils, hydrophytic vegetation, and water (Mitsch and Gosselink 2007). Accidental wetlands can form on abandoned or underutilized land at low-lying landscape positions. Often, stormwater or wastewater is intentionally routed to these areas to prevent flooding in developed upland areas. In inland cities, low-lying parts of the landscape persist because streams, rivers, and wetlands that formerly existed in these areas were drained, filled, developed, and then abandoned (Figure 1). A lack of stormwater management in these areas following abandonment results in a renewal of flooding. Fill soils are often used to elevate development above flood levels in lowland areas. In coastal cities, many accidental wetlands develop adjacent to these artificially elevated areas. For example, Liberty State Park (Jersey City, NJ) was originally an intertidal mud flat/salt marsh connected with Upper New York Bay, in the lower Hudson River watershed. The site was filled to build a train yard (Figure 2a) and was then abandoned over 50 years later. At this time, large portions of the site were fenced off and left relatively undisturbed for over 40 years (Figure 2b). Flooding persisted in depressional areas left after site abandonment, due to their relatively low-lying position in the urbanized landscape (Figure 3).

Once stormwater, wastewater, and/or precipitation enter these sites, persistent flooded conditions are often promoted because soil profiles contain compacted or impervious layers from previous development (see Figure 4). Under continued neglect or abandonment, these sites will experience ongoing flooding, which facilitates colonization by wetland plant and animal communities (Gallagher *et al.* 2008; Bateman *et al.* 2015), and creates reduced (low oxygen) conditions in soils, favoring anaerobic microbial processes (Palta *et al.* 2013, 2014). The resulting system may resemble a wide range of wetlands, including but not limited to freshwater and salt marshes and swamps, oxbows, and sloughs.

Accidental wetlands are fed by different water sources. Precipitation, runoff from upland areas, and discharge of treated wastewater are water sources for accidental wetlands in New Jersey and Arizona (Palta *et al.* 2014; Bateman *et al.* 2015). A news publication in Tampa, FL, documented what appear to be accidental wetlands (dense wetland vegetation in standing water) at street corners and next to driveways in low-lying neighborhoods with poor drainage infrastructure; the article noted that stormwater feeds these wetland patches with "water flow that's nearly constant" (Bradshaw 2015). In Bucharest, Romania, an accidental wetland system (Lake Văcăreşti) developed after a large hole was dug for a reservoir and then abandoned in the 1970s. According to news reports, groundwater sources not envisaged by designers of the reservoir began to emerge soon after con-

Figure 2. *Liberty State Park in (a) the early 1930s and (b) 2007. Map imagery obtained from NJOIT, Office of Geographic Information Systems. The white box in (b) highlights where one of the many accidental wetlands on this site formed, shown enlarged in Figure 3.*

struction, causing the development of shallow wetlands (Vino 2013). Floodwaters from rivers and sea-level rise and/or subsidence in urban areas can also potentially create accidental wetlands. News stories from New York City, NY, and New Orleans, LA, and blogs in Dallas, TX, and Milwaukee, WI, report on what appear to be accidental wetlands in developed or abandoned urban residential or industrial areas. These areas became reconnected with nearby estuaries or rivers after abandonment owing to their low-lying position in the landscape (Sandifer 2012; Daniel 2013; Kensinger 2014; Campanella 2015).

Estimating the extent and total area of accidental urban wetlands is a challenge. Because they form unintentionally, their existence goes largely unnoticed or undocumented. Further, because wetlands and streams are protected from development and managed under separate guidelines in many regions, delineation of an area as a wetland or stream can incur legal obligations for homeowners, developers, and local officials. Finally, wetland delineation often excludes information on intention or design, and the history behind wetland development may not be known. Despite these challenges, we hypothesize that accidental wetlands exist in urbanized regions worldwide. This hypothesis is based on several lines of evidence: because urban development is fundamentally contingent on water availability and use, (1) most major cities develop near or on aquatic systems (Mitsch and Gosselink 2007; Grimm *et al.* 2008), (2) the development of most large cities involved draining and/or filling of wetlands (Kentula *et al.* 2004; Steele and Heffernan 2014), and (3) all major cities have some form of wastewater. This means that most cities will have low-lying sections of landscape that could host wetlands, and that all cities need a way to rid developed land of excess water. The latter usually involves allowing water to travel to areas that are not inhabited or actively maintained.

We argue that in most cities, some portion of urban land has the potential to support the formation of accidental wetlands. In 2000, a survey of 70 cities in the US found that, on average, 15% of urban land was deemed vacant, with land use ranging from undisturbed open space to abandoned, contaminated brownfields (Pagano and Bowman 2000). This percentage has likely increased subsequently due to the Great Recession of 2008–2009. Although urbanization and urban populations have increased worldwide over the past century, vacant land has increased substantially in many US, European, and Asian cities because economic downturns, failing industry (and resulting unemployment), and shifting demographics within certain regions have caused "urban shrinkage" (Haase *et al.* 2014). Increases in urban vacant land create opportunities for unanticipated "natural" environments with associated services (Haase *et al.* 2014; Shuster *et al.* 2014; Ager 2015). Since accidental wetland development requires a water source and poor drainage, not all urban vacant land has the capacity to support accidental wetlands. However, even if total accidental wetland area is small in any given city, its contribution to ecosystem services may be disproportionately large relative to its extent. Recent literature suggests that small lakes, ponds, and wetlands tend to provide higher rates or levels of ecosystem services per unit area than larger aquatic and wetland ecosystems, and serve as hotspots of biodiversity, nutrient processing, and carbon sequestration in many types of landscapes (Downing 2010; Ghermandi *et al.* 2010; Capps *et al.* 2014; Van Meter and Basu 2015).

■ Unique characteristics

Accidental wetlands exhibit characteristics of novel ecosystems (WebPanel 1). Given that these systems form in areas previously or currently under urban development, their soils and hydrology often differ greatly from native

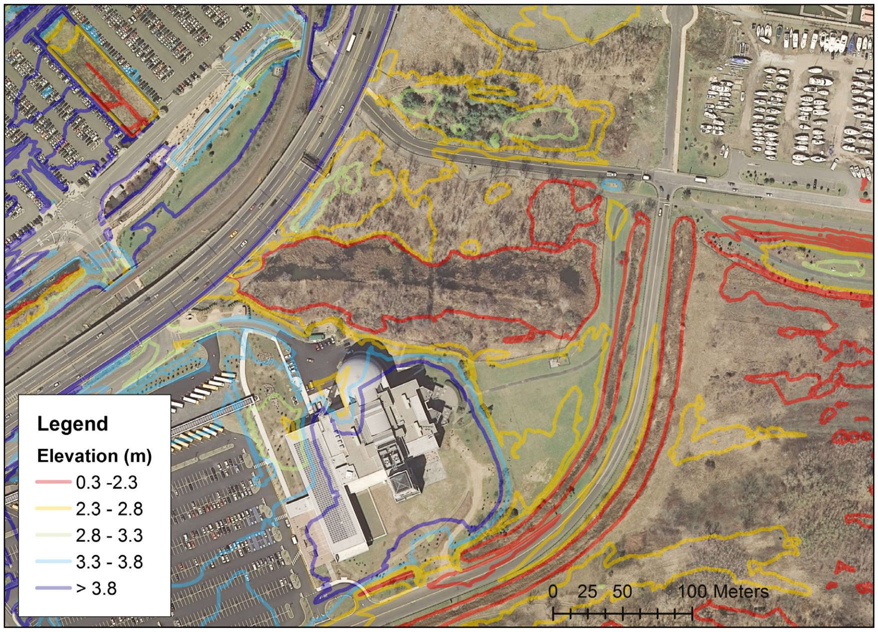

Figure 3. *Contour map of the area surrounding an accidental wetland at Liberty State Park. Areas outlined in red tend to support standing water for much of the year.*

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Figure 4. *Soil profile at Liberty State Park. The A horizon is composed primarily of coal rock, and the soil horizon below is a compacted, low permeability fill layer.*

wetland systems in the same region. Urban soils are composed of a mixture of materials that differ from adjacent agricultural or forest areas (ie natural soils), and/or are heavily modified by human activity (De Kimpe and Morel 2000). Geomorphic alterations such as ditching, berms, and waste dumps are common in urban landscapes, and contribute to high variability in soil surface elevation and water tables in urban wetlands and watersheds (Ehrenfeld 2004). Depending on site history, soils may contain a number of contaminants such as heavy metals (eg Gallagher *et al.* 2008). Urban soils form from heterogeneous, often non-soil material, and urban landscapes exhibit spatiotemporal variability in disturbance regime (eg earthmoving) based on use. The normal heterogeneity encountered within wetland soils may therefore be greatly magnified in urban wetlands (Ehrenfeld 2004). For example, geomorphic, biologic, and hydrologic alterations on and around the site studied by Palta *et al.* (2014, 2016b) led to considerable variation in soils. Native soils persisted from when the area was a freshwater marsh/stream system, fill soils were added for commercial use of the site in the early–mid 1900s, debris materials were deposited during nearby highway construction in the 1950s, piles of trash were deposited in the 1960s, and organic soils remained in former tidal channels running through the site.

It is not clear how the characteristics and extent of accidental wetlands differ between cities and geographic regions. Percent vacant land varies considerably by city and region (Pagano and Bowman 2000), as does flood and sewage infrastructure (Hopkins *et al.* 2015). Although intentionally created aquatic ecosystems in urban areas may be similar in type and extent regardless of geographic region (Steele *et al.* 2014; Steele and Heffernan 2014), unintentional aquatic systems may be more constrained geographically in how they develop and what they contain. Alternatively, accidental wetlands form within highly designed environments that have similarities in terms of soil types (eg fill), drivers of soil modification (eg compaction), and urban-adapted or human-cultivated species compositions (eg invasive reed grasses, generalist bird species). They may therefore conform to the process of "ecological homogenization" that causes human-dominated systems to be more similar to each other than the native ecosystems they replace at regional and continental scales (Groffman *et al.* 2014).

Accidental functions, services, and disservices

As with constructed or native wetlands, accidental wetlands may provide ecosystem services, including nutrient removal, heat mitigation, recreation and enjoyment, carbon sequestration, water storage, groundwater recharge, and provision of wildlife habitat. Furthermore, such services potentially involve less monetary input or regulatory effort than that for constructed wetlands, because they arise unintentionally from the presence of extant organisms and unwanted water in the urban environment. The presence of trash and contaminants in their soils and water, and exotic and invasive species within their plant and animal communities, may compromise some functions and services (but see Davis *et al.* 2011; Hagmann *et al.* 2015). However, designing or restoring aquatic systems to perform particular functions may actually compromise soil formation or biodiversity by disrupting the ecosystem (eg Bernhardt and Palmer 2007), leading to lower service provision or even the emergence of disservices. It is not known whether accidental wetlands develop structure and functions associated with ecosystem services at a comparable, slower, or faster rate than constructed wetlands. In created wetlands, habitats (for birds, invertebrates, and herpetofauna), plant biomass, and capacity for nutrient and pathogen removal can develop within a few years or decades of construction, although not always at the same magnitude as native reference wetlands (Mander and Jenssen 2003; Snell-Rood and Cristol 2003; Spieles 2005; Soomets *et al.* 2016). Other functions found in native wetlands, such as carbon sequestration, are reliant on soil physical properties that can take hundreds of years to develop (eg low bulk density, high soil aggregation). It is therefore unknown whether constructed wetlands will ever be equivalent to native wetlands in offering these processes (Hossler and Bouchard 2010; but see Mitsch *et al.* 2012).

Habitat for plants and wildlife

Urbanization can substantially diminish habitat for plants and wildlife, particularly for wetland and aquatic communities (Gibbs 2000; Wenger *et al.* 2009). Green spaces (eg golf courses) and infrastructure (eg drainage ditches, canals) in cities can serve as critical habitat for wetland plants and wildlife (Chester and Robson 2013; Winchell and Gibbs 2016), including rare or key species. Accidental urban wetlands in New Jersey (Arnold 2008; Gallagher *et al.* 2008; Ravit *et al.* 2008) and in Arizona (Bateman *et al.* 2015) have developed diverse wetland plant, bird, mammal, and herpetofaunal communities within a few decades following land abandonment. Social media and news stories report observations of facultative or obligate wetland wildlife, including locally protected, native, and endemic species, in wetlands that have appeared on abandoned or developed land after brief or prolonged periods of flooding (WebTable 1). News stories from Albuquerque, NM, and Sacramento, CA, describe how redirection of rivers through vacant urban areas for flood control and sedimentation has unexpectedly attracted large wetland bird populations (Fleck 2012; Austin 2015).

Although restoration can create habitat for urban species, the associated disturbance to soils and vegetation can potentially compromise habitat complexity and community establishment. For example, despite being lower in bird and herpetofaunal richness than actively restored or non-urban reference sites in the same river system, accidental wetlands in Phoenix, AZ, had higher plant community richness and cover than these other site types (Bateman *et al.* 2015). Actively restored reaches had diminished seed banks due to bulldozing and other soil disruptions during the restoration phase (Bateman *et al.* 2015).

Nutrient removal

Accidental wetlands can intercept substantial amounts of urban atmospheric deposition, streamflow, and stormflow, and can be nitrogen (N) and phosphorus (P) sinks in urban watersheds. Some N removal may be due to plant uptake, but accidental wetlands studied in New Jersey, Arizona, and Maryland appear to support redox conditions (ie low oxygen) that facilitate high rates of microbial denitrification within a few decades following formation (Harrison *et al.* 2011; Palta *et al.* 2013, 2016b). Accidental wetlands in New Jersey demonstrated comparable or higher rates of denitrification than remnant wetlands surrounded by urban development or native wetland systems, and these rates often matched or exceeded loading of nitrate (NO_3^-) (WebTable 2). Denitrification rates in these wetlands were mediated by soil pore structure and water dynamics, and limited by NO_3^- availability (Palta *et al.* 2013, 2014, 2016b). Harrison *et al.* (2011, 2012, 2014) studied oxbow wetlands created accidentally during stream restoration in Maryland (Figure 5). These sites supported comparable rates of denitrification relative to native wetlands (WebTable 2) and captured 1–7% of cumulative streamflow during storm events (Harrison *et al.* 2014). The oxbow wetlands were N sinks during storm events but were a net source of dissolved phosphate (PO_4^{3-}) to the adjacent stream. Wetland N and P removal efficiency varied with the nature and extent of connectivity to the stream, loading rate, and retention time.

We examined percent nutrient removal in accidental wetlands in the bed of the Salt River in Phoenix by comparing nutrient concentrations at the farthest point upstream (ie at the stormwater outfall feeding the wetland) and at a point 0.7–1.0 km downstream. Samples were collected 1–2 times per month during baseflow conditions, and immediately following (within 24 hours) rainstorms from May 2012 to September 2013. Percent removal of NO_3^- was generally high, and matched or exceeded removal in native or constructed wetlands in the same region (WebTable 2). The wetlands were often a net source of dissolved PO_4^{3-}, but on average removed 21–28% of P entering the wetlands (M Palta, unpublished data).

Figure 5. *In Minebank Run (an urban watershed in Towson, MD), two oxbow wetlands formed unintentionally as the result of rerouting a stream during restoration to improve geomorphic stability and to reduce channel incision. A closer view of one of these wetlands is shown in (a). Stone boulders were placed along the edges of the stream to increase stability, cutting off existing meander bends in the stream; the meander bend that created the wetland shown in (a) is indicated with an arrow in (b). The wetlands persist because of occasional overflow of stream water from the main channel, groundwater seepage, and return flow from adjacent uplands.*

Social benefits

Urban design elements that are more flexible and less expensive, and that take advantage of ecosystem properties translating to services, are particularly beneficial to people without the financial means to mitigate environmental stressors. Urban dwellers in general, but low-income neighborhoods and people experiencing homelessness in particular, are at risk for higher heat exposure, particularly in southwestern US cities (Jenerette *et al.* 2011). Use of public parks in Phoenix by low-income populations has been anecdotally observed and linked to their potential to provide cool refugia (Jenerette *et al.* 2011). Accidental wetlands in the same city also serve as a refuge from heat exposure, and provide running water, privacy, and enjoyment for homeless individuals (Palta *et al.* 2016a) (Figure 6). Existing institutions (eg shelters) designed to assist the Phoenix homeless community do not always provide these services (Palta *et al.* 2016a). The accidental wetlands of Lake Văcăreşti serve as a permanent residence for some, and are used as a source of wild mint, fish, decorative willow branches, lumber, and firewood, as well as being mined for scrap metal by the city's "massive underclass" (Bird 2014) (Figure 6). Accidental wetlands therefore have the potential to be intrinsically linked to the resilience and sustainability of disadvantaged communities, particularly in terms of risk factors linked to urbanization and climate change.

Disservices

Urban wetlands in general are associated with several disservices, although these harms can sometimes be counteracted by ecosystem services. For example, standing water can provide habitat for disease vectors (eg mosquitoes, waterfowl). Stormwater and wastewater can convey waterborne illnesses or toxicants, compromising the health of those coming into contact with the water. These health concerns have resulted in legislation and infrastructure minimizing standing water and promoting water drainage. However, with the development of wetland structure and functions, accidental wetlands may be able to mitigate some of these health concerns. The high biodiversity of wetlands relative to that of the surrounding urban environment can "dilute" pathogens and limit the spread of disease more than do urban residential or commercial areas (Johnson *et al.* 2012; Civitello *et al.* 2015). Accidental wetlands removed pathogen indicators in water exiting stormwater outfalls in Phoenix (Palta *et al.* 2016a). However, pathogen indicator levels met bathing standards in only a subset of these wetlands, and far exceeded bathing standards in all wetlands during storms (Palta *et al.* 2016a).

Additional disservices identified in accidental wetlands are greenhouse-gas production (Palta *et al.* 2013) and habitat provision for nuisance species (Ravit *et al.* 2008). However, these disservices are often comparable to or lower than those associated with other urban ecosystems. Carbon dioxide (CO_2) and nitrous oxide (N_2O) production in accidental wetlands in New Jersey was far lower than that in urban unrestored upland sites and constructed wetlands receiving wastewater, respectively (Palta *et al.* 2013). In Maryland, Harrison *et al.* (2011) found lower rates of N_2O:N_2 production in accidental wetlands than in forested wetlands, and accidental wetlands were not a major source of N_2O as compared to other wetland systems. Ravit *et al.* (2008) found higher percentages of invasive exotic plant species in accidental wetlands in New Jersey than in forested wetlands in the region, but the percentages were comparable to or lower than those of invasive exotic plants found in urban areas in the northern US.

Figure 6. *Accidental urban wetlands can provide important services for vulnerable people. (a) Accidental urban wetlands in Phoenix, AZ are used by homeless people for shelter, running water, and heat mitigation. (b) The accidental wetlands of Lake Văcăreşti in Bucharest, Romania have been home to many poor families, mainly Roma, and low-income residents of Bucharest, who fish and forage for natural resources (eg firewood) in the wetlands.*

Research needs

Extent

We have argued that accidental wetlands are likely to be widespread in urban areas, contributing to the total extent of aquatic habitat and influencing nutrient and water cycling. Because accidental wetlands are not specifically managed to provide ecosystem services, and because they form via different (low-cost, low-energy) means as compared to other types of human-created aquatic systems, more research is needed to confirm the extent of accidental wetlands within cities, and to differentiate them from other types of urban water bodies.

Other potential services and disservices

Although important services provided by accidental urban water bodies are outlined in this paper, other services (or disservices) typically associated with native or constructed wetlands may be provided by accidental wetlands (eg removal of other nutrients, pathogens, or toxicants; carbon sequestration; flood abatement; water storage and recharge; and urban heat island mitigation). These services, their drivers, and importantly, potential trade-offs between them, merit further investigation to determine how resource managers and urban planners can optimize the benefits of accidental wetlands in cities.

Perceptions and values

Wetlands have long been perceived as undesirable, nuisance systems (Mitsch and Gosselink 2007), and vacant urban lots are not typically considered desirable or aesthetically pleasing. Many cities have ordinances mandating vacant lots be maintained by clipping "weeds" and draining water from the site (to reduce mosquito populations). Many urban dwellers may consider accidental wetlands to be unsightly, disease-breeding, garbage-collecting blights on the landscape, rather than viable ecosystems that provide important ecological and sociological services. However, some see them as areas for recreating, viewing wildlife, and observing local traditions or cultural activities (eg Shih 2007). An important research need is to engage with people to determine their perceptions and values in terms of urban environments and the services they can provide. This may allow urban planners to help people living in cities use accidental wetlands more effectively, and could increase the perceived value of these environments.

Management and policy implications

Given the potential ecological and social services they provide to cities, accidental wetlands should be integrated into urban planning and design. Municipal authorities should carefully consider and evaluate them as they occur. Ideally, city managers would take advantage of services that arise from the lack of management in accidental wetland areas and also use selected management practices to augment desired services and minimize disservices. In most cities, a portion of abandoned land retains standing water. Three approaches – maintaining or conserving some of this vacant land, facilitating the routing of wastewater or stormwater to these areas, and allowing primary or secondary succession to proceed therein (depending on the extent to which the land was developed before abandonment) without extensive human intervention – could offer low-cost means of creating highly functional environments. This may prove challenging, however, in cities where space is limited (eg New York City), water is increasingly scarce (eg Phoenix), or flooding is problematic due to low topographic relief and/or high water tables (eg Tampa). Flooding, in particular, will likely be exacerbated in the near future in urban coastal areas due to a combination of urbanization and sea-level rise (Chaussard *et al.* 2013; Rotzoll and Fletcher 2013; Uddameri *et al.* 2014).

Recognition by municipalities of the benefits of integrating or preserving green space with minimal infrastructure will be critical for sustaining the services that many wetlands provide, including accidental wetlands. More research will be needed, however, to determine what role design, engineering, or management of landscapes should play in facilitating the formation of systems that are both largely self-organizing and provide net benefits. Little is known about how management intention or intervention influences most wetland functions, as compared to no intention or intervention. Additionally, urban wetlands will likely be highly dynamic in their characteristics and performance over time, as urbanization and climate change progress. Increased flooding in coastal cities due to urbanization and sea-level rise could facilitate, for example, the formation of additional accidental wetlands, but could also result in the loss of remnant and constructed wetlands, or changes in wetland function as former freshwater systems become brackish (Rotzoll and Fletcher 2013).

An important consideration in management or policy related to urban accidental wetlands is that trade-offs occur between services, particularly because these trade-offs often involve both vulnerable ecosystems and vulnerable groups of people. Minimizing human disturbance of wetlands is important for maintaining some services, but it is also critical to balance the needs of wetland ecosystems with the needs of urban dwellers, especially those who directly rely on the natural environment for provisioning, regulating, and cultural services (Figure 6). Additional trade-offs between the benefits of wetland use (eg mitigating heat stress by bathing in wetlands) and the harms associated with wetland use (eg exposure to pathogens through bathing) further complicate how to best optimize services and mitigate vulnerability for users (Palta *et al.* 2016a). Policies that do not wholly restrict use, but also promote community knowledge, stewardship, and safe use of urban accidental wetlands (eg posting informational signs), will be needed to address some of these trade-offs.

References

Ager S. 2015. Taking back Detroit. *National Geographic Magazine*. Apr 16: 56–83.

Arena S, Battisti C, and Carpaneto GM. 2011. The ecological importance of wetlands for aerial insectivores (swifts, martins and swallows) along the Tyrrhenian coast. *Rend Lincei-Sci Fis* **22**: 395–402.

Arnold M. 2008. A historical perspective on the urban wetlands of the Teaneck Creek Conservancy. *Urban Ecosyst* **5**: 153–65.

Austin C. 2015. Yolo Bypass Symposium, part 1: a flood of plans and possibilities. http://bit.ly/2o3aTFu. Viewed 9 Aug 2016.

Bateman HL, Stromberg JC, Banville MJ, *et al.* 2015. Novel water sources restore plant and animal communities along an urban river. *Ecohydrology* **8**: 792–811.

Bernhardt ES and Palmer MA. 2007. Restoring streams in an urbanizing world. *Freshw Biol* **52**: 738–51.

Bird M. 2014. The hole in Bucharest that's become a nature reserve. *City Metric*. Oct 17.

Bradshaw K. 2015. Can't stop the rain: so why can't somebody figure out how to keep our roads from flooding? *Creative Loafing Tampa Bay*. Jun 18.

Campanella R. 2015. How Gentilly's wild "Accidental Forest" escaped development for centuries. *The Times-Picayune*: online. Oct 8.

Capps KA, Rancatti R, Tomczyk N, *et al.* 2014. Biogeochemical hotspots in forested landscapes: the role of vernal pools in denitrification and organic matter processing. *Ecosystems* **17**: 1455–68.

Chaussard E, Amelung F, Abidin H, and Hong S-H. 2013. Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. *Remote Sens Environ* **128**: 150–61.

Chester ET and Robson BJ. 2013. Anthropogenic refuges for freshwater biodiversity: their ecological characteristics and management. *Biol Conserv* **166**: 64–75.

Civitello DJ, Cohen J, Fatima H, *et al.* 2015. Biodiversity inhibits parasites: broad evidence for the dilution effect. *P Natl Acad Sci USA* **112**: 8667–71.

Daniel E. 2013. Saving the last wetland in Milwaukee's estuary: the Grand Trunk. http://bit.ly/2o8cXfg. Viewed 10 Apr 2016.

Davis M, Chew MK, Hobbs RJ, *et al.* 2011. Don't judge species on their origins. *Nature* **474**: 153–54.

De Kimpe CR and Morel JL. 2000. Urban soil management: a growing concern. *Soil Sci* **165**: 31–40.

Downing JA. 2010. Emerging global role of small lakes and ponds: little things mean a lot. *Limnetica* **29**: 9–23.

Ehrenfeld JG. 2004. The expression of multiple functions in urban forested wetlands. *Wetlands* **24**: 719–33.

Ehrenfeld JG, Palta M, and Stander E. 2011. Wetlands in urban environments. In: Douglas I, Goode D, Houck MC, and Rusong W (Eds). The Routledge handbook of urban ecology. New York, NY: Routledge.

Fleck J. 2012. More on the definition of "drought": a dry spot. http://bit.ly/2nACZa3. Viewed 9 Aug 2016.

Gallagher FJ, Pechmann I, Bogden JD, *et al.* 2008. Soil metal concentrations and vegetative assemblage structure in an urban brownfield. *Environ Pollut* **153**: 351–61.

Ghermandi A, van den Bergh JCJM, Brander LM, *et al.* 2010. Values of natural and human-made wetlands: a meta-analysis. *Water Resour Res* **46**: W12516.

Gibbs JP. 2000. Wetland loss and biodiversity conservation. *Conserv Biol* **14**: 314–17.

Grimm NB, Faeth SH, Golubiewski NE, *et al.* 2008. Global change and the ecology of cities. *Science* **319**: 756–60.

Grimm NB, Sheibley RW, Crenshaw CL, *et al.* 2005. N retention and transformation in urban streams. *J N Am Benthol Soc* **24**: 626–42.

Groffman PM, Cavender-Bares J, Bettez ND, *et al.* 2014. Ecological homogenization of urban USA. *Front Ecol Environ* **12**: 74–81.

Gumprecht B. 2001. The Los Angeles River: its life, death, and possible rebirth. Baltimore, MD: Johns Hopkins University Press.

Haase D, Haase A, and Rink D. 2014. Conceptualizing the nexus between urban shrinkage and ecosystem services. *Landscape Urban Plan* **132**: 159–69.

Hagmann DF, Goodey NM, Mathieu C, *et al.* 2015. Effect of metal contamination on microbial enzymatic activity in soil. *Soil Biol Biochem* **91**: 291–97.
Harrison MD, Groffman PM, Mayer PM, *et al.* 2011. Denitrification in alluvial wetlands in an urban landscape. *J Environ Qual* **40**: 634–46.
Harrison MD, Groffman PM, Mayer PM, and Kaushal SS. 2012. Nitrate removal in two relict oxbow urban wetlands: a ^{15}N mass-balance approach. *Biogeochemistry* **111**: 647–60.
Harrison MD, Miller AJ, Groffman PM, *et al.* 2014. Hydrologic controls on nitrogen and phosphorus dynamics in relict oxbow wetlands adjacent to an urban restored stream. *J Am Water Resour As* **50**: 1365–82.
Holt AR, Mears M, Maltby L, and Warren P. 2015. Understanding spatial patterns in the production of multiple urban ecosystem services. *Ecosyst Serv* **16**: 33–46.
Holzer KA. 2014. Amphibian use of constructed and remnant wetlands in an urban landscape. *Urban Ecosyst* **17**: 955–68.
Hopkins KG, Morse NB, Bain DJ, *et al.* 2015. Assessment of regional variation in streamflow responses to urbanization and the persistence of physiography. *Environ Sci Technol* **49**: 2724–32.
Hossler K and Bouchard V. 2010. Soil development and establishment of carbon-based properties in created freshwater marshes. *Ecol Appl* **20**: 539–53.
Jenerette GD, Harlan SL, Stefanov WL, and Martin CA. 2011. Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, USA. *Ecol Appl* **21**: 2637–51.
Johnson BJ, Munafo K, Shappell L, *et al.* 2012. The roles of mosquito and bird communities on the prevalence of West Nile virus in urban wetland and residential habitats. *Urban Ecosyst* **15**: 513–31.
Kensinger N. 2014. Queens' "forgotten river" looks ahead to cleanup and change. *Curbed New York*: online. Oct 9.
Kentula ME, Gwin SE, and Pierson SM. 2004. Tracking changes in wetlands with urbanization: sixteen years of experience in Portland, Oregon, USA. *Wetlands* **24**: 734–43.
Lawrence BA and Zedler JB. 2013. Carbon storage by *Carex stricta* tussocks: a restorable ecosystem service? *Wetlands* **33**: 483–93.
Mander U and Jenssen PD. 2003. Constructed wetlands for wastewater treatment in cold climates. Southampton, UK: WIT Press.
McLaughlin DL and Cohen MJ. 2013. Realizing ecosystem services: wetland hydrologic function along a gradient of ecosystem condition. *Ecol Appl* **23**: 1619–31.
Mitsch WJ and Gosselink JG. 2007. Wetlands. Hoboken, NJ: John Wiley & Sons.
Mitsch WJ, Zhang L, Stefanik KC, *et al.* 2012. Creating wetlands: primary succession, water quality changes and self-design over 15 years. *BioScience* **62**: 237–50.
Pagano MA and Bowman AO. 2000. Vacant land in cities: an urban resource. Washington, DC: The Brookings Institution.
Palta M, du Bray MV, Stotts R, *et al.* 2016a. Ecosystem services and disservices for a vulnerable population: findings from urban waterways and wetlands in an American desert city. *Hum Ecol* **44**: 463–78.
Palta MM, Ehrenfeld JG, Gimenez D, *et al.* 2016b. Soil texture and water retention as spatial predictors of denitrification in urban wetlands. *Soil Biol Biochem* **101**: 237–50.
Palta MM, Ehrenfeld JG, and Groffman PM. 2013. Denitrification and potential nitrous oxide and carbon dioxide production in brownfield wetland soils. *J Environ Qual* **42**: 1507–17.
Palta MM, Ehrenfeld JG, and Groffman PM. 2014. "Hotspots" and "hot moments" of denitrification in urban brownfield wetlands. *Ecosystems* **17**: 1121–37.
Paul MJ and Meyer JL. 2001. Streams in the urban landscape. *Annu Rev Ecol Syst* **32**: 333–65.
Ravit B, Rohleder L, Johnson L, *et al.* 2008. A vegetation survey of Teaneck Creek wetlands. *Urban Habitats* **5**: 199–214.
Roach WJ and Grimm NB. 2011. Denitrification mitigates N flux through the stream–floodplain complex of a desert city. *Ecol Appl* **21**: 2618–36.
Rotzoll K and Fletcher CH. 2013. Assessment of groundwater inundation as a consequence of sea-level rise. *Nat Clim Chang* **3**: 477–81.
Sandifer B. 2012. Ghost of an old swamp in the Great Trinity Forest. http://bit.ly/2mPZvNf. Viewed 10 Apr 2016.
Shih E. 2007. Get out your Succoth scythe: camping out with an eye toward tradition. http://bit.ly/2o87RQ3. Viewed 10 Aug 2016.
Shuster WD, Dadio S, Drohan P, *et al.* 2014. Residential demolition and its impact on vacant lot hydrology: implications for the management of stormwater and sewer system overflows. *Landscape Urban Plan* **125**: 48–56.
Snell-Rood EC and Cristol DA. 2003. Avian communities of created and natural wetlands: bottomland forests in Virginia. *Condor* **105**: 303–15.
Soomets E, Rannap R, and Lohmus A. 2016. Patterns of assemblage structure indicate a broader conservation potential of focal amphibians for pond management. *PLoS ONE* **11**: e0160012.
Spieles DJ. 2005. Vegetation development in created, restored, and enhanced mitigation wetland banks of the United States. *Wetlands* **25**: 51–63.
Steele MK and Heffernan JB. 2014. Morphological characteristics of urban water bodies: mechanisms of change and implications for ecosystem function. *Ecol Appl* **24**: 1070–84.
Steele MK, Heffernan JB, Bettez N, *et al.* 2014. Convergent surface water distributions in US cities. *Ecosystems* **17**: 685–97.
Uddameri V, Singaraju S, and Hernandez EA. 2014. Impacts of sea-level rise and urbanization on groundwater availability and sustainability of coastal communities in semi-arid South Texas. *Environ Earth Sci* **71**: 2503–15.
Van Meter KJ and Basu NB. 2015. Signatures of human impact: size distributions and spatial organization of wetlands in the Prairie Pothole landscape. *Ecol Appl* **25**: 451–65.
Vino A. 2013. The strange case of Bucharest's Lake Văcăreşti. *This Big City*: online. Oct 8.
Walsh CJ, Roy AH, Feminella JW, *et al.* 2005. The urban stream syndrome: current knowledge and the search for a cure. *J North Am Benthol Soc* **24**: 706–23.
Wenger SJ, Roy AH, Jackson CR, *et al.* 2009. Twenty-six key research questions in urban stream ecology: an assessment of the state of the science. *J North Am Benthol Soc* **28**: 1080–98.
Winchell KM and Gibbs JP. 2016. Golf courses as habitat for aquatic turtles in urbanized landscapes. *Landscape Urban Plan* **147**: 59–70.

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