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Designing Wetlands as an Essential Infrastructural Element for Urban Development in the era of Climate Change

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Abstract: The increasing development of urban infrastructure has led to the significant loss of natural wetlands and their ecosystem services. Many novel urban development projects currently attempt to incorporate environmental sustainability, cross-disciplinary collaboration, and community engagement into the intricate challenges we all face in an era of climate change. This paper aims to communicate several key findings on design elements that can be adopted or incorporated in the design of created wetlands as infrastructural elements. Three major design elements—microtopography, hydrologic connectivity, and planting diversity—are presented, and their relations to restoring ecosystem services of urban wetlands, in particular water and habitat quality, are discussed. These design elements can be easily adopted or incorporated in the planning, designing, and construction stages of urban development. The success of urban infrastructure projects may require both better communication among stakeholders and a great deal of community engagement. The Rain Project, a floating wetland project on an urban college campus, demonstrates the role of interdisciplinary collaboration and community engagement as a model for sustainable stormwater management, a critical part of today's urban development. Further efforts should be made to advance the science of designing urban wetlands and its communication to transform cultural attitudes toward sustainable urban development.

Keywords: urban created wetlands; urban development; wetland design; design elements; wetland ecosystem services; urban infrastructure; sustainable stormwater management; community engagement

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1. Urban Development and Loss of Wetland Ecosystem Services

Many parts of the world have experienced intensive and/or extensive urban development over the past 30 years. Northern Virginia is, for instance, no exception, and changes in the environment by urban real estate developments have been more palpable than in other parts of the state. By 2050, most of the world's population is predicted to live in cities or developed urban areas [1]. Urban developments have inevitably led to the loss of natural wetlands and continue to do so. When wetlands are impacted for urban development, the ecosystem services of these wetlands are lost. Lost services that many cities currently need include flood mitigation, water quality improvement, habitat quality for biodiversity, and public amenities such as nature education and aesthetics. These services are part of important considerations in contemporary urban design and development.

Creating and restoring wetlands to mitigate the loss of natural wetlands, often called "wetland mitigation", has been a popular and well-established measure to serve up the "no-net-loss" policy of the Clean Water Act (Section 404) in the past three decades [2,3]. Although wetland mitigation received some criticism and showed cases of failure in the early days of practice (i.e., in the mid- through late 1990s), it gradually improved and succeeded to replace the natural wetlands impacted by urban development with newly created ones that met the legal criteria for mitigation success. Created wetlands also showed the signs of structural and functional maturity over time [4,5]. On the basis of the research and monitoring we have conducted for more than a decade [5–8], it seems to take significant time (e.g., 5 years or often >10 years) for soils in created wetlands to develop the characteristics often found in their natural counterparts that are the basis for ecological and biogeochemical processes to support desired ecosystem services. While there have been numerous wetland mitigation projects with reported successes across the United States, a knowledge gap exists concerning urban wetlands. More specifically, little research has focused on how to best design wetlands as part of urban infrastructure.

Climate change is a story of water, especially stormwater [9]. Water is also a big part of urban sustainability [9,10]; sustainable stormwater management is one of the biggest issues in urban development these days. We have recently witnessed many extreme weather events and devastation such as major flooding in urban areas and city centers throughout the country [11]. Many U.S. cities are currently looking out for innovative green infrastructure that mimics the way nature collects and cleans water. Urban wetland creation can be strategically integrated with other urban development activities beyond wetland preservation so that cities can be more resilient to extreme weather events.

Green stormwater infrastructure (GSI) is now a ubiquitous feature of urban development; conventional grey infrastructure features including the storm sewer network, detention areas, and water control structures such as culverts and ditches are increasingly being complemented by green infrastructure relying on natural materials, such as plants and soil, to protect, restore, or mimic the natural water cycle [12,13]. Stormwater best management practices (BMPs) including rain gardens, bioswales, and the ubiquitous retention ponds can provide decentralized street- to landscape-scale methods serving stormwater purposes that include the attenuation of stormwater flow into natural waterways as an effort to reduce stream bank erosion and the risk of flooding downstream. While these "micro-scale" features can be installed with redundancy across a watershed to efficiently reduce runoff at the source [14], urban created wetlands provide a unique opportunity to couple such stormwater functions of flow control, infiltration, detention, and/or retention with landscape-scale ecosystem conservation and/or restoration [15–17]. Wetlands can be integrated into the existing urban fabric through creative problem-solving on the part of urban planners and stormwater managers—for example, floating treatment wetlands (FTWs) which retrofit wet retention ponds by providing a growing medium for wetland vegetation [18]. A well-planned network of centralized and/or decentralized urban wetlands can combine water quantity and water quality functions to optimize the benefits derived from green stormwater infrastructure [14].

It is often said that we must keep at least over 1%, or optimally 5%, of the watershed to be wetlands for ecological health and functioning [19]. However, we still do not know how to best design wetlands in terms of their types, size, and placement in a watershed targeted for urban development, especially given the placement of existing stormwater infrastructure. Out of few that addressed the issue, Zedler et al. [20] emphasized the importance of sizing and locating wetlands to be created or restored when developing a watershed for the sake of maximizing ecosystem service benefits. For example, a large-scale complex wetland downstream can be designed to serve as a measure of flood mitigation while cleaning the water for the watershed to be developed, whereas multiple sets of small wetlands upstream can be designed to provide habitats for diverse flora and fauna, thereby supporting urban biodiversity. Newly created urban wetlands are novel and complex ecosystems with emerging properties and processes, some of which are unknown to us. Thus, we must develop a new framework and way of tracking their ecological progress over time for assessment.

Our research at George Mason University (GMU) has aspired to inform urban design interventions related to wetland ecosystem services by studying certain design elements that, when incorporated into designing and constructing urban wetlands, can positively impact the development of desirable ecosystem functions and services. Given the more well-studied relationship between wetland design and ecosystem services related to water quantity (detention, infiltration, etc.), we hope to expand the traditional scope of urban created wetlands as green stormwater infrastructure to, more broadly, investments in resilience that a) improve water quality by removing pollutants such as nitrogen, and b) protect and enhance habitat quality for fish and wildlife by encouraging a diversity and abundance of wetland plants capable of adapting to a disturbance. Finally, as urban land use is inseparable from urban planning, our research has far-reaching impacts for local and regional planners and highlights the importance of including science, art and design, and the overarching community of stakeholders in land development decisions and practices.

2. Design Elements for Creating Wetlands as Urban Infrastructure

Our research at GMU has informed us that there are certain design elements that, when incorporated into constructing urban wetlands, can encourage a trajectory of wetland development that produces desirable ecosystem services [5–8,21]. The three design elements of microtopography (MT), hydrologic connectivity (HC), and planting diversity (PD) can be applied or managed while designing and/or constructing urban wetlands to facilitate the development of ecosystem services. Figure 1 summarizes the knowledge produced through our decade-long research on the three design elements and their relations to two major ecosystem services regarding water and habitat quality in created urban wetlands. The outcome of the research [4–8,16,17,21–33] reveals how the design elements interact or are interrelated and how they influence key variables of wetland hydrology, soils, and plant community which drive and control the two ecosystem services (Figure 1). Planners, designers, and wetland construction specialists may determine if their watershed development goals are best served through a specific combination of these design elements.

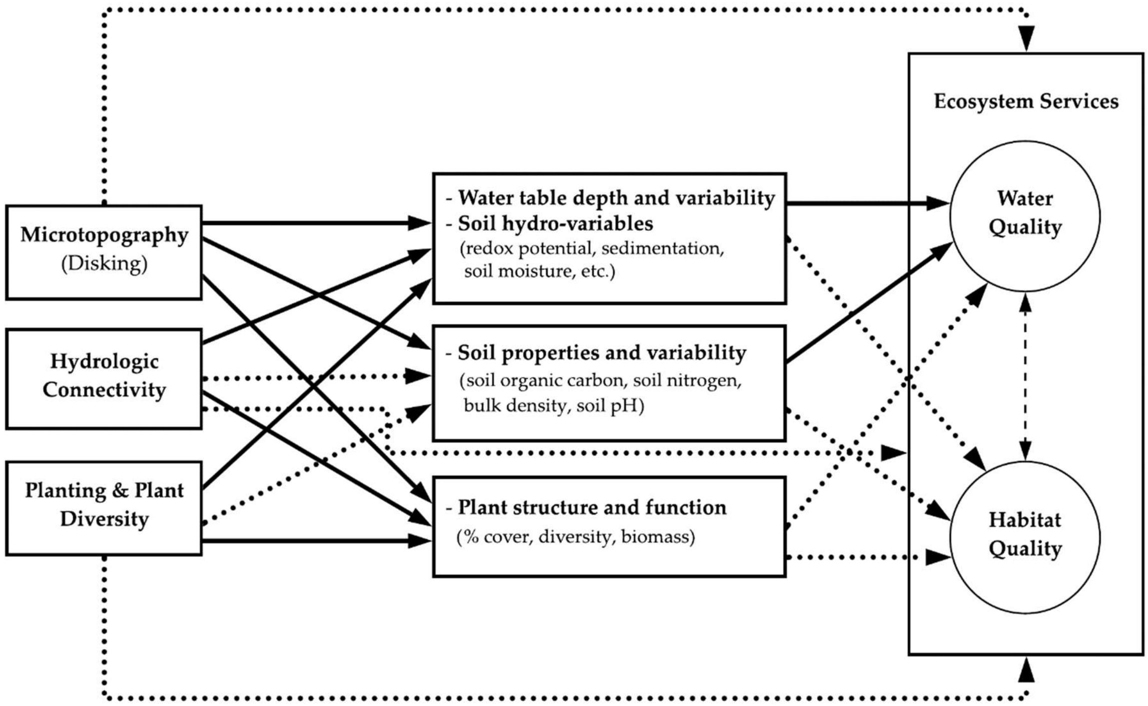

Figure 1. A conceptual model of the relationships and correlations among three design elements, hydrogeochemical and plant variables, and two target ecosystem services to be restored in a created urban wetland. Arrows indicate causal relationships among variables. There are three different types of arrows that represent direct causal relationships or correlations among variables. Each represents the different status of our current knowledge (→: we know from our previous studies; ··►: we know some, but not all yet; - ►: we know little).

The first design element we studied was MT and its influence on the ecosystem development of created urban wetlands. MT, or topographic heterogeneity at small (<1m) scales, often naturally evolves in wetlands and drives many surface processes, including variations in depths to water table and flooding regime that tend to support biodiversity [34]. MT can be defined by surface relief, e.g., elevation differences between hummocks and hollows, as well as surface roughness, e.g., tortuosity or the extent to which distance along a surface deviates from the linear distance between two points; it is indeed a hydrologic variable at a micro-scale. A common practice of wetland construction is to grade soil surfaces, so most created wetlands begin with no surface heterogeneity; this ultimately discourages the many benefits of MT in ecosystem development [35]. We set out to determine if disking of soil surfaces to artificially induce MT during wetland construction would not only counteract surface homogeneity, but also beneficially influence wetland ecosystem development and thus promote urban ecosystem services.

Our research identified that disking can induce MT and positively impact wetland development through its interactions with wetland water table depth and variation, soil properties, and vegetation (Figure 1) [6,21,24,36]. Disking gives a soil surface more relief and roughness, forming hollows that become sinks for downward water flow and hummocks at relatively high elevations. Thus, whereas a wetland lacking MT may have a slight rise in near-surface water table depth but no standing water after rainfall, wetlands with induced surface relief can gain standing water in hollows while maintaining oxygenated soils within hummocks. Similarly, in areas with induced MT, soils can develop properties that encourage water quality improvement: denitrification, or the process by which nitrates within wetlands are removed and returned to the atmosphere as N_2, is enhanced through the promotion of nitrification in oxygenated hummocks, the transport of nitrates from higher (hummocks) to lower (hollows) elevations, and, finally, the encouragement of nitrate removal in depressions with standing water [24]. Finally, the interaction between MT, hydrology, and soil properties produce many micro-habitats that support a diversity of microbiota and encourage more plant species to become established, including tussock-forming species that grow in drier areas and eventually contribute to biogenic MT in a wetland [6,21,24,36]. Disking-induced MT can positively impact wetland hydrology, soil properties including improved (lowered) densities, and plant diversity, and ultimately improves water quality and enhances habitat quality on a site- or plot-sized scale (Figure 1). Over time, natural processes can enhance or diminish the MT induced by disking; thus, we suggest that, on a site-to-site basis, the inclusion of MT into wetland design be accompanied by careful management to provide the most desirable trajectory of wetland development [24].

The second design element we investigated, HC, characterizes how connected a wetland is to nearby bodies of water; stormwater systems can greatly modify a wetland's HC through creating artificial channels of water leading to a wetland, or reducing flow to a stream near a wetland [5]. Wetlands can be open systems receiving a substantial portion of their water budget from surface waters, primarily streamwater and stormwater; on the other hand, wetlands can act as stand-alone systems, primarily fed by precipitation or groundwater. A function of watershed-scale processes, HC can affect wetlands' capacity to improve downstream water quality. Thus, we investigated how HC can affect wetland development and ecosystem services, particularly water quality, with implications for urban watershed managers looking to most appropriately site and design created wetlands [5].

We determined that HC was an important factor in driving water table depth and its variability, with more connected wetlands experiencing greater fluctuations in the water table [5]. Additionally, while several features of soil development were not necessarily predictable on the basis of HC, our research indicated that more connected wetlands act as sinks for river systems with high pollutant loads; thus, wetland connectivity to nutrient-rich waters can allow wetlands to act as efficient water filtration systems (Figure 1). A high degree of hydrologic openness is also beneficial to wetland plant community development. With higher nutrient loads, vegetation becomes more productive; additionally, low-velocity stream overflows can maintain or encourage any MT present in wetlands, further supporting the growth of tussock-forming species [24].

While HC is an essential design component to connect wetlands to urban pollutants, it requires foresight in wetland creation; desired ecosystem services can only be optimized when considering wetland site at the watershed scale. Designers and managers may have to choose between water quality improvements and habitat quality for both wildlife and humans: the addition of high concentrations of nutrients and pollutants into a wetland system may negatively impact floral and faunal diversity [37]. Furthermore, as surface waters enter wetlands which recharge groundwater and raise the water table, there may exist a potential concern for surrounding urban infrastructure including commercial buildings and houses. This may be localized to nearby (e.g., <3 m) buildings but requires more research [38]. On the other hand, high nutrient loads are beneficial to wetland plant community productivity. Overall, the trade-offs should be met with serious consideration and discussion between designers/developers and wetland ecologists as early as possible in the planning stage of an urban development project.

Finally, the third design element is PD [29–33]. Our team has been studying the biogeochemical processes and ecosystem functionality of urban wetlands since 2012 using a set of 60 ecological mesocosms (i.e., medium-sized, outdoor experimental tubs—see www.changwooahn.com for more) that allow controlled experiments and observation of PD and its relation to wetland ecosystem development. We introduced various levels of PD to determine how creating a wetland with a certain level of planting richness would affect plant community development that ties critically with wetland ecosystem maturation over time.

Our studies related PD to properties of wetland hydrology, soils, and vegetation, with each of the three components influencing biodiversity. We found strong support for the theory that planting diverse species at the time of wetland creation encourages greater diversity in an established macrophyte community over time (Figure 1) [29–32]. Hydrology may have a strong impact on this relationship, though; wet conditions can deter the establishment of volunteer species, which could otherwise outcompete initially planted wetland vegetation, and often periods of dry conditions ("drawdown") support the growth of less flood-tolerant species [30,31]. Furthermore, PD may influence the flooding regime of a wetland (Figure 1), but this relationship often depends on individual traits of the species planted [31]. We also found that PD can affect soil properties, including nutrient cycling and organic matter accumulation; these processes likewise depend on the identities of the planted species and their interactions [8]. For example, the aboveground tissue of the sturdier common rush (*Juncus effuses*) and Allegheny monkeyflower (*Mimulus ringens*) acted as the largest carbon sinks to provide another ecosystem service, carbon sequestration [31]. Biomass production, or productivity, was likewise dependent on PD and the characteristics of the planted species. High productivity indicates an efficient uptake of nutrients and rapid nutrient turnover, whereby productive vegetation can improve habitat quality through high secondary productivity and can improve water quality through vigorous nutrient uptake in their belowground biomass; furthermore, biomass itself can act as an indicator of water quality [39–41]. While we found that PD and biomass productivity were positively related in the first growing season, interactions between species led to a tradeoff between diversity and productivity of biomass after the first growing season [29]. Finally, we discovered that PD can enhance vegetation community resilience (i.e., regeneration of the plant community) to disturbances (i.e., aboveground biomass harvesting) [32].

Our research has identified several important relationships between all three design elements and two desirable ecosystem services: water and habit quality (Figure 1). While all design elements produced beneficial impacts on wetland development, the overlap and complementarity of their benefits can allow wetland designers to critically assess which design element(s) to incorporate into urban development projects. For example, PD that incorporates tussock-forming plants may eventually induce MT in a much more natural manner, whereas hydrologic openness can enhance greater sediment and nutrient loads to wetlands, yet it may impact MT and biodiversity negatively. One of the most important question marks that remains is the relationship between water quality and habitat quality; there seems to be a trade-off between the two ecosystem services in an urban wetland, which warrants further research. It would be beneficial to quantitatively compare the relative contributions of each one of the design elements upon harnessing the two somewhat conflicting services in an urban wetland to be created, which may involve an intensive structural equation modeling exercise of all the key variables involved [8].

3. Community Engagement for Sustainable Stormwater Management

Urban created wetlands can come in a variety of creative forms and shapes. Intertwined with existing structures and developing through community engagement and collaboration among different disciplines, FTWs can be a great intervention as a form of an urban wetland for sustainable urban stormwater management. Retrofits like FTWs modify existing structures through a transient structure (e.g., a floating mat) which adds to or improves the overall structure's stormwater functions in a simple, manageable way that can offer an opportunity for community engagement while simultaneously advancing community connection with and awareness of urban water.

In addition to studying the three design elements for urban wetland infrastructure planning and development, our team successfully completed an urban green infrastructure project that addressed sustainable stormwater management with strong community engagement. In 2015, "The Rain Project" was launched to develop an innovative interdisciplinary higher education and community engagement model for sustainable stormwater management [9]. The goal of the project was to raise awareness of urban stormwater issues and to showcase an interdisciplinary, year-long (Fall 2014 through Fall 2015) collaboration activity for the campus community. More than two dozen undergraduate students from various disciplines (e.g., art, biology, environmental science, communication, civil engineering, and film/media) worked as a team to design and implement a floating wetland as green infrastructure for the main stormwater pond on the urban campus of GMU. The "floating wetland" (Figure 2) was designed to slow down surface water flow and to improve water quality in the stormwater pond by removing nutrients (e.g., nitrogen and phosphorus), whose excessive amounts often lead to algal blooms and degrade water quality. Removal of nutrients from the stormwater was provided by the large surface area of hanging roots of wetland plants that trapped and filtered sediments and by bacterial communities living in the roots. By the end of our project, a total of 2684 g of plant biomass was produced, 3100 g of sediment was captured, and 191 g of nitrogen was removed from the pond by the small floating wetland we implemented during the three summer months [16,17]. The wetland also became a beautiful habitat for a variety of birds, turtles, and macroinvertebrates and a point of conversation for urban sustainability among different members of the campus community, especially at a time when the campus is facing extreme infrastructure development and renovation. The discussion continued beyond the campus, as the progress of the project was covered by NBC 4 Washington and a local TEDx talk (see the videos at www.changwooahn.com for more).

The Rain Project has been featured as an exemplary case of cross-disciplinary collaboration for community impact in the National Academies' recent report (2018) [42]. The approach and the outcome of the Rain Project showed its applicability as a framework in a larger community setting. Green infrastructure such as floating wetlands can be built nationwide and used for sustainable stormwater management, not only for water quality benefits, but also as an opportunity to both train the next generation of ecologically literate citizens and form a sense of community among participants and stakeholders.

We hope that, in the future, continued efforts will explore many ways for universities to work with urban and real estate development projects to facilitate the much-needed communication required to change cultural attitudes toward both sustainable urban development and higher education. Universities often guide land use decisions in their local environments and can build an active partnership with real estate development through research and training. This type of collaboration or partnership can be initiated as we incorporate ecological and environmental sustainability research into the early stage of a project to study and shape infrastructure [43]. One of the best models for this future type of collaboration is the Olentangy River Wetland Research

Park (https://senr.osu.edu/research/schiermeier-olentangy-river-wetland-research-park) located in Columbus, Ohio, on the extended campus of The Ohio State University [44]. For more than two decades, this urban wetland park, slightly over 30 acres in size, has provided a great deal of training and scholarship for higher education as well as opportunities for local community engagement in numerous urban development projects that benefitted, both environmentally and culturally, the city and its residents [44]. The kind of partnership between universities and urban developers that can build from this model may also support more creative and sustainable urban development planning that faces ever-increasing uncertainty in environmental conditions due to climate change.

Figure 2. The Rain Project floating wetland on Mason Pond in the summer of 2015 (Photo credit: Susie Beyer-Wait).

4. Final Thoughts

Created wetlands can be sited, designed, and monitored in a way that optimizes the essential ecosystem services of water quality and habitat improvement that are often lost when natural wetlands are impacted by urban development projects. In addition to the ample aesthetic and recreational value they hold in urban areas, wetlands provide water storage and flood attenuation, remove some pollutants and retain others in sediments and/or plants, and provide habitat for urban wildlife. Incorporating design elements that are known to enhance ecosystem functions in urban created wetlands should be factored in the early stage of urban development and infrastructure planning, especially for sustainable stormwater management. Communication will be key in facilitating the much-needed collaboration between ecologists and urban designers and engineers for successful outcomes. Universities have a role to play in the community to improve environmental literacy for sustainable urban development through engagement and research [43]. We encourage the partnership between higher education and urban development in the future, which may improve the science of urban wetland ecology as well as experiential learning among all community members involved, while also assisting the urban development industry to both communicate its goals better and offer exciting interdisciplinary entrepreneurship opportunities for today's higher education.

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