DESIGN GUIDELINES FOR
URBAN
STORMWATER
WETLANDS

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As the frequency and intensity of storm events continue to increase, the role of stormwater management has expanded in many cities to support urban resilience and meet water quality standards. In arid cities, stormwater can also serve as an important opportunity for alleviating water scarcity. Although constructed wetlands and detention basins have long been used to manage urban stormwater, their design has been largely driven by hydrologic performance alone.

Based on two years of interdisciplinary research at the MIT Norman B. Leventhal Center for Advanced Urbanism, a team of planners, designers, and engineers has created an illustrative guide of innovative designs for urban wetlands and ponds that integrate hydrologic, ecologic, and recreational functions for urban designers and landscape architects to use in cities. Based on modular and scalable forms, these designs can be customized for a wide variety of sites, climates, and desired urban design uses.

By merging fluid dynamics, landscape architecture, and urban design, this research project shows how natural treatment systems can be integrated into cities as multifunctional infrastructures to manage flooding, add resilience, improve water quality, enhance biodiversity, and create public amenities.
# Design Guidelines for Urban Stormwater Wetlands

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Chapter 1
Introduction

Urban stormwater—the rainfall that washes over our streets, lawns, parking lots, and rooftops—poses major flooding risks to cities and contributes dangerous amounts of pollution to hydrologic ecosystems we rely on. Unfortunately, more stormwater is in our future. Nearly everywhere on earth, climate change is increasing the intensity of storms, delivering more rainfall in less time to overburdened city infrastructure. Thus, climate change is only half the problem. The other half is the way cities and urban infrastructure have traditionally been built. Traditional engineered stormwater infrastructure is expensive to build and maintain, and necessary upgrades have not kept pace with modernity’s explosive urban growth. That growth has entailed paving over natural areas, often wetlands, leading to the loss of biodiversity and natural protections, as well as creating even more impervious area that generates stormwater. Moreover, traditional engineered stormwater solutions add little to no public realm to the fabric of neighborhoods.

Overall, the narrow civil engineering problem-solving methods of the past inadequately address the complex environmental issues cities face today. With these mounting challenges, cities need innovative ways to develop, integrate, and manage new types of landscape infrastructure to handle increased stormwater and flooding problems, whilst also positively contributing to urban life. Using large-scale wetlands and ponds to clean, store, or reuse stormwater can create novel urban ecosystems that offer recreational, aesthetic, and ecological benefits.

Yet in order to deliver multiple benefits, wetlands and ponds require careful and intentional design. The vast majority of traditional engineering projects for stormwater gave no consideration to ecology or improving the urban context in which they were built. In fact, even in constructed wetlands, ecological success has largely happened by chance, not by design. When urban design considerations are taken into account, landscape architects are often relegated to the end of the design process in order to add paths or planting around an engineer’s design. Thus, traditional engineered stormwater wetlands and ponds often fail to integrate hydrology, ecology, and urbanism. In his 1996 essay “Why Aren’t All Engineers Ecologists?” political scientist Albert Wurth explains that the engineering focus on “human needs and wants” creates


unforeseen negative externalities. While engineering and ecology have different starting points, a synthesis is possible if the scope of engineering broadens.\(^3\) Our research goes further, suggesting that the physical form of the city and subsequent urban design considerations can also be integrated into stormwater solutions.

In this context, we present the Design Guidelines for Urban Stormwater Wetlands. This work is an illustrative, conceptual guide demonstrating innovative designs for constructed wetlands and detention ponds that integrate hydrologic, ecologic, and recreational functions. These new designs are based on sculptural island landforms that are scalable and modular. As a result, they can be customized for a wide variety of sites, climates, and urban functions.\(^4\) The forms arose from our research in an engineering lab that tested thirty-four unique models in physical experiments to rate their hydrologic performance. Next, we scored each model based on its potential to provide four vegetative habitats, introducing heterogeneity into the landscape, a characteristic that supports biodiversity, and in turn, ecosystems services.\(^5\) From the thirty-four tested models, a few optimal designs emerged. These optimal designs and our lessons learned about landforms and water flow will be useful to designers and practitioners, as will the urban design framework developed to employ these designs on an urban site. Using Los Angeles and Houston as case studies, we created an urban design framework that explains how to integrate a wetland into its urban surroundings and provide public programs. Thus, a wetland site can become a stormwater landscape that contributes as much to hydrology as to urbanism. In this way, our research begins to unlock the possibilities for integrating engineered form, hydrological performance, ecological benefits, and new kinds of urban landscapes for public occupation.

These guidelines are the culmination of a Massachusetts Institute of Technology (MIT) research project funded by the MIT Abdul Latif Jameel World Water and Food Security Lab and the MIT Norman B. Leventhal Center for Advanced Urbanism (LCAU) from 2015 to 2017. This project was an interdisciplinary collaboration between urban designers and planners at the LCAU and environmental engineers at the Nepf Environmental Fluid Mechanics Lab.

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5. Thomas Elmqvist et al., eds., Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities (Dordrecht: Springer Netherlands, 2013).
The following sections of Chapter 1: Introduction provide relevant background on stormwater and introduce the two case study cities: Los Angeles and Houston. Chapter 2: Sculpting Wetlands presents all the tested wetland designs, highlights the optimal ones as shown by our experiments, and discusses lessons learned from testing. Chapter 3: Wetland Urbanism explores how these topographical designs create useful urban landscapes with open space, recreational opportunities, and contextual functionality. Finally, Chapter 4: Topography Design Catalog illustrates each of the thirty-four tested designs in detail and outlines their performance metrics for reference.

The aim of these guidelines is to inform decision makers, planning agencies, consulting engineers, landscape architects, and urban designers about the efficacy of using ecologically designed constructed wetlands and ponds to manage stormwater while creating new public realms. Our hope is that cities will adopt and apply our findings in projects around the world, opening a door to more explorations of multifunctional urban stormwater landscapes in the age of urban resiliency.
The Stormwater Imperative

In every part of the contiguous United States, storms have become significantly more intense over the past few decades and will continue to do so. In the northeast, the amount of rain falling during the heaviest storms increased by an astounding 71 percent between 1958 and 2012. Even in the dry West, 5 percent more rainfall has fallen during heavy storms over this time period. This phenomenon is by no means unique to the United States. Around the world, nearly all countries will experience increased precipitation intensity, especially in middle and high latitudes.

More intense storms overwhelm cities’ already undersized infrastructure, posing serious water pollution and flooding risks. At the time of writing, the year 2016 saw the most billion-dollar (in damage) flooding events since 1980 in the United States. Yet 2017 will likely eclipse 2016 once the costs of Hurricanes Harvey, Irma, Jose, and Maria are fully assessed. Hurricane Harvey in particular, which hit the Texas Gulf Coast, broke the rainfall record in the continental United States. Unfortunately, cities meet these threats inadequately equipped. First, urbanization has largely destroyed or degraded the natural ecosystems—particularly wetlands—that purify and store water (Figure 1.1). Wetlands, the world’s most valuable terrestrial ecosystem, provide a multitude of ecosystem services: water treatment, flood protection, carbon storage, habitat, recreation, and aesthetic value. Yet half of American wetlands have been lost since colonization. Within several major urban regions, the loss has been nearly total. Los Angeles County, for example, has


The Ballona wetlands in Los Angeles is one of the few remaining wetland systems in the region.


lost 95 percent of its original wetlands (Figure 1.2); in New York City, 85 percent of coastal wetlands and 90 percent of freshwater wetlands are gone.11 Those urban wetlands that remain suffer compromised functionality. Without the natural protective benefits of wetlands and other natural ecosystems, cities and their residents become more vulnerable to climate change risks.

Second, city wastewater infrastructure is typically outdated and undersized for major storms, which leads to the release of untreated stormwater into natural water bodies. Stormwater carries all manner of pollutants from the urban environment, from trash, debris, and sediment to bacteria from pet fecal matter, heavy metals from vehicles, nutrients from lawn fertilizers, and chemicals from pesticides and other substances. According to the US Environmental Protection Agency (EPA), stormwater alone impairs around 60,000 miles of rivers and streams; 767,000 acres of lakes, reservoirs, and ponds; and 17,000 square miles of bays and estuaries.12 These figures do not include the combined sewer overflows that occur in 772 American cities, which impair 4,000 miles of rivers and streams; 22,000 acres of lakes, reservoirs, and ponds; and 700 square miles of bays and estuaries.13

While stormwater is a problem, it is also an opportunity. Just as urbanization has obliterated wetlands, urbanization can build them anew. While constructed wetlands are not in all aspects comparable to natural wetlands, they can partially restore some lost ecosystem services, especially in locations where wetlands do not currently exist.
Case Study Cities

To ground this research, we chose two case study cities with urgent stormwater problems: Los Angeles, California, and Houston, Texas. Both are among the most rapidly growing American metropolitan areas. In fact, Houston was the top fastest growing metro between 2010 and 2016 (metro Los Angeles was ranked seventh). Los Angeles and Houston have a population of about 13 and 7 million people respectively. Both experience severe flooding issues, as evidenced recently by the winter 2016 floods in Los Angeles, and in Houston, Hurricane Harvey in 2017 and the Tax Day floods in 2016 (Figure 1.3). In terms of urban form, both are highly extensive, mostly suburban metropolitan areas. Finally, they are opposites on the climactic spectrum. While both have warm climates, Houston receives on average about 139 centimeters (55 inches) of rainfall per year and Los Angeles receives 33 centimeters (13 inches) (Figure 1.4 on pages 8–9). This difference allows us to compare wetland designs across climates, as will be evident in Chapter 3. In each city, we chose comparable sites to test our wetland designs. Both sites are approximately 16 hectares (40 acres) in size, adjacent to the local river, and currently vacant land.


Los Angeles: Taylor Yard
A former railway depot, Taylor Yard is a site adjacent to the Los Angeles River (Figures 1.5 and 1.6 on page 10). The city is investing heavily in the revitalization of the Los Angeles River, and according to the Mayor, Taylor Yard is the “crown jewel” in the effort to transform the river. In fact, the city spent nearly $60 million dollars to purchase this site in early 2017. Now, the city is currently planning long-term and interim projects for the public use of Taylor Yard, but the implementation of those will likely be delayed due to the remediation of contaminated soils.

Located north of downtown at Cypress Park, Taylor Yard is unique in that it is a large site next to a major river in a metropolitan area. Its adjacency to the Los Angeles River (west of the site) is also unique because that part of the river does not have a concrete bed. The riparian species growing there would act as a seed source for the Taylor Yard site. On the east side, the site borders Rio de Los Angeles State Park and a complex of four high schools and one middle school.

Houston: Buffalo Bayou
Buffalo Bayou runs just north of downtown Houston and is one of the city’s most iconic bayous. Houston is known for its network of bayous, or slow-moving streams, which are the main natural drainage infrastructure in this otherwise flat landscape with clay soils. The Bayou Greenways project has dedicated millions of dollars in recent years to revitalize Houston bayous by reconstructing their banks to accommodate recreational trails, and where possible, widening and stabilizing them for flood protection. However, these revitalization efforts have not yet reached Buffalo Bayou to the east of downtown, where it crosses Highway 69. Here is a grouping of vacant lands that lie in the transition between downtown Houston and traditionally disadvantaged neighborhoods such as the Second and Fifth Wards (Figures 1.7 and 1.8 on page 11). Disadvantaged neighborhoods typically suffer elevated flood risks and deprivation of natural open space. Thus, this site offers an opportunity to provide flood protection, connect neighborhoods, and offer recreational opportunities in a deprived part of the city.
Graph comparing average monthly rainfall in Los Angeles and Houston and variation in 2-year and 100-year storms. Data: NOAA 1981–2010 Climate Normals.
Introduction

Chapter 1

100-Year Storm

2-Year Storm

First Flush

100-Year Storm

2-Year Storm

First Flush

Los Angeles

Houston

- Monthly Average Rainfall
- Dry Season
Los Angeles: Taylor Yard

Taylor Yard site and context in Los Angeles, California.
Site Area: 46 acres

Los Angeles River
Taylor Yard Site
South to Downtown

Aerial view of Taylor Yard looking south.
Houston: Buffalo Bayou

Buffalo Bayou site and context in Houston, Texas.

Site Area: 46 acres

Aerial view of Buffalo Bayou looking south toward downtown Houston.
Chapter 2
Sculpting Wetlands

Sculptural landforms define the wetland designs in these guidelines. More precisely, the designs use streamlined islands arranged in strategic configurations, resulting in a complex topographic landscape. In physical experiments at the Nepf Environmental Fluid Mechanics Lab, these sculptural forms were found to be hydraulically efficient—ensuring the proper treatment of water. The forms are also topographically heterogeneous—creating deep, shallow, and dry zones that provide habitat for diverse vegetation. These designs display an advantage in both of these factors when compared to conventional open basin or baffle designs for stormwater wetlands or ponds. Moreover, the sculptural nature of these designs allows landscape designers to flexibility embed urban functions and public spaces into the very form of the wetland, as opposed to making those functions adjacent to or circumscribed around the wetland (see Chapter 4). In this way, landforms knit together hydraulic performance, ecological function, and urban amenities.
Finding Form

Why sculptural landforms? These forms naturally emerged from a series of physical experiments in the lab. At the start of our research, we sought to test basic wetland design principles using tracer tests, a standard fluid mechanics experimental method. First, we cast in concrete a kit of rectangular berms, circular islands, and pinch points of different sizes (Figure 2.1) and fabricated a table-sized model wetland basin for testing. Our preliminary experiments consisted of arranging concrete shapes in the wetland basin in specific configurations, then filling the basin with water and injecting a dye tracer at the inlet (Figure 2.2). At the outlet, we measured the concentration of the dye every second as water circulated through the basin. The outlet dye concentration as a function of time allows us to compute various hydraulic performance metrics.

In these preliminary experiments, we found that a cluster of...
islands near the inlet (Figure 2.3 on page 16) performed the best out of twenty tested configurations (Figure 2.5 on page 17). Specifically, this island configuration best eliminated the short-circuiting of water between the inlet and the outlet, providing better treatment because water has more time to undergo the chemical, mechanical, and biological processes that remove pollutants. A cluster of islands performed better than common wetland design configurations, such as an empty basin or a serpentine baffle scenario. The islands, when placed in a specific cluster, serve to block, splinter, and slow down the incoming jet of water (delivered from a pipe in reality) (Figure 2.4 on page 16).

After passing the island cluster, water is more evenly spread across the width of the remaining section of the wetland basin. In other words, the island cluster acts as a structure that conditions the flow for the remaining length of the wetland basin or cell. In contrast, in an empty channel, most of the water tends to go straight from the inlet to the outlet at relatively high velocities. This short-circuiting undermines the performance of the wetland by letting

Manoel Xavier injects dye tracer at the inlet of the wetland basin for phase one tests.
Perspective view of the best-performing concrete configuration, CLU-1, a cluster of islands near the inlet. Water flows from bottom left to upper right.

Diagram showing how the island cluster works to dissipate an incoming jet.
Plan view of phase one concrete configurations. Water flows from bottom to top.

[2.5]
water exit too quickly to be sufficiently treated, rendering most of the wetland area unused. Engineers have devoted a lot of time to researching optimal configurations of wetlands that diminish short-circuiting, for example, proposing long aspect ratios, placing deep zones perpendicular to water flow, or creating sinuous channels. In these studies, however, ecology and urbanism were not considered jointly with hydraulic performance. Other engineers have also found simple islands helpful in improving water circulation, but have stopped short of making more elaborate studies.

Given the promising results of the island cluster in our initial research, our subsequent experiments explored more complex designs for island clusters near inlets. Our preliminary island cluster was made of perfectly extruded circular shapes. For phase two of our research, we chose a geometric, faceted island shape because it was easier to model and faster to fabricate (Figure 2.6 on page 19). However, designers can play with shape and curvature to a certain degree without significantly altering performance, so long as the geometry at the scale of the cluster remains similar. This margin of design is the key to embedding multifunctionality in our forms,
Examples of various island shapes that would likely exhibit similar hydrologic performance since they all adhere to the same gross island dimensions and configuration. Designers have a margin of flexibility when shaping the exact form of islands.
because landform can be shaped to favor ecological and urban function while still maintaining hydraulic performance. We call our subsequent designs “topographies” because they shape landform in more sculptural ways.

In the second phase of our experiments, we tested thirty-four topographies, including an empty basin as a control and a serpentine baffle case (Figure 2.9 on page 22). These designs explored how island size, shape, and placement affect hydraulic flow and provide ecological habitat. To test our topographies, we constructed 40.5 cm by 60 cm (16 inch by 24 inch) models (Figure 2.7) of each design out of high-density foam shaped by a CNC milling machine (Figure 2.8). In the lab, these topographies were placed inside a flume, a long channel made of plexiglass filled with water circulated by a pump (Figure 2.10 on page 24). Similar to the preliminary experiments, a dye tracer was injected at the inlet and measured every second by an instrument (a fluorometer) placed at the outlet (Figure 2.11 on page 25). Using the fluorometer data, we computed the hydraulic performance of each design. In separate experiments, we also visually observed the movement of dye through the models using fluorescent dye to study the patterns of water flow (Figures 2.12 and 2.13 on pages 26–27). We also compared their potential construction costs and assessed their ecological value using a habitat diversity index. For in-depth information about our experimental methodology, please refer to our technical paper in *Ecological Engineering*.20
Physical models were fabricated out of high-density foam on an ONSRUD milling machine at MIT.

Drawing of model for physical testing, measuring 40.5 cm wide by 93 cm long.
Plan view of the thirty-four topography designs for phase two. Water flows from top to bottom.
Project team members prepare the flume for physical experiments in the Nepf Environmental Fluid Mechanics Lab. The flume is a long channel made of plexiglass with a pump that circulates water.
Diagram of the experimental setup for physical testing in the flume at the Nepf Environmental Fluid Mechanics Lab.
Project team members observe and record a fluorescent dye experiment to make visual diagrams of water flow for each design.
Video stills of a fluorescent dye experiment for design A2, showing how the dye moves through the topography. These fluorescent dye experiments were used to make visual diagrams of water flow.
Optimal Topographic Forms

Out of the thirty-four designs tested in the second phase of research, our experiments showed that multiple topographies perform equally well in hydraulic terms, but have different ecological potential, as will be discussed later. Using the data from our experiments, we calculated two hydraulic performance metrics: $T_{10}/T_{nc}$ and $C_e/C_0$. The first represents a measure of short-circuiting (the amount of time it takes for 10 percent of the dye to exit the wetland, normalized by the nominal residence time of an empty basin). The second represents the pollutant removal efficiency ($C_e$ is the expected dye concentration at the outlet under steady-state conditions with inlet concentration $C_0$). Unlike $T_{10}/T_{nc}$, a smaller $C_e/C_0$ indicates better performance. In this research, we emphasize the results of the short-circuiting metric $T_{10}/T_{nc}$. For a given topography, $T_{10}/T_{nc}$ is the same at any wetland scale, allowing test results to be directly attributed to full-scale systems. In contrast, $C_e/C_0$ is dependent on the chosen value of reaction rate, which can differ between real systems. As a result, this metric is less reliable for predicting full-scale wetland performance.

Of the topographies tested, all performed better than the control (no topography) based on the short-circuiting $T_{10}/T_{nc}$ metric and twenty-three of them performed better than the serpentine case (for results on each design, see Chapter 4: Topography Design Catalog) (Figure 2.17 on page 32). The top performers were designs C1A.s1 (two rows of similarly sized islands) and I1 (five rows of islands that decrease in size with distance from the inlet) (Figure 2.14 and Figures 2.15 and 2.16 on pages 30–31). While both have identical short-circuiting metrics ($T_{10}/T_{nc} = 0.57 \pm 0.03$), I1 requires three times the earthwork volume of C1A.s1. Thus, designers have choices amongst high-performing cases with more or less earthwork, which may have different impacts on construction cost and habitat creation, as we will see later on in this chapter.

In terms of the pollutant removal metric, $C_e/C_{0}$, again, all of the designs produced greater reductions in concentration than the control, and most were better than the serpentine (Figure 2.18 on page 33). However, the top performers in the $T_{10}/T_{nc}$ metric do not necessarily perform equally well in the $C_e/C_{0}$ metric, which yields an important lesson for topography design. Adding topography subtracts volume from a wetland's potential water storage capacity.

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21. Nominal residence time ($T_n$) is the total water volume a system can hold ($V$) divided by the water inflow rate ($Q$). $T_n = V/Q$. $T_{nc}$ designates the nominal residence time of the control case with no topography (equal to 63 ± 3 seconds), which was used to normalize the results of all other cases to account for their loss of water volume relative to the control.

22. Assuming a first-order reaction with rate constant $k = 1/T_{nc}$. For more information on these metrics and results, see Celina Balderas Guzmán et al. "Island Topographies to Reduce Short-Circuiting in Stormwater Detention Ponds and Treatment Wetlands." Ecological Engineering, 2018.
The residence time distribution (RTD) graph (below) for the control and the serpentine cases compared to the optimal designs I1 and C1A.s1 illustrated in plan (right). The RTD shows the different times that individual parcels of water stay in the wetland. The vertical line designates the nominal residence time of each case. Notice how the peak occurs well before the nominal residence time for the control and serpentine cases.
The two top-performing topographies and all their metrics. Topography volume refers to solid volume of islands. Water flows from bottom left to upper right.

Hydraulic Metrics

\[
\frac{T_{10}}{T_{nc}} = 0.57 \pm 0.03
\]

\[
\frac{C_e}{C_0} = 0.42 \pm 0.03
\]

Topography Volume

1,001 cm³

While more topography helps to reduce short-circuiting, it also means that the water will exit sooner simply because there is less water volume, leading to less pollution treatment. In our experiments, we saw an optimal topography volume of around 1,500 cm³, which corresponded to about 10 percent of the volume of our test basin.\(^{23}\)

Strategically placing a moderate amount of topography will reduce short-circuiting and allow for substantial pollution reduction. Too much topography may minimize short-circuiting but not allow sufficient time for pollution treatment due to the overall

\(^{23}\) This observed optimum assumes a spatially uniform uptake rate; however, wetlands with topographical and vegetative heterogeneity could create spatial variation in pollution removal. In this case, the optimum may shift.

[2.15]
loss of water volume. Wetland engineers and designers must make carefully considered design decisions based on hydraulic goals, balanced with ecological and urban goals as well. Yet, regardless of the goal, the precise design of topography matters. Whether a little or a lot, topography has the potential to negatively impact performance, compared to other designs using equivalent volume. The following section discusses some lessons learned from our experiments about topographical design.

C1 and I1 are top performers relative to the control (no topography) and the serpentine case. Topography volume refers to the solid volume of islands. Water flows from bottom left to upper right.

### Hydraulic Metrics

**Control**

\[
\frac{T_{i}}{T_{c}} = 0.21 \pm 0.01 \\
\frac{C_{i}}{C_{c}} = 0.54 \pm 0.04
\]

**Serpentine**

\[
\frac{T_{i}}{T_{c}} = 0.43 \pm 0.02 \\
\frac{C_{i}}{C_{c}} = 0.48 \pm 0.002
\]

### Topography Volume

**Control**

0 cm$^3$

**Serpentine**

2.148 cm$^3$
$T_{10}/T_{nc}$ results. Higher values indicate better performance. [2.17]
$C_e / C_0$ results. Lower values indicate better performance.  

![Graph showing $C_e / C_0$ vs. Topography Volume [cm$^3$]]
Lessons Learned

The results of our thirty-four experiments show that all islands—even a single one—reduce short-circuiting ($T_{10}/T_{nc}$) and increase pollution removal ($C_e/C_o$) compared to an empty basin. The single island design that performed the best in the short-circuiting metric was S3, which measured one-third of the basin width. Smaller islands (S1 and S5) and wider islands (S4) performed worse than S3. While adding even a single island improves performance relative to an empty basin, adding more islands in strategic ways can dramatically improve performance.

Side Islands
In eight comparative cases, we found that flanking the central island with an additional island on either side improved short-circuiting performance relative to the parent case of a single central island (Figure 2.19). Visually, we observed that the central island helps to split the jet into two segments, while the side islands help to deflect the segments toward an even distribution across the basin, helping to spread the flow more evenly throughout the width of the basin (Figure 2.20 on page 36). Without the side islands, more of the split jet segments ran directly toward the basin walls and then down along the basin walls, creating considerable recirculation in the center of the basin. This central recirculation always occurred except in cases where downstream topography blocked flow through the center, for example; compare C3 versus C3.s2 (Figure 2.21 on page 37).
Table of cases comparing similar designs with and without side islands. With one exception, $T_{10}/T_{nc}$ performance improved with the addition of side islands compared to the parent case (in bold).

<table>
<thead>
<tr>
<th>Design</th>
<th>$T_{10}/T_{nc}$</th>
<th>$\delta (T_{10}/T_{nc})^*$</th>
<th>Topography Volume [cm$^3$]</th>
<th>Topography Volume Percentage Increase from Parent Case (bold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. S1</td>
<td>0.39 $\pm 0.02$</td>
<td>323</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>S1.s1</td>
<td>0.46 $\pm 0.02$</td>
<td>491</td>
<td>152%</td>
<td></td>
</tr>
<tr>
<td>S1.s2</td>
<td>0.52 $\pm 0.04$</td>
<td>803</td>
<td>249%</td>
<td></td>
</tr>
<tr>
<td>2. S2</td>
<td>0.42 $\pm 0.02$</td>
<td>323</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>S2.s1</td>
<td>0.44 $\pm 0.02$</td>
<td>491</td>
<td>152%</td>
<td></td>
</tr>
<tr>
<td>3. S4</td>
<td>0.40 $\pm 0.04$</td>
<td>548</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>S4.s1</td>
<td>0.56 $\pm 0.04$</td>
<td>716</td>
<td>131%</td>
<td></td>
</tr>
<tr>
<td>4. S5</td>
<td>0.38 $\pm 0.03$</td>
<td>337</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>S5.s3</td>
<td>0.36 $\pm 0.02$</td>
<td>674</td>
<td>200%</td>
<td></td>
</tr>
<tr>
<td>S5.s4</td>
<td>0.50 $\pm 0.02$</td>
<td>1,010</td>
<td>300%</td>
<td></td>
</tr>
<tr>
<td>5. C1A</td>
<td>0.43 $\pm 0.07$</td>
<td>832</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>C1A.s1</td>
<td>0.57 $\pm 0.03$</td>
<td>1,001</td>
<td>120%</td>
<td></td>
</tr>
<tr>
<td>6. C4</td>
<td>0.46 $\pm 0.02$</td>
<td>1,227</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>C4.s1</td>
<td>0.47 $\pm 0.02$</td>
<td>1,395</td>
<td>114%</td>
<td></td>
</tr>
<tr>
<td>C4.s2</td>
<td>0.50 $\pm 0.03$</td>
<td>1,707</td>
<td>139%</td>
<td></td>
</tr>
<tr>
<td>7. C5</td>
<td>0.46 $\pm 0.04$</td>
<td>1,508</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>C5.s2</td>
<td>0.52 $\pm 0.05$</td>
<td>1,988</td>
<td>132%</td>
<td></td>
</tr>
<tr>
<td>8. C2</td>
<td>0.47 $\pm 0.02$</td>
<td>1,665</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>0.47 $\pm 0.03$</td>
<td>2,235</td>
<td>134%</td>
<td></td>
</tr>
</tbody>
</table>

Exception (identical performance within uncertainty):

<table>
<thead>
<tr>
<th>Design</th>
<th>$T_{10}/T_{nc}$</th>
<th>$\delta (T_{10}/T_{nc})^*$</th>
<th>Topography Volume [cm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>0.45 $\pm 0.04$</td>
<td>436</td>
<td>—</td>
</tr>
<tr>
<td>S3.s1</td>
<td>0.45 $\pm 0.02$</td>
<td>603</td>
<td>138%</td>
</tr>
</tbody>
</table>

$^* \delta (T_{10}/T_{nc})$ denotes the 95% confidence interval
Diagram of circulation patterns in plan view of topography S1 (left) and S1.s1 with small side islands (right). Water flows from top to bottom. Adding side islands improves the evenness of flow.

Fast Flow [—–]
Regular Flow [—–]
Slow Flow [—–]
Eddy [—–]

**S1**

\[ \frac{T_{10}}{T_{\infty}} = 0.39 \pm 0.02 \]
\[ \frac{C}{C_0} = 0.49 \pm 0.004 \]

**S1.s1**

\[ \frac{T_{10}}{T_{\infty}} = 0.46 \pm 0.02 \]
\[ \frac{C}{C_0} = 0.45 \pm 0.02 \]
Diagram of circulation patterns in plan view of topography C3 (left) and C3.s2 with side islands (right). Water flows from top to bottom.

**Fast Flow** [———]

**Regular Flow** [———]

**Slow Flow** [———]

**Eddy** [———]

### C3

\[ \frac{T_{\text{ef}}}{T_{\text{nc}}} = 0.47 \pm 0.02 \]

\[ \frac{C}{C_0} = 0.46 \pm 0.004 \]

### C3.s2

\[ \frac{T_{\text{ef}}}{T_{\text{nc}}} = 0.54 \pm 0.03 \]

\[ \frac{C}{C_0} = 0.48 \pm 0.02 \]
Island Distance

Given that side islands can be beneficial to hydraulic efficiency, three comparative cases showed that the distance between islands in the same row can make a significant difference in performance (Figure 2.22). Smaller distances between islands improved performance compared to larger distances because they help spread the jet more evenly by reducing recirculation zones, or eddies (Figure 2.23).

<table>
<thead>
<tr>
<th>Design</th>
<th>Distance Between Islands [cm]</th>
<th>$T_{10}/T_{nc}$</th>
<th>$\delta (T_{10}/T_{nc})^*$</th>
<th>Percentage Increase in Topography Volume from Parent Case (bold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. S5.s3</td>
<td>8.3</td>
<td>0.36</td>
<td>±0.02</td>
<td>—</td>
</tr>
<tr>
<td>1. S5.s4</td>
<td>2.3</td>
<td>0.50</td>
<td>±0.02</td>
<td>150%</td>
</tr>
<tr>
<td>2. S1.s1</td>
<td>7.0</td>
<td>0.46</td>
<td>±0.02</td>
<td>—</td>
</tr>
<tr>
<td>2. S1.s2</td>
<td>2.0</td>
<td>0.52</td>
<td>±0.02</td>
<td>164%</td>
</tr>
<tr>
<td>3. C4.s1</td>
<td>6.3</td>
<td>0.47</td>
<td>±0.02</td>
<td>—</td>
</tr>
<tr>
<td>3. C4.s2</td>
<td>1.5</td>
<td>0.50</td>
<td>±0.03</td>
<td>122%</td>
</tr>
</tbody>
</table>

* $\delta (T_{10}/T_{nc})$ denotes the 95% confidence interval
Diagram of circulation patterns in plan view of topography S5.s3 (left) and S5.s4 (right), where the latter has a smaller distance between the islands. Water flows from top to bottom. S5.s4 has better hydraulic performance than S5.s3.

\[ T_{10} / T_{nc} = 0.36 \pm 0.02 \]
\[ C_e / C_0 = 0.52 \pm 0.03 \]

\[ T_{10} / T_{nc} = 0.50 \pm 0.02 \]
\[ C_e / C_0 = 0.43 \pm 0.01 \]
$T_{io}/T_{nc}$ performance relative to number of rows of islands. Higher values indicate better performance.

$T_{io}/T_{nc}$
$C_e/C_0$ performance relative to number of rows of islands. Lower values indicate better performance. [2.25]
Island Rows

The B-series of designs explores the impact of adding rows of islands, whereby each additional row features smaller islands that help to further split and widen the jet. The $T_{10}/T_{nc}$ results suggest that less is more (Figure 2.24 on page 40). B4, the case with only two rows, performs much better than its sibling cases with three, four, and five rows (B1, B2, and B3 respectively) (Figure 2.26). In fact, B1, B2, and B3 have nearly equivalent performance. This finding suggests that while the additional rows may help to further split the jet, they may also occupy more volume, which is detrimental to overall residence time. Strategically placing islands is more important to short-circuiting performance than the total number of islands.

Plan view of B-series designs with performance metrics below.

<table>
<thead>
<tr>
<th>Design</th>
<th>$T_{10}/T_{nc}$</th>
<th>$C_e/C_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.47 ± 0.03</td>
<td>0.51 ± 0.01</td>
</tr>
<tr>
<td>B2</td>
<td>0.44 ± 0.05</td>
<td>0.45 ± 0.01</td>
</tr>
<tr>
<td>B3</td>
<td>0.47 ± 0.02</td>
<td>0.52 ± 0.01</td>
</tr>
<tr>
<td>B4</td>
<td>0.55 ± 0.07</td>
<td>0.46 ± 0.02</td>
</tr>
</tbody>
</table>
Merging Islands

Cases B3 and I1 are identical except for the fact that I1 merges islands across two rows together to create two larger triangular islands. This change significantly improves $T_{10}/T_{nc}$ performance from 0.47 for B3 to 0.57 for I1, with an additional 8 percent in topography volume. The improvement is likely because the large merged islands take up volume that was previously a stagnant zone, helping water to move more efficiently and creating more habitat in the process (Figure 2.27).

Diagram of circulation patterns in plan view of topography B3 (left) and I1 (right), where I1 is identical to B3 except islands in the middle are merged to form large, triangular islands. Water flows from top to bottom. Merging islands in places with little water flow optimizes hydraulic efficiency.

\[ \begin{align*}
\text{B3} & \quad T_{10}/T_{nc} = 0.47 \pm 0.02 \\
& \quad C/C_0 = 0.52 \pm 0.01 \\
\text{I1} & \quad T_{10}/T_{nc} = 0.57 \pm 0.03 \\
& \quad C/C_0 = 0.45 \pm 0.01
\end{align*} \]
Streamline Shape

In all of the designs, we use a streamline shape for the islands, whereby the width of the island narrows to form a tail. Streamline shapes keep the flow from separating from the sides of the islands, and the added slope contributes more emergent and submersed vegetative habitat. We explicitly tested the effect of the streamline shape by considering the same topography in two orientations; the first used the streamline shape with the widest part of the islands facing toward the inlet (A1), and the second used the opposite of a streamlined shape, with the tails facing toward the inlet (A1-Reversed) (Figure 2.28). A1, with the streamlined islands, clearly performed better than the backwards islands, with a $T_{10}/T_{nc}$ of 0.41 compared to 0.57. Notably, A1-Reversed performed the worst of all cases in terms of pollutant removal ($C_r/C_o$), even worse than the control. When islands have a streamlined shape with the widest part facing the flow, the tapering tail of the islands promotes spreading of the jet as the flow widens to follow the streamline form. Ideally, streamline shapes have an optimal width divided by length of roughly 0.25 or side angles of 7 to 10 degrees.24

Diagram of circulation patterns in plan view of topography A1 (left) and A1-Reversed (right), where the latter is identical to A1 but rotated 180°. Water flows from top to bottom. A1 performs significantly better than A1-Reversed because the streamline shape optimizes jet spreading.

A1
\[
\frac{T}{T_{n0}} = 0.41 \pm 0.02
\]
\[
\frac{C}{C_0} = 0.51 \pm 0.01
\]

A1-Reversed
\[
\frac{T}{T_{n0}} = 0.37 \pm 0.02
\]
\[
\frac{C}{C_0} = 0.57 \pm 0.01
\]
Construction Costs

To understand the implications of each design for construction, we calculated construction costs for each of the thirty-four designs. Specifically, we calculated the earthwork cost (excavation, rough grading, and fine grading) for each design on a theoretical site at field scale.\(^{25}\) While we hoped that construction costs would differentiate designs, instead we found that earthwork costs are nearly equivalent across the thirty-four designs.

**Earthwork Cost**

We chose to focus on earthwork costs because other costs, such as site preparation (clearing and grubbing or dewatering a wet site), would apply to any design and are dependent on the particular characteristics of a real site. We also assume that landscape architects would balance the cut and fill from the wetland basin by creating other topographic features on site, if necessary, so that hauling excess soil is not an added cost. We also did not include erosion control materials, such as gabions or coir netting, because the choice of material and quantity depends on flow rates and soils, and may not need to be applied to all islands uniformly (Figure 2.29). Finally, we did not include maintenance costs because these are also site-dependent. Yet we do acknowledge that designs may incur different, and currently unknown, maintenance costs. These costs are a significant part of operating a constructed wetland or detention pond.

The cost calculations were performed for each design as one modular element measuring approximately 21 meters wide by 47 meters long (68 feet by 155 feet) with a water depth of about 0.8 meters (2.5 feet), without vertically exaggerated slopes. Because the designs are modular and scalable, in reality, the number of modular elements and their chosen field scale would be unique to each project. With the input of Mark Lindley, Senior Engineer with Environmental Science Associates, we calculated the earthwork costs as comprising the sum of excavation, two passes of rough grading, and one pass of fine grading (Figure 2.30). Costs represent a US average in dollars.

Potential materials for erosion control.

Coir Netting

Gabions

Cost parameters used in earthwork cost calculation. References below.

1. Excavation
   - Removal of earth within area not comprising islands
   - Using a dozer (80 horsepower, 50' haul) on an open site with clay soil
   - $5.60 per cubic yard

2. Rough Grading
   - Two passes over the surface area of islands
   - Using a dozer on a site 8,100–10,000 square feet
   - $0.16 per square foot for each pass

3. Finish Grading
   - One pass over the entire site surface area
   - Using a dozer on a site 8,100–10,000 square feet
   - $0.21 per square yard for each pass

References:


Results

The average earthwork cost was about $7,500 (US average) for any design implemented at the field scale of 21 by 47 meters (68 by 155 feet) with a water depth of 0.8 meters (2.5 feet) (Figure 2.31). The costs did not vary significantly across the thirty-four designs, ranging from $7,369 (Serpentine) to $7,823 (A1). To find the cost

![Earthwork cost results plotted with $T_{1d}/T_{nc}$ performance.](image)
of a specific design, see Chapter 4: Topography Design Catalog. The costs were roughly equivalent for all designs because of the trade-off between excavation and island creation. Specifically, the topographies with fewer islands required more excavation and less grading, while the designs with more islands required less excavation but more grading. Thus, it is possible that earthwork cost is not a major differentiating factor between designs, but other costs such as erosion control materials or maintenance may have significant cost implications.

**Constructability**

While it may seem that these complex island forms would be difficult to build, there is already a precedent for a similarly intricate landscape. In Sweden, the design firm Snøhetta built the landscape surrounding the MAX IV Laboratory to serve performative, ecological, and public space functions. The 19-hectare (47-acre) landscape is composed of a radial array of mounds increasing in size, designed to dampen ground vibrations from an adjacent road (a function needed to avoid disrupting the laboratory’s sensitive equipment) (Figure 2.32 on page 50). The mounds are planted with native meadow species and function as a public park (Figure 2.33 on page 51). Ponds provide stormwater storage on site. This landscape was built in six months with a 3D model loaded onto GPS-guided bulldozers, which efficiently moved earth displaced by the laboratory building construction to create the mounds. New advances in construction technology will continue to render such complex landscapes increasingly feasible.

**Operation and Maintenance**

Cities face a learning curve with operating and maintaining landscape infrastructure. The skills, equipment, and knowledge required to care for storm pipes and treatment plants is different than those required to care for dynamic wetland and pond landscapes. Cities have run on the former model for many decades; thus, there is less precedent and knowledge for the maintenance of green infrastructure. Although cities are interested in stormwater wetlands, they are also hesitant to build such projects because of negative perceptions and the economic and political risk involved with building a new infrastructural type. More pilot projects and monitoring are needed.

---

Aerial view of Snøhetta's mound landscape for the MAX IV Laboratory in Sweden.
On-the-ground view of the mounds, planted with local meadow species, at the MAX IV Laboratory.
Habitat Diversity Index

Habitat heterogeneity supports biodiversity, which underlies the provision of ecosystem services. Heterogeneity in landscape is key to creating habitat. The EPA recommends eschewing rectangular basins in favor of sinuous edges, and using varied slopes and grades to create different water depths. Other researchers have noted the contribution of topography in constructed wetlands to habitat diversity and species richness. In mitigation wetlands, microtopography has also been found to aid nitrogen cycling and removal.

To measure the heterogeneity of each design, we calculated the amount of surface area in each design that falls into four possible habitats corresponding to water depth: upland (above water), emergent (between 0 to 30 centimeters or 0 to 12 inches), submergent (between 30 to 46 centimeters or 12 to 18 inches), and open water (greater than 46 centimeters or 18 inches) (Figure 2.34). As with construction costs, each design was scaled to approximately 21 meters wide by 47 meters long (68 feet by 155 feet) with a water depth of about 0.8 meters (2.5 feet). Using the Shannon-Weaver entropy measure, we created...
an index that scores each design (Figure 2.36 on page 54). Because there are four habitats, the maximum possible index score is 1.39. The minimum score is zero, which corresponds to a design with only one habitat. The control, a basin with no topography, scores zero because it only has open water habitat.

The conventional serpentine design scores 0.77. The highest scoring design was I1 (0.99), which also has the largest island volume. Naturally, designs with more island volumes create more habitat because they add area to the upland, emergent, and submergent zones. As discussed in the previous sections, since earthwork cost is roughly equivalent amongst designs, I1 is the optimum choice in terms of habitat diversity. However, in order to accommodate more solid volume, I1 gives up water volume. As a result, there is a tradeoff between water storage volume and habitat creation for a given maximum water depth.

Wildlife at the Ballona Wetlands in Los Angeles, California.
Results of the habitat diversity index for all thirty-four tested designs.

\[ T_{10} / T_{nc} \]
Modularity & Scaling

The topographies are adaptable to different contexts because they are modular and scalable. This feature means the size and number of landforms can be controlled as needed to accommodate local factors such as low or high rainfall amounts or the size of a site. This flexibility in form is also the key to how our designs are able to create public spaces, as discussed in the next chapter, Wetland Urbanism.

The 40.5 cm by 60.0 cm (16 inch by 24 inch) physical models we constructed for testing represent a scaled-down version of the landforms that would be built in a real project. Thus, our designs can be scaled to any size needed in the field, so long as the inlet size and flow rate are also proportionately scaled. Modularity means that each topography can be repeated as many times as necessary to span the width of a wetland or pond, with each module receiving water from a manifold inlet pipe. For example, for a wetland with a desired water depth of 0.8 meters (2.5 feet), each topography would represent 21 meters wide by 47 meters long (68 feet by 155 feet). If the basin was about 42 meters (140 feet) wide, then two island topographies could be constructed side by side within the same basin (Figure 2.37 on page 56).

If instead a water depth of 1.5 meters (5 feet) is desired in the 42 meter (140 feet) wide basin, then one topography would therefore scale to 42 meters wide by 94 meters long (137 feet by 310 feet). In this case, only one topography module would be necessary to span the basin width (Figure 2.38 on page 57). By scaling and repeating topographies appropriately, these designs can be adapted to manage more or less water depending on local climate. Moreover, the choice of topography can also serve to balance the specific hydraulic, ecologic, and urban goals of local projects.

For any given basin width, using a topography design at a larger scale entails fewer modules across the width of the basin. The resulting islands are larger and deeper (see below). At the outlet to a cell, a deep zone (right) or inverse islands (opposite) could be used to reset the water flow.

[2.37] **Large-Scale Islands**

Used at a larger scale, the islands are larger and the water deeper. At a larger scale, the designs promote water storage.
For any given basin width, using a topography design at a smaller scale entails more modules across the width of the basin. The resulting islands are smaller and shallower (see below), which would be conducive to wetland habitat. At the outlet to a cell, a deep zone (opposite) or inverse islands (right) could be used as a transition between cells.

[2.38] **Small-Scale Islands**

Using a design at a smaller scale, the islands are smaller and shallower. At a smaller scale, the designs promote wetland habitat.
Chapter 3
Wetland Urbanism

In the late nineteenth century, Frederick Law Olmsted designed and built large-scale hydrological landscapes that contributed as much to water treatment as to the creation of dynamic public realms. Olmsted designed landscapes with careful integration of water flows, vegetation patterns, views, circulation, and public spaces. Many of the places Olmsted’s projects were implemented in, however, were relatively undeveloped or not fully urbanized. Urbanists and landscape architects today work in contextually constrained, highly regulated sites where adjacent development restricts design options. For this reason, designers could benefit from a wetland framework that is adaptable for different site size, use, and programming goals. The adaptability of the topographic designs in this report—the modularity and scalability—allows designers tremendous flexibility to embed urban functionality and public spaces into wetland sites.

This chapter presents a framework for assembling functional wetland sites with urban programming using the topographies as building blocks. It describes how a site can be organized to fit the local context, retrofitted with performative wetland topography, and programmed for public use. At the site scale, wetlands can be designed as public space. At the urban scale, wetlands must be stitched together to reclaim destroyed hydrological gradients, critical habitats, and biodiversity lost to urban development. To illustrate these concepts, we use the Taylor Yard site in Los Angeles, California (Figures 3.1–3.3 on pages 60–61), and the Buffalo Bayou site in Houston, Texas (Figures 3.4–3.6 on pages 62–63).
Taylor Yard site with local landmarks.

Site Area: 46 acres

Los Angeles: Taylor Yard

[3.1]
Taylor Yard site and urban context in Los Angeles, California.

Los Angeles River

Taylor Yard Site

South to Downtown

Aerial view of Taylor Yard looking south.
Buffalo Bayou site with local landmarks.

Site Area: 46 acres

[3.4] **Houston: Buffalo Bayou**
Buffalo Bayou site and context in Houston, Texas.

Aerial view of Buffalo Bayou looking south toward downtown Houston.
Site Organization

Stormwater volumes can vary tremendously throughout the year in many cities. For this reason, we suggest that urban wetland sites bifurcate incoming stormwater flows into two distinct channels where water can flow in parallel: a “wetland” and a “floodplain” channel. The relative sizes of these channels reflect local stormwater patterns. The wetland channel is smaller, but receives steady water flows throughout the year that correspond to a city’s low-flow stormwater volumes. By providing moderated flows, the wetland channel is shielded from drastic changes in water volumes that disrupt the ecosystem, allowing a protected wetland habitat to flourish. The creation of a wetland channel is an opportunity to create high-quality wetland habitat, which is extremely rare in all urban contexts. In contrast, the floodplain channel is the larger and more hardened channel that accommodates storm volumes, protecting adjacent development from periodic flooding. The floodplain channel experiences more severe changes in water flow. For example, in Los Angeles the floodplain channel will be dry most of the year except in large winter storms. The creation of the floodplain channel is an opportunity to use that space for urban programs during dry periods.

Next, the wetland and floodplain channel lengths are split into at least three sequential cells that allow water flows to “reset.” As discussed in the last chapter, water has a tendency to short-circuit. Over time, vegetation growth patterns reinforce short-circuited paths in a positive feedback loop. Segmenting the channels into cells dampens this process. A cell is composed of an inlet and outlet. Instead of using engineered structures such as culverts, we create outlets by mirroring our topography designs to recollect water instead of dispersing it. Thus, the changeover points between one cell to the next are a dense collection of mirrored islands that span the width of a site. These island corridors form the backbone of programmable open space and circulation (Figures 3.8 and 3.9 on pages 66–69).
Cross sections through Taylor Yard and Buffalo Bayou sites showing potential relative differences between wetland and floodplain channels given local rainfall amounts and seasonality.

Los Angeles: Taylor Yard

Houston: Buffalo Bayou
Site organization diagram (below) for Taylor Yards site in Los Angeles, California with individual layered components (left).
Site organization diagram (below) for Buffalo Bayou site in Houston, Texas, with individual layered components (left).

[3.9] **Houston: Buffalo Bayou**

- Interstate 69
- Bruce Elementary School
- Bayou Greenway
- Elysian Street
- Clayton Homes
  Houston Housing Authority
- Buffalo Bayou
Island Corridors

The island corridors allow a primary circulation system of flexible bridges to form across a wetland site. Connectivity across a wetland site helps to integrate it with its urban surroundings. These corridors can carry pedestrian trails or small roads through a combination of bridging across wet channels and following the softly undulating upland landscape. The starting and ending points of island corridors can connect existing streets and destination points around the wetland site. Because the length and shape of the channels and cells is flexible, the overall design of the hydrologic wetland system can respond to the surrounding urban fabric (Figures 3.8 and 3.9 on pages 66–69).

From the primary spine, smaller circulation paths branch out into other parts of the wetland as dictated by programmable topography. These smaller paths create access routes to public programs around the site, such as habitat areas or recreational spaces specifically adapted for those topographic conditions and wetness gradients. Overall site circulation resembles a dendritic gradient, where wide and narrow paths offer diverse ways to connect with water (Figure 3.11 on pages 74–75).
Programmable Topography

Each island’s location and elevation creates a unique palette for design using proximity to water, gradients of wetness and dryness, varied slopes, and vegetation patterns. These characteristics also result in specific habitat and programming opportunities, which can be accentuated by a designer’s choice of materials, such as earth, gabions, or pavers. Crossing steepness (steep, moderate, flat) with proximity to water (wet, semi-wet, dry) and size of slope yields a matrix of programming opportunities for people and nature (Figure 3.10 on page 73 and 3.11 on pages 74–75).

New Habitats
- Deep Pond
- Emergent Wetland
- Upland Forest
- Upland Grassland
- Urban Gardens
- Riparian Corridor

Public Programming
Public Spaces
- Event Spaces
- Playgrounds
- Picnic Areas
- Community Agriculture
- Amphitheater
- Pedestrian trails

Recreation
- Sports Fields
- Golf Courses
- Mountain Biking Trails
- Kayaking
- Hiking
- Skate Park
- Birdwatching
- Fishing
Multiple programs are possible across larger wetlands and topographies, and certain habitats can be increased according to needs of target species across regional locations. Designers have great flexibility in modifying the terrain to achieve urban and ecological goals (Figures 3.12–3.15 on pages 76–91). The deployment of island topography allows for creative rebalancing of cut and fill volumes, which should be used to accentuate programming opportunities. For example, a small hill can be created as a viewing platform over the entire site, or a large, inaccessible island can be created exclusively for wildlife.

Designers also have leeway in the precise design of islands. As discussed in the previous chapter, hydrologic functionality is not compromised so long as the overall configuration of islands remains intact. Thus, designers have control over the precise sculpting of island shapes and slopes. For example, an island in a floodplain channel can be terraced as an amphitheater (Figure 3.13 on pages 82–83). Maintaining an overall rhythm and coherent design language throughout the site helps to create a sense of order, while allowing “messier” natural processes space to evolve on the tops or lowlands of islands (Figure 3.15 on pages 90–91). Providing an orderly frame for ecologically rich landscapes improves public acceptance.32

Most importantly, introducing a new complex terrain increases the level of landscape heterogeneity that has been significantly reduced or removed in the modern urban landscape, by providing distinct habitats and microclimates. It is also beneficial for people, who can enjoy a wide offering of urban programs and experiences that increase awareness of urban rainfall cycles and the buffering role of the landscape in mitigating flooding and decreasing water pollution.

Matrix of programming opportunities shows how a variety of programs and habitats are possible given particular conditions of steepness (steep, moderate, flat) and proximity to water (wet, semi-wet, dry).

Diagrammatic plan (overleaf).
Chapter 3

Wetland Urbanism

Wetland Channel | Recreational Corridor | Existing Urban Fabric
SEM-I-WET       | SEMI-DRY              | ALWAYS DRY
Los Angeles: Taylor Yard

Taylor Yard diagrammatic site section showing wetland topography and programmed public spaces.

← Elysian Valley Neighborhood

Blake Avenue
Commercial Area
Los Angeles River Floodplain Channel

Existing Grade

Event Space

Flood Water Level

Los Angeles River

Floodplain Channel
Riverside Trail

Event Space

Skate Park

Floodplain Channel
Rendering of a new edge to the Los Angeles River created by the floodplain channel with programmed public spaces (overleaf).
Houston: Buffalo Bayou

Buffalo Bayou diagrammatic site section showing wetland topography and programmed public spaces.

← Downtown Houston

Clayton Homes
Houston Housing Authority

Trail

Riparian Zone  Buffalo Bayou
Rendering of Houston wetland channel showing ecological wetland, conservation areas, and recreational trails (overleaf).
Conclusion

As the frequency and intensity of rain events continues to increase as a result of climate change, cities must reintroduce the absorptive, wet landscapes that have been continually displaced by urban development in order to buffer these recurrent threats. Although constructed wetlands and detention basins have long been used to manage urban stormwater, their design has been largely driven by hydrologic performance alone.

By merging fluid dynamics, landscape architecture, and urban design, these guidelines offer important strategies for creating a new type of urban wetland that weaves together hydraulic performance, ecological function, and urban programming to manage flooding, add resilience, improve water quality, enhance biodiversity, and create valuable public amenities.
Topography
Design Catalog

For reference, the following pages catalog the design and data for each of the thirty-four designs tested in the Nepf Environmental Fluid Mechanics Lab.

A1 __________________________ 96
A1-Reversed ____________________ 98
A2 ___________________________ 100
B1 ___________________________ 102
B2 ___________________________ 104
B3 ___________________________ 106
B4 ___________________________ 108
B5 ___________________________ 110
C1 ___________________________ 112
C1A __________________________ 114
C1A.s1 _______________________ 116
C2 ___________________________ 118
C3 ___________________________ 120
C3.s2 _________________________ 122
C4 ___________________________ 124
C4.s1 _________________________ 126
C4.s2 _________________________ 128
C5 ___________________________ 130
C5.s2 _________________________ 132
I1 ___________________________ 134
S1 ___________________________ 136
S1.s1 _________________________ 138
S1.s2 _________________________ 140
S2 ___________________________ 142
S2.s1 _________________________ 144
S3 ___________________________ 146
S3.s1 _________________________ 148
S4 ___________________________ 150
S4.s1 _________________________ 152
S5 ___________________________ 154
S5.s3 _________________________ 156
S5.s4 _________________________ 158
Serpentine ______________________ 160
Control ______________________ 162
Summary of Results ___________ 164
A1

A1 has five rows of identical islands arranged in an offset pattern. Water flows from bottom left to upper right.

[4.1]

Residence time distribution derived from experimental results.

[4.2]
Longitudinal section. Water flows from left to right. [4.3]

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom. [4.4]

### Hydraulic Metrics

- $T_{10} = 29$ s
- $T_{det} = 45$ s
- $T_n = 52$ s
- $T_{10}/T_n = 0.41 \pm 0.02$
- $C_c/C_0 = 0.51 \pm 0.01$

### Earthwork Cost

$7,823$

### Habitat Diversity Index

0.93

- Upland Area: 9%
- Emergent Area: 13%
- Submergent Area: 8%
- Open Water Area: 70%

### Topography Volume

$2,980$ cm$^3$
A1-Reversed

A1-Reversed is similar to A1 but rotated 180° so that the tail of the islands faces the flow. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

Hydraulic Metrics

\[ T_{10} = 23 \text{ s} \]
\[ T_{det} = 38 \text{ s} \]
\[ T_n = 46 \text{ s} \]
\[ T_{10} / T_n = 0.37 \pm 0.02 \]
\[ C_e / C_0 = 0.57 \pm 0.01 \]

Earthwork Cost
$7,823

Habitat Diversity Index
0.93

Upland Area: 9%
Emergent Area: 13%
Submergent Area: 8%
Open Water Area: 70%

Topography Volume
2,980 cm³
A2 has three rows of identical islands arranged in an offset pattern. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

Hydraulic Metrics
- $T_{10} = 36$ s
- $T_{det} = 60$ s
- $T_n = 56$ s
- $T_{10}/T_n = 0.55 \pm 0.03$
- $C_e/C_0 = 0.41 \pm 0.01$

Earthwork Cost
- $7,653$

Habitat Diversity Index
- 0.59
- Upland Area: 5%
- Emergent Area: 6%
- Submergent Area: 4%
- Open Water Area: 85%

Topography Volume
- 1,446 cm³
B1 has three rows of islands with larger islands in the first two rows. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

Hydraulic Metrics
- $T_{10} = 28$ s
- $T_{det} = 45$ s
- $T_n = 47$ s
- $T_{10}/T_n = 0.47 \pm 0.03$
- $C_e/C_o = 0.51 \pm 0.01$

Earthwork Cost
$7,517$

Habitat Diversity Index
0.79
- Upland Area: 10%
- Emergent Area: 8%
- Submergent Area: 5%
- Open Water Area: 77%

Topography Volume
2,235 cm$^3$
B2 adds an extra row to B1. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.

![Diagram of water flow and residence time distribution](image)

[4.21] Residence time distribution derived from experimental results.

[4.22]
Longitudinal section. Water flows from left to right. [4.23]

Plan view. Water flows from top to bottom. [4.24]

Hydraulic Metrics

\[
\begin{align*}
T_{10} &= 32 \text{ s} \\
T_{det} &= 54 \text{ s} \\
T_n &= 50 \text{ s} \\
\frac{T_{10}}{T_n} &= 0.44 \pm 0.02 \\
\frac{C}{C_0} &= 0.45 \pm 0.01
\end{align*}
\]

Earthwork Cost

$7,606

Habitat Diversity Index

0.90

Upland Area: 11%
Emergent Area: 11%
Submergent Area: 7%
Open Water Area: 72%

Topography Volume

2,733 cm³
B3 adds an extra row to B2 with narrower islands. Water flows from bottom left to upper right. [4.25]

Residence time distribution derived from experimental results. [4.26]
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

**Hydraulic Metrics**

\[ T_{T_0} = 29 \text{ s} \]
\[ T_{det} = 43 \text{ s} \]
\[ T_{n} = 44 \text{ s} \]
\[ T_{T_0} / T_{n} = 0.47 \pm 0.02 \]
\[ C_e / C_0 = 0.52 \pm 0.01 \]

**Earthwork Cost**

$7,673

**Habitat Diversity Index**

0.96

- Upland Area: 12%
- Emergent Area: 12%
- Submergent Area: 7%
- Open Water Area: 68%

**Topography Volume**

2,999 cm³
B4 contains two rows of large islands. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

Hydraulic Metrics
\[ T_{10} = 35 \text{ s} \]
\[ T_{det} = 52 \text{ s} \]
\[ T_{n} = 54 \text{ s} \]
\[ T_{10} / T_{n} = 0.55 \pm 0.03 \]
\[ C_e / C_0 = 0.46 \pm 0.04 \]

Earthwork Cost
$7,426

Habitat Diversity Index
0.59

Upland Area: 7%
Emergent Area: 5%
Submergent Area: 3%
Open Water Area: 84%

Topography Volume
1,576 cm$^3$
B5 features a second row of elongated islands. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Hydraulic Metrics

- $T_{t0} = 36 \text{ s}$
- $T_{det} = 51 \text{ s}$
- $T_n = 53 \text{ s}$
- $T_{t0} / T_n = 0.54 \pm 0.03$
- $C / C_0 = 0.46 \pm 0.02$

Earthwork Cost

$7,452$

Habitat Diversity Index

0.71

- Upland Area: 9%
- Emergent Area: 7%
- Submergent Area: 4%
- Open Water Area: 80%

Topography Volume

2,037 cm$^3$
C1

C1 is similar to B4 except without side islands in the first row. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics
\[ T_{10} = 28 \text{ s} \]
\[ T_{det} = 58 \text{ s} \]
\[ T_n = 57 \text{ s} \]
\[ T_{10} / T_n = 0.43 \pm 0.02 \]
\[ C_e / C_o = 0.45 \pm 0.03 \]

Earthwork Cost
$7,453

Habitat Diversity Index
0.46

Upland Area: 5%
Emergent Area: 4%
Submergent Area: 2%
Open Water Area: 89%

Topography Volume
1,096 cm³
C1A

C1A has the same island layout as C1 except with narrower islands. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics

\[ T_{10} = 26 \text{ s} \]
\[ T_{det} = 51 \text{ s} \]
\[ T_n = 58 \text{ s} \]
\[ T_{10}/T_n = 0.43 \pm 0.02 \]
\[ C_e/C_0 = 0.50 \pm 0.08 \]

Earthwork Cost

$7,478

Habitat Diversity Index

0.38

Upland Area: 4%
Emergent Area: 3%
Submergent Area: 2%
Open Water Area: 92%

Topography Volume

832 cm³
C1A.s1 adds side islands to the first row of C1A. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

**Hydraulic Metrics**

- $T_{10} = 35$ s
- $T_{det} = 60$ s
- $T_n = 56$ s
- $T_{10} / T_n = 0.57 \pm 0.03$
- $C_e / C_0 = 0.42 \pm 0.03$

**Earthwork Cost**

$7,490$

**Habitat Diversity Index**

0.44

- Upland Area: 4%
- Emergent Area: 4%
- Submergent Area: 2%
- Open Water Area: 90%

**Topography Volume**

1,001 cm$^3$
C2 features three rows of islands. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics
\[ T_{\text{IO}} = 30 \text{ s} \]
\[ T_{\text{det}} = 54 \text{ s} \]
\[ T_{\text{n}} = 53 \text{ s} \]
\[ T_{\text{io}} / T_{\text{n}} = 0.47 \pm 0.02 \]
\[ C_e / C_0 = 0.45 \pm 0.01 \]

Earthwork Cost
$7,543

Habitat Diversity Index
0.63

Upland Area: 7%
Emergent Area: 6%
Submergent Area: 4%
Open Water Area: 83%

Topography Volume
1,665 cm³
C3 eliminates the outermost islands in the third row in C2. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.

[4.55] C3

[4.56] Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

**Hydraulic Metrics**

\[ T_{10} = 32 \text{ s} \]
\[ T_{det} = 55 \text{ s} \]
\[ T_n = 57 \text{ s} \]
\[ T_{10}/T_n = 0.47 \pm 0.02 \]
\[ C_e/C_0 = 0.46 \pm 0.004 \]

**Earthwork Cost**

$7,511

**Habitat Diversity Index**

0.59

Upland Area: 6%
Emergent Area: 6%
Submergent Area: 3%
Open Water Area: 85%

**Topography Volume**

1,508 cm³
C3.s2

C3.s2 adds side islands to the first row of C3. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Topography Design Catalog

Chapter 4

Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

Hydraulic Metrics

\[ T_{10} = 32 \text{ s} \]
\[ T_{det} = 50 \text{ s} \]
\[ T_{n} = 50 \text{ s} \]
\[ T_{10}/T_{n} = 0.54 \pm 0.03 \]
\[ C/C_{0} = 0.48 \pm 0.02 \]

Earthwork Cost

$7,481

Habitat Diversity Index

0.71

Upland Area: 9%
Emergent Area: 7%
Submergent Area: 4%
Open Water Area: 80%

Topography Volume

1,988 cm³
C4 features a small central island in the third row. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics

- $T_{10} = 31$ s
- $T_{det} = 57$ s
- $T_n = 58$ s
- $T_{10}/T_n = 0.46 \pm 0.02$
- $C/C_0 = 0.44 \pm 0.01$

Earthwork Cost

$7,473$

Habitat Diversity Index

0.50

- Upland Area: 5%
- Emergent Area: 4%
- Submergent Area: 3%
- Open Water Area: 88%

Topography Volume

1,227 cm$^3$
C4.s1

C4.s1 adds small side islands to C4. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.

[4.69]

[4.70]
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics
\[
\begin{align*}
T_{10} &= 34 \text{ s} \\
T_{det} &= 63 \text{ s} \\
T_n &= 62 \text{ s} \\
T_{10}/T_n &= 0.47 \pm 0.02 \\
C_e/C_0 &= 0.41 \pm 0.02
\end{align*}
\]

Earthwork Cost
$7,486

Habitat Diversity Index
0.55

Upland Area: 6%
Emergent Area: 5%
Submerged Area: 3%
Open Water Area: 86%

Topography Volume
1,395 cm$^3$
C4.s2

C4.s2 adds larger side islands to C4. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics

\[ T_{10} = \text{31 s} \]
\[ T_{det} = \text{54 s} \]
\[ T_n = \text{55 s} \]
\[ T_{10} / T_n = 0.50 \pm 0.03 \]
\[ C_e / C_0 = 0.45 \pm 0.02 \]

Earthwork Cost

$7,444

Habitat Diversity Index

0.63

Upland Area: 8%
Emergent Area: 6%
Submergent Area: 3%
Open Water Area: 83%

Topography Volume

1,707 cm³
C5 creates an open area in the center by pulling out a central island. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

**Hydraulic Metrics**

\[ T^{10} = 29 \text{ s} \]

\[ T^{det} = 57 \text{ s} \]

\[ T^n = 55 \text{ s} \]

\[ T^{10}/T^n = 0.46 \pm 0.02 \]

\[ C/e C_0 = 0.45 \pm 0.01 \]

**Earthwork Cost**

$7,511$

**Habitat Diversity Index**

0.59

- Upland Area: 6%
- Emergent Area: 6%
- Submergent Area: 3%
- Open Water Area: 85%

**Topography Volume**

1,508 cm$^3$
C5.s2

C5.s2 adds side islands to C5. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right. [4.83]

Plan view. Water flows from top to bottom. [4.84]

Hydraulic Metrics

- $T_{T_{10}} = 34$ s
- $T_{T_{det}} = 50$ s
- $T_n = 53$ s
- $\frac{T_{T_{10}}}{T_n} = 0.52 \pm 0.02$
- $C_e/C_0 = 0.48 \pm 0.04$

Habitat Diversity Index

- 0.71
- Upland Area: 9%
- Emergent Area: 7%
- Submergent Area: 4%
- Open Water Area: 80%

Earthwork Cost

- $7,481$

Topography Volume

- $1,988$ cm$^3$
I1 has five rows of progressively smaller islands and the second and third rows are merged to create larger islands. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

### Hydraulic Metrics

- $T_{10} = 36$ s
- $T_{det} = 52$ s
- $T_n = 42$ s
- $T_{10}/T_n = 0.57 \pm 0.03$
- $C_e/C_e^0 = 0.45 \pm 0.01$

### Earthwork Cost

$7,560$

### Habitat Diversity Index

0.99

Upland Area: 14%
Emergent Area: 12%
Submergent Area: 7%
Open Water Area: 67%

### Topography Volume

3,181 cm$^3$
S1 features one narrow, central island that is 40% wider than the inlet. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

Hydraulic Metrics

\[ T_{10} = 26 \text{ s} \]
\[ T_{det} = 52 \text{ s} \]
\[ T_n = 62 \text{ s} \]
\[ T_{10} / T_n = 0.39 \pm 0.02 \]
\[ C_f / C_0 = 0.49 \pm 0.004 \]

Earthwork Cost

$7,473

Habitat Diversity Index

0.18

- Upland Area: 2%
- Emergent Area: 1%
- Submergent Area: 1%
- Open Water Area: 97%

Topography Volume

323 cm³
S1.s1

S1.s1 adds small side islands to S1. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

Hydraulic Metrics

- $T_{t_0} = 28$ s
- $T_{det} = 57$ s
- $T_n = 58$ s
- $T_{t_0} / T_n = 0.46 \pm 0.02$
- $C/C_0 = 0.45 \pm 0.02$

Earthwork Cost

$7,485$

Habitat Diversity Index

0.25

Upland Area: 2%
Emergent Area: 2%
Submergent Area: 1%
Open Water Area: 95%

Topography Volume

491 cm$^3$
S1.s2

S1.s2 adds large side islands to S1. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics
\[ T_{10} = 34 \text{ s} \]
\[ T_{det} = 58 \text{ s} \]
\[ T_n = 61 \text{ s} \]
\[ T_{10} / T_n = 0.52 \pm 0.02 \]
\[ C_i / C_0 = 0.43 \pm 0.01 \]

Earthwork Cost
$7,443

Habitat Diversity Index
0.36

Upland Area: 4%
Emergent Area: 3%
Submergent Area: 1%
Open Water Area: 92%

Topography Volume
803 cm$^3$
S2 features one central island farther from the inlet. Its width is 40% larger than the inlet. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.

![Graph 1](image1.png)

**Figure 4.104**

Dye Concentration [μg/L] vs. Time [seconds]

![Graph 2](image2.png)

**Figure 4.105**

Dye Concentration [μg/L] vs. Time [seconds]
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

<table>
<thead>
<tr>
<th>Hydraulic Metrics</th>
<th>Habitat Diversity Index</th>
<th>Earthwork Cost</th>
<th>Topography Volume</th>
</tr>
</thead>
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<tr>
<td>$T_{10} = 27\text{ s}$</td>
<td>0.18</td>
<td>$7,473\text{ }$</td>
<td>323 cm$^3$</td>
</tr>
<tr>
<td>$T_{det} = 53\text{ s}$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$T_n = 61\text{ s}$</td>
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<td></td>
</tr>
<tr>
<td>$T_{10} / T_n = 0.42 \pm 0.02$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$C_e / C_0 = 0.48 \pm 0.02$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Upland Area: 2%</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Emergent Area: 1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submergent Area: 1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Water Area: 97%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Habitat Diversity Index

0.18

Upland Area: 2%
Emergent Area: 1%
Submergent Area: 1%
Open Water Area: 97%
S2.s1 adds small side islands to S2. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics

- \( T_{10} = 26 \text{ s} \)
- \( T_{det} = 54 \text{ s} \)
- \( T_{n} = 58 \text{ s} \)
- \( T_{10}^n / T_n = 0.44 \pm 0.02 \)
- \( C_e/C_o = 0.47 \pm 0.02 \)

Habitat Diversity Index

- 0.25

Upland Area: 2%
Emergent Area: 2%
Submergent Area: 1%
Open Water Area: 95%

Earthwork Cost

- $7,485

Topography Volume

- 491 cm³
S3

S3 features a central island that is 50% wider than the inlet. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right. [4.114]

Plan view. Water flows from top to bottom. [4.115]

Hydraulic Metrics

\[
T_{io} = 27 \text{ s} \\
T_{det} = 54 \text{ s} \\
T_{n} = 58 \text{ s} \\
T_{io} / T_{n} = 0.454 \pm 0.02 \\
C_{e} / C_{0} = 0.48 \pm 0.02
\]

Earthwork Cost

$7,459

Habitat Diversity Index

0.22

Upland Area: 2% 
Emergent Area: 1% 
Submergent Area: 1% 
Open Water Area: 96%

Topography Volume

436 cm$^3$
S3.s1 adds side islands to S3. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics

$T_{10} = 30 \text{ s}$
$T_{det} = 58 \text{ s}$
$T_n = 60 \text{ s}$
$T_{10}/T_n = 0.45 \pm 0.02$
$C_e/C_0 = 0.45 \pm 0.02$

Habitat Diversity Index

0.29

Upland Area: 3%
Emergent Area: 2%
Submerged Area: 1%
Open Water Area: 94%

Earthwork Cost

$7,472$

Topography Volume

603 cm$^3$
S4

S4 features a central island that is 60% wider than the inlet. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics

- $T_{10} = 25$ s
- $T_{det} = 55$ s
- $T_n = 59$ s
- $T_{10} \, / \, T_n = 0.40 \pm 0.02$
- $C_e / C_0 = 0.48 \pm 0.06$

Habitat Diversity Index

- 0.27

Earthwork Cost

- $7,446$

Topography Volume

- $548 \text{ cm}^3$
S4.s1 adds small side islands to S4. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics

\[ T_{to} = 33 \text{ s} \]
\[ T_{det} = 60 \text{ s} \]
\[ T_n = 55 \text{ s} \]
\[ T_{to} / T_n = 0.56 \pm 0.03 \]
\[ C_i / C_o = 0.43 \pm 0.002 \]

Earthwork Cost

$7,459

Habitat Diversity Index

0.33

Upland Area: 3%
Emergent Area: 2%
Submerged Area: 1%
Open Water Area: 93%

Topography Volume

716 cm³
S5

S5 features one streamlined central island with a width that is 25% of the length. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{to}$</td>
<td>23 s</td>
</tr>
<tr>
<td>$T_{det}$</td>
<td>55 s</td>
</tr>
<tr>
<td>$T_{n}$</td>
<td>63 s</td>
</tr>
<tr>
<td>$T_{to}/T_{n}$</td>
<td>0.38 ±0.02</td>
</tr>
<tr>
<td>$C_e/C_0$</td>
<td>0.47 ±0.02</td>
</tr>
</tbody>
</table>

Earthwork Cost

$7,495

Habitat Diversity Index

0.19

Upland Area: 1%
Emergent Area: 1%
Submergent Area: 1%
Open Water Area: 97%

Topography Volume

337 cm³
S5.s3 adds half side islands to S5. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

Hydraulic Metrics
\[ T_{10} = 23 \text{ s} \]
\[ T_{det} = 47 \text{ s} \]
\[ T_n = 58 \text{ s} \]
\[ T_{10} / T_n = 0.36 \pm 0.02 \]
\[ C_e / C_0 = 0.52 \pm 0.03 \]

Earthwork Cost
$7,513

Habitat Diversity Index
0.33

Upland Area: 2%
Emergent Area: 3%
Submergent Area: 2%
Open Water Area: 93%

Topography Volume
674 cm³
S5.s4 adds full side islands to S5. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.

Plan view (left) and observed flow diagram (right, legend below). Water flows from top to bottom.

Hydraulic Metrics
- $T_{10} = 32$ s
- $T_{det} = 61$ s
- $T_n = 56$ s
- $T_{10}/T_n = 0.50 \pm 0.02$
- $C_e/C_0 = 0.43 \pm 0.01$

Earthwork Cost
$7,530

Habitat Diversity Index
0.44

Upland Area: 4%
Emergent Area: 4%
Submergent Area: 3%
Open Water Area: 90%

Topography Volume
1,010 cm$^3$
Serpentine

The serpentine uses five baffles. Water flows from bottom left to upper right.

[4.142]

Residence time distribution derived from experimental results.

[4.143]
Longitudinal section. Water flows from left to right.

Plan view. Water flows from top to bottom.

Hydraulic Metrics
\[ T_{10} = 27 \text{ s} \]
\[ T_{det} = 50 \text{ s} \]
\[ T_{n} = 51 \text{ s} \]
\[ T_{10} / T_{n}, T_{det} = 0.43 \pm 0.02 \]
\[ C_{f}/C_{0} = 0.48 \pm 0.002 \]

Earthwork Cost
$7,369

Habitat Diversity Index
0.77

Upland Area: 12%
Emergent Area: 7%
Submergent Area: 4%
Open Water Area: 77%

Topography Volume
2,272 cm³
The control case represents an empty basin with no topography. Water flows from bottom left to upper right.

Residence time distribution derived from experimental results.
Longitudinal section. Water flows from left to right.  

Plan view. Water flows from top to bottom.  

Hydraulic Metrics

\[ T_{10} = 14 \text{ s} \]
\[ T_{det} = 48 \text{ s} \]
\[ T_{n} = 64 \text{ s} \]
\[ T_{10} / T_{n} = 0.21 \pm 0.01 \]
\[ C / C_0 = 0.54 \pm 0.04 \]

Earthwork Cost

$7,478

Habitat Diversity Index

0

Upland Area: 0%
Emergent Area: 0%
Submergent Area: 0%
Open Water Area: 100%

Topography Volume

0 cm³
## Summary of Wetland Design Performance Results

<table>
<thead>
<tr>
<th>Design</th>
<th>$T_{10}$ [sec]</th>
<th>$\delta T_{10}$ [sec]</th>
<th>$T_{10}/T_{nc}$</th>
<th>$\delta(T_{10}/T_{nc})$</th>
<th>$C/C_0$</th>
<th>$\delta(C/C_0)$</th>
<th>Topography Volume [cm³]</th>
<th>Habitat Diversity Index</th>
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</tbody>
</table>

[$\delta X$ are the 95% confidence interval]
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Chapter 1: Introduction
[1.2] pg.5. Celina Balderas Guzmán.
[1.6] pg.10. Alan M. Berger.

Chapter 2: Sculpting Wetlands
[2.2] pg.15. Waishan Qiu.
[2.14] pg.29. Tyler Swingle (plans), Samantha Cohen (graph).
Celina Balderas Guzmán is an environmental urbanist with extensive research experience in urban wetlands and stormwater, beginning with her 2013 MIT Master's thesis. She has three degrees from MIT in urban planning, urbanism, and architecture. She was a researcher at the MIT Norman B. Leventhal Center for Advanced Urbanism (LCAU) for over three years. In 2017, she began her PhD at the University of California, Berkeley in landscape architecture, funded by a National Science Foundation Graduate Research Fellowship.

Dr. Heidi Nepf is internationally known for her work in environmental fluid mechanics, with 100+ peer-reviewed papers. The Nepf Lab studies the interaction of flow with aquatic vegetation and the feedbacks to sediment transport, chemical flux, and ecosystem function, developing models for physical processes that determine how vegetated habitats, such as seagrass, marsh, and mangroves, provide coastal protection, improve water quality, and provide blue carbon reservoirs.

Alan M. Berger is Professor of Landscape Architecture and Urban Design at MIT. He is founding director of MIT’s P-REX lab, which focuses on environmental problems caused by urbanization, including the design, remediation, and reuse of waste landscapes worldwide. He is also Codirector of the LCAU. Prior to MIT, Berger was Associate Professor of Landscape Architecture at the Harvard Graduate School of Design. He is a Prince Charitable Trusts Fellow of The American Academy in Rome.