Yale University
Sustainable Stormwater Management Plan

Update 2018

Office of Facilities
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Contents

Introduction

This document provides an update to the Sustainable Stormwater Management Plan 2013–2016, and defines strategies for managing stormwater on campus. It also achieves initial fulfillment of the Stormwater and Water Management goal in the Yale Sustainability Plan 2025.

Moving forward, the University intends to incorporate stormwater management progress and planning into the Campus Resilience Plan, High Performance Design Standards, Sustainability Progress Reports, and supporting documents. Collectively, these plans invite generative work and collaboration between the academic and operational sides of the University. The significance of operational commitments is expanded beyond Yale's campus with related applied research, teaching, and service.

Vision for Stormwater Management

Yale University's 1,155-acre campus includes academic, residential, and administration buildings, laboratories, green spaces, sports fields, and a golf course. Within its boundaries are more than 500 buildings with over five million square feet of roof area that, along with other paved surfaces on campus, cover approximately 55% of Yale University's total property.1

When rain falls onto these roofs, roads, walkways, and parking lots, the surfaces create an impervious barrier that prevents rainfall from infiltrating into the ground and instead transforms it into stormwater runoff that flows off these surfaces and into city sewer systems. A number of issues are associated with stormwater:

Issues

Pollution

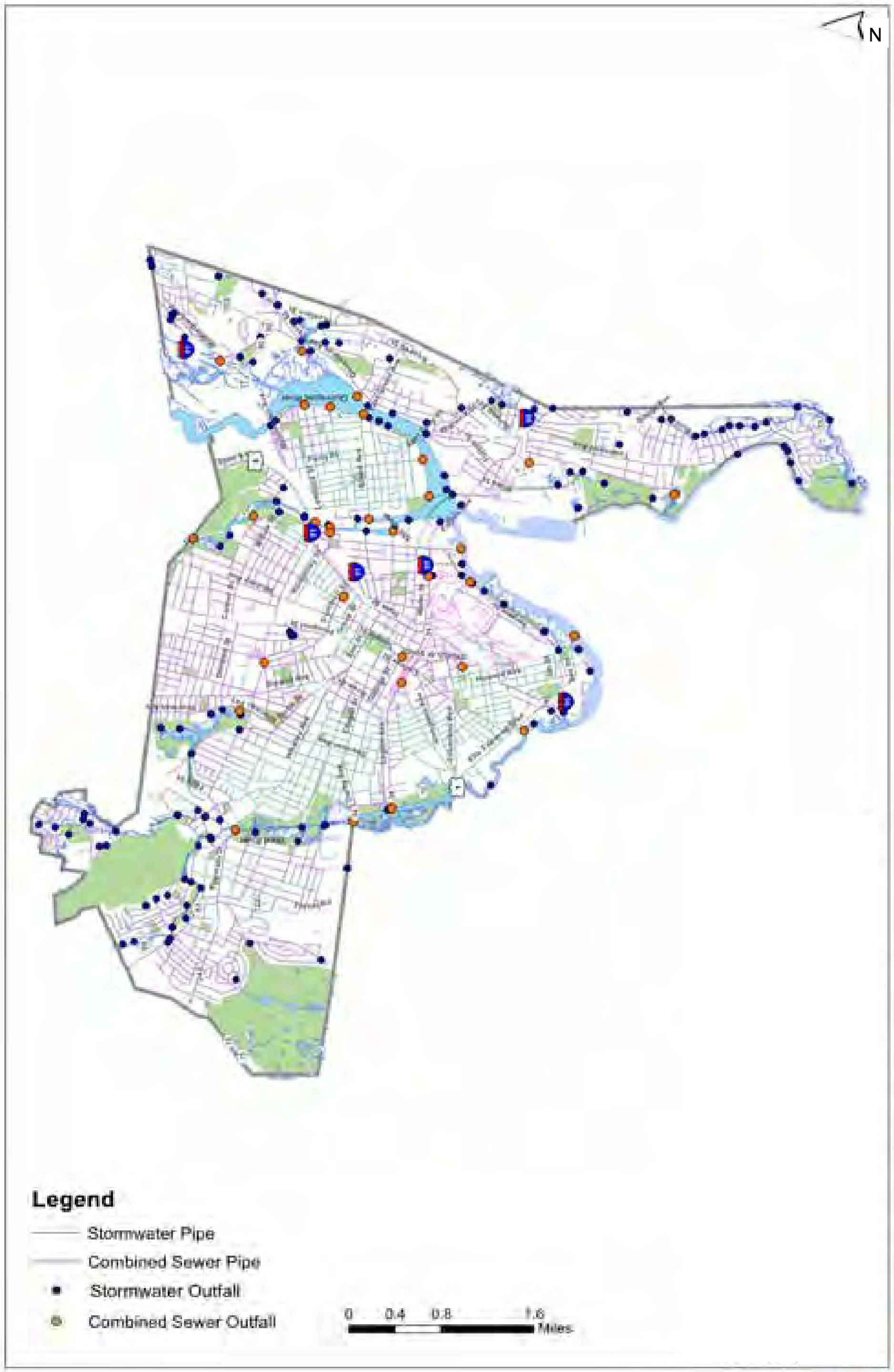
Campus stormwater runoff drains into two different sewer systems. Some portions of New Haven's sewer system contain areas where the sanitary and stormwater flow drain into one pipe, known as a combined system. Other areas within the city drain into a sewer system where stormwater flows into a dedicated pipe that is separate from the sanitary drainage, known as a separate storm sewer system (Figure 1).

Stormwater runoff draining to the combined sewer system in New Haven will generally drain to the Greater New Haven Water Pollution Control Authority (GNHWPCA)'s East Shore Water Pollution Abatement Facility for treatment and eventual discharge into Long Island Sound. However, when storm events create greater stormwater volumes, the runoff will overload the treatment system, causing the combined sewage to overflow without treatment into nearby receiving waters, with eventual discharge into Long Island Sound through structures called combined sewer overflows (CSOs).

Between May 2016 and April 2017, there were 27 CSO events in New Haven. Due to these events, approximately 31 million gallons of combined sewage were discharged into Long Island Sound.2

Stormwater that flows directly into the separate sewer system also contributes to local water-body pollution. Stormwater runoff that enters separate storm sewers from campus properties in New Haven, Orange, and West Haven discharges directly into the New Haven Harbor, Mill River, and West River, untreated. These water bodies suffer impairments due to the pollutants carried in the runoff such as fertilizer, pesticides, and litter.3

Figure 1. New Haven sewer system (City of New Haven)



Flooding
In addition to pollution, stormwater runoff contributes to inland flooding. Impervious surfaces on campus prevent natural infiltration of stormwater runoff into the soil, leading to flash flooding events. Storm sewers can also back up, leading to flood damage in basements of buildings and contributing to CSOs.4 Flooding can impact the University's critical operations responsible for the life, health, safety, and security of staff, students, and patients, and lead to long-term building and infrastructure damage, such as mold damage. It also creates concern for the University's critical research, safety, and cultural assets.

Resilience
Stormwater management falls under the Stewardship Ambition of the Yale Sustainability Plan 2025—to plan and preserve resilient and sustainable infrastructure.5 Proactive stormwater management can help prepare Yale for the effects of climate change and related environmental challenges of the 21st century. Stronger storms are one of the most severe climate stresses predicted to impact the Northeast, with the situation worsened in coastal urban centers due to concentrated stormwater runoff and sea level rise.6

Yale's capacity to respond to chronic stresses (e.g., pollution and aging infrastructure) and acute shocks (e.g., severe weather events and floods) can have a direct impact on human and ecological health, safety, social equity, and economic well-being. In this regard, stormwater management also connects to the other nine ambitions of the Plan, particularly Leadership, Climate Action, and Built Environment.

Future efforts in stormwater management planning shall be guided by a set of shared principles. Like the Sustainability Planning Principles,7 these principles leverage the strength of near-term activities, provide direction for future development, and should be taken collectively to motivate and focus work:

Principles

Recognize stormwater as a resource. Stormwater has great impact on the health and economic vitality of the campus, the region, and the environment. Yale shall manage stormwater as a resource to enhance its positive effects on the environment and to reduce associated risks to Yale assets and infrastructure.

Prioritize restoration of watershed function. Watershed function is restored with low-impact stormwater management strategies, including natural features, landscapes, and green infrastructure systems. Yale shall implement stormwater management strategies following a fundamental order of priority: (1) infiltration of stormwater where it falls, (2) storage for infiltration or reuse, (3) temporary detention and gradual release of stormwater to the storm sewer, and (4) temporary detention and gradual release of stormwater to the combined storm and sewer system.

Promote stormwater research. Sustainable stormwater management offers and necessitates robust research and educational opportunities for students and faculty. Yale shall encourage University-wide participation and stewardship of stormwater management strategies using the campus as a living laboratory.

Incorporate adaptive management. Data gathered by surveying campus infrastructure, monitoring stormwater discharge, and modeling campus performance provide a foundation for future goal setting. Yale shall commit to collecting data, sharing data, and using an iterative decision-making process for ongoing stormwater management.

Yale also aligns with local and regional stormwater priorities—pollution prevention, flood prevention, and sustainability planning—and should consider these drivers whenever stormwater management is involved.

Alignment

Pollution Prevention

GNHWPCA manages New Haven's combined sewer system and separate sanitary sewers. One of the goals of GNHWPCA is to reduce the volume of CSOs. Toward this goal, for new construction projects to be permitted within areas serviced by a combined system, GNHWPCA requires that "the post-development stormwater runoff for a 2-year, 6-hour storm frequency (rainfall = 2.05 inches) shall be detained by underground infiltration/detention systems designed by a professional engineer licensed in the state of Connecticut."8

GNHWPCA is also working on a project entitled "CSO Reduction Utilizing Green GNHWPCA in the West River Watershed." The goal of the project is to install at least 75 right-of-way green infrastructure projects like bioswales and green infrastructure curb bump-outs. The design is mostly complete and awaiting approvals from the Connecticut Department of Energy & Environmental Protection (CT DEEP).

The City of New Haven, the City of West Haven, and the Town of Orange regulate Yale's separate storm sewers. While separate storm sewers do not contribute to CSOs, there are issues associated with aging infrastructure, capacity, and pumping. Reduction of total stormwater volume and rate ease stress on this infrastructure.

In addition, each municipality has a Stormwater Management Plan, in fulfillment of DEEP's Municipal Separate Storm Sewer System (MS4) General Permit. Required through the federal Clean Water Act, CT DEEP established the MS4 General Permit to protect water quality and reduce the discharge of pollutants from a municipality's storm sewer system.9 These plans were updated in July 2017.

The MS4 General Permit requires that all new development or redevelopment projects with greater than one acre of soil disturbance retain the volume of runoff generated by one inch of rainfall on the site.10 Section 60 of New Haven's Zoning Ordinance goes beyond the one-acre requirement by including sites that disturb one-half or more acres of total land area on site.11 Further details on retention requirements can be found in each municipality's Stormwater Management Plan, and are summarized in Table 1.

Table 1: Local Stormwater Entities, Drivers, and Strategies

Entity	Driver	Strategy
GNHWPCA (sanitary sewers & combined sewers)	Limit CSOs	Permitting: Require projects to retain 2.05" in combined sewer systems Projects: 75-100 bioswales and ongoing separation efforts
City of New Haven (storm sewers)	Meet MS4 requirements Aging infrastructure Flooding (high-risk areas)	Permitting: Require projects ≥ 0.5 acres in storm sewer to retain 1" of rainfall onsite Projects: 200 bioswales, modeling, and system upgrades
City of West Haven[12] Town of Orange[13] (storm sewers)	Meet MS4 requirements	Permitting: Require projects ≥ 1 acre to retain 1" of rainfall on the site

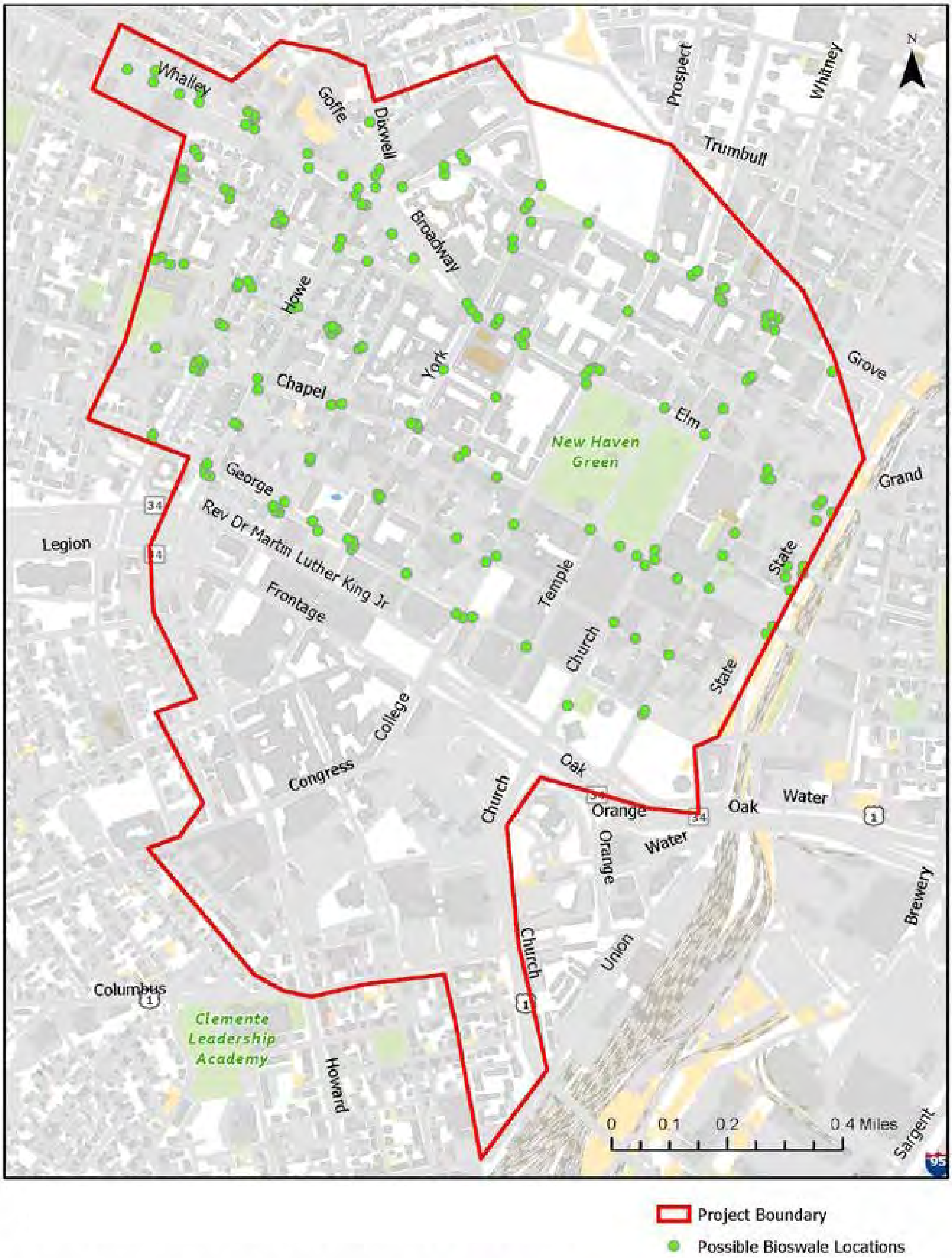
Flood Prevention

In January 2017, the City of New Haven developed a Natural Hazard Mitigation Plan to protect people and properties at risk from natural disasters such as inland flooding. The City is required by the Disaster Mitigation Act of 2000 to update this plan every five years and have it approved by the Federal Emergency Management Agency to be eligible to receive specific disaster and mitigation funding.14

To address local flooding issues, the City of New Haven is currently working on a series of projects called "Hill Neighborhood and Union Avenue Drainage Improvements" funded by federal Housing and Urban Development (HUD) Community Development Block Grant Disaster Recovery (CDBG-Dr) grants. Initial activity included the completion of a Storm Water Management Model (SWmm) of the downtown storm sewer system (Figure 2). The City has sited and will be installing over the next 18 months 200 bioswales in the right of way (Figure 3). Additional strategies to mitigate flooding during high-intensity rainfall events will be further evaluated.

Figure 2. Downtown sewershed map.

Figure 3. Proposed locations for downtown bioswales (City of New Haven).



Sustainability Planning

In January 2018, the City of New Haven published the New Haven Climate and Sustainability Framework (NHCSF), which proposes goals and actions to advance climate and sustainability objectives and limit temperature rise to two degrees Celsius. NHCSF is organized into six strategies. The Land Use and Green Infrastructure strategy recognizes the opportunity to interweave nature and society to promote a sustainable New Haven, and presents the following goals that shall influence future stormwater efforts at Yale: increase stormwater infiltration on private and public property; improve quality of soil and water bodies within and surrounding the city.15 Specifically, the City of New Haven plans to update the stormwater section of the Zoning Ordinance to increase the retention volume capture and incentivize vegetation-based infiltration systems, where possible.

Progress to Date

Since the release of the Sustainable Stormwater Management Plan 2013–2016, Yale has integrated stormwater management into its projects, planning, and scholarship. The following sections provide examples of stormwater practices that have been implemented at Yale since 2013.

Projects

Since 2013, Yale has completed a number of stormwater management projects that include green roofs, downspout disconnection, bioretention, and subsurface infiltration/detention systems.

Sage Hall
205 Prospect Street

The Sage Rain Garden was developed by two students from the Yale School of Forestry & Environmental Studies to collect rainwater from the roof of Sage Hall in fall 2014. The downspout on Sage Hall was disconnected, and Yale Facilities completed berms that would keep up to 1.5 feet of stormwater from running onto Prospect Street. The garden is composed of local plant species and diverts an estimated 300 to 500 gallons of stormwater from the sewer systems during heavy storms.[16]

Wright Laboratory
272 Whitney Avenue

Wright Laboratory was built in 1996 and includes a green roof. More recently, in conjunction with 2016 renovation, Yale Facilities added native vegetation to the roof to enhance both the area's biodiversity and stormwater retention capacity. The project used a pollinator mix that included perennial and annual plantings.

Baker Hall
100 TowerParkway

Baker Hall is expected to open in August 2018. Stormwater runoff from the site was not managed previously. The new system will include four underground infiltration areas holding 11,455 cubic feet (~86,000 gallons) to treat and retain stormwater from a one-inch rainfall. During two-, 10-, 25-, and 100-year rainfall design events, the overall peak runoff flow rates and volume are reduced. Rendering by Pirie Associates Architects.

Pauli Murray and Benjamin Franklin Residential Colleges
90–130 Prospect Street

Pauli Murray and Benjamin Franklin Residential Colleges opened in fall 2017. To mitigate stormwater runoff, infiltration systems were installed below the large courtyards of each college. A detention system was installed along Prospect Street, and meadow plantings were located along the Farmington Canal Greenway. Additionally, water-quality structures beneath the courtyards contribute to the management of stormwater runoff.[17]

Planning

Several planning efforts have been implemented since 2013 or are currently in process relating to stormwater management on campus.

Sustainable Water Feasibility Study. Yale Facilities has completed feasibility studies and preliminary permitting reviews to develop a campus-level reclaimed water system to supply nonpotable water to the Sterling power plant. A system of this scale could remove approximately 100M gallons from the sewer system annually, while offering new teaching and research opportunities associated with urban water infrastructure.

Science Hill Landscape Master Plan. A landscape master plan is being developed by Reed Hilderbrand for the Science Hill area of Yale's campus. Home to Yale's world-class research institutions, this area of campus is fragmented and suffers from unclear circulation and diminished canopy and vegetation. This master plan foresees a 10-year campaign to rebuild Science Hill, emphasizing its drumlin character, capitalizing on the University gardens, and pursuing an urban forestry management approach to a notable tree population.18

Standards for Bioswale Maintenance. The Urban Resources Initiative developed a Bioswale Maintenance Guide that provides standards for maintaining the new bioswales in the City of New Haven. Approximately 50 bioswales will border Yale property.

LEED v4. Yale is still committed to Leadership in Energy and Environmental Design (leeD) certification. Each project assesses leeD v4 for applicability.

Environmental Health & Safety (EH&S) Standards. eH&S has developed a number of informational and instructional standards covering stormwater management best practices, including construction pollution prevention, wastewater discharge types, and operational best practices. A training seminar was developed in 2015 for wastewater discharge types and permitting that eH&S maintains on the behalf of the University.

Scholarship

A wide range of research interests is related to stormwater management on campus. The following highlight the breadth of scholarship at Yale around campus stormwater management.

Downspout Disconnection Feasibility Assessment and User Guide. In spring 2014, two graduate students at the Yale School of Forestry & Environmental Studies conducted a research project on downspouts on Yale buildings. Over 1,800 downspouts across more than 500 campus buildings were identified, mapped, and assessed for their disconnection potential. The assessment helped to create priorities for downspout disconnection, and stored data in a spreadsheet and in ArcGIS databases.

Yale Experimental Watershed (YEW) Assessment. The YeW is a 5.5-acre wetland in the Science Hill portion of Yale's campus. An assessment of the YeW was released in 2014 providing detailed information on research conducted in 2013–2014 by the Hixon Center for Urban Ecology. New monitoring devices were installed to refine and streamline hydrologic data collection, including upgrades to the discharge monitoring system, which can help improve stormwater flow calculations.19

Technical Skills Modules (MODs). In fall 2015, incoming students at the Yale School of Forestry & Environmental Studies helped assess locations for the placement of New Haven's bioswales as part of their Urban mODs programming. The City of New Haven used this information for final placements of bioswale installations in the downtown area.

New Haven Bioswale Monitoring. Since 2015, the Urban Resources Initiative and the Yale Hixon Center for Urban Ecology have collaborated with the City of New Haven on constructing and monitoring eight bioswales on West Park Avenue, and seven more on Daisy Street in the Newhallville neighborhood of New Haven. Academic research conducted by Professor Gaboury Benoit and graduate students at the Yale School of Forestry & Environmental Studies helped to inform design standards for the bioswales that will be installed in downtown New Haven to address flooding and water quality issues.

Cities in Hot Water. In spring 2016, this capstone course was co-taught at the Yale School of Forestry & Environmental Studies by Professor Xuhui Lee and Associate Dean Brad Gentry. Students worked in groups to assess the biophysical threats and social impacts of climate change, including flooding in New Haven, providing policy recommendations for the city's new Hazard Mitigation Plan.

Moving Forward

The following section describes strategies toward the University's immediate stormwater management goals and longer-term vision for active and adaptive stormwater stewardship. These strategies build on the progress and analyses made since the Sustainable Stormwater Management Plan 2013–2016 and provide a coherent and flexible framework for future activities.

Strategy 1 ImPrOve DAtA qUAlItY relAteD tO CAmPUS StOrmWAter mANAGemeNt

Consolidate campus information that relates to the risks and opportunities presented by stormwater on campus. Conduct testing and analysis to improve our understanding of stormwater impact on campus and beyond.

During the past three years, various research projects at Yale have expanded our understanding of stormwater management issues and techniques on campus. We are planning to continue efforts to improve our understanding of stormwater challenges and opportunities through the following tactics:

- Index stormwater management practices and impacts on both capital and operational projects completed at Yale beginning in 2012 through 2020.
- Consolidate existing information within operations about priority flooding locations on campus into one accessible document.
- Create and implement a stormwater quality testing program for campus that is managed by eH&S.
- Create a comprehensive master plan that provides a detailed view of stormwater management challenges and opportunities on campus.

To increase our understanding of current stormwater management on campus, Yale should begin indexing stormwater management practices on capital projects at Yale. The 2012 timeline is chosen to align with local efforts. Under the 2017 MS4 General Permit, municipalities are required to annually track the total acreage of Directly Connected Impervious Areas (DCIA) that is disconnected from the MS4 as a result of redevelopment or retrofit projects within their municipality. Impervious surfaces are considered disconnected when the required portion of stormwater is retained through infiltration or reused for other purposes without a surface or storm sewer discharge.20 Starting on July 1, 2021, municipalities shall reduce 1% of their total DCIA acreage per year to the maximum extent possible, incorporating all DCIA disconnections that occurred in the city since July 1, 2012. Tracking stormwater projects will provide a comprehensive view of stormwater practices implemented at Yale on a project-by-project basis, providing data to consider holistic impacts of individual projects over time.

Currently, flooding at Yale is managed in anticipation of and in response to acute weather events. Information regarding flooding sites and strategies on campus is generally shared across multiple operational teams. To advise future planning efforts and choose priority locations for flood mitigation, the information needs to be consolidated into one document that can be accessed by necessary University personnel and used to inform master planning efforts.

To better understand the impact of stormwater runoff from Yale's campus, a stormwater quality testing program will need to be initiated. eH&S will choose several testing sites each year. The information will better guide our understanding of priority areas to mitigate stormwater and pollutants to target.

Finally, the University will take the necessary steps to engage a third-party consultant to comprehensively assess and prioritize issues and opportunities for proactive stormwater management. This would provide a capital and operational road map with cost/benefit analysis per strategy and list of sites that may be implemented over time.

Strategy 2

StrAteGY 2: AlIGN DeSIGN StANDArDS AND PlANNING DOCUmeNtS

Update existing design standards and planning documents specifying preference for low-impact development (LID) and green infrastructure.

Yale shall implement stormwater management strategies following a fundamental order of priority: (1) infiltration of stormwater where it falls, (2) storage for infiltration or reuse, (3) temporary detention and gradual release of stormwater to the storm sewer, and (4) temporary detention and gradual release of stormwater to the combined storm and sewer system. In doing so, Yale will take a holistic approach in meeting the specified regulations by developing multi-project strategies, considering the best possible options to reduce stormwater runoff.

Yale will continue its commitment to leeD v4 requirements, specifically following the recommendations of credit SSc4 Rainwater Management. To achieve Option 1, Path 1, of SSc4 (2 points), runoff from the developed site for the 95th percentile (~1.4 inches) of regional or local rainfall events has to be managed using lID and green infrastructure. To achieve Option 1, Path 2, of SSc4 (3 points), runoff from the 98th percentile (~2.16 inches) of regional or local rainfall events needs to be managed using lID or green infrastructure. To achieve Option 1, Path 3, of SSc4 for zero lot line projects only (3 points), runoff from the 85th percentile (~0.76") would need to be managed using lID or green infrastructure. Option 2 of SSc4 (3 points) can be achieved by managing on site the annual increase in runoff volume from the natural land cover condition to the post developed condition.

Future projects, including those designated as Comprehensive Scope, Limited Scope, and Small Scope, will be executed in accordance with design standards and planning documents updated with stormwater management goals. Sections of Division 15 of the Yale Design Standards for Capital Projects were updated in spring 2016 and will continue to be updated to reflect requirements for stormwater management as it evolves.

Yale intends to incorporate all lessons learned to date, standards, and guidelines in the update and adoption of High Performance Design Standards by 2019 in accordance with the Yale Sustainability Plan 2025.

Strategy 3 IMPLEMENT STORMWATER MANAGEMENT PROJECTS ON CAMPUS

Implement stormwater management techniques on campus with a preference for LID and green infrastructure projects to reduce impervious surface on campus.

Yale seeks to manage the runoff from its impervious areas on campus to reduce stormwater pollution and local flooding. Impervious surfaces increase the amount of stormwater runoff from a site, decrease infiltration and groundwater recharge, alter natural drainage patterns, and reduce the ability of natural pollutant removal mechanisms.21 Yale should reduce its impervious cover through the following tactics:

- Beyond meeting retention requirements, major capital projects shall explicitly consider and assess opportunities for innovative stormwater management.
- Implement green infrastructure projects outside of capital projects that reduce impervious surface on campus by 45,000 square feet by fiscal year 2020.

Yale has significant opportunities to design, install, and demonstrate impact of green infrastructure for stormwater management across its capital program. Major capital projects with applicable retention requirements can go beyond those requirements by installing innovative technology, monitoring impacts, or retaining greater volumes of water. Each major capital project will formally assess such opportunities moving forward.

Moreover, one of the goals outlined in NHCSF is an update to the stormwater section of New Haven's Zoning Ordinance. Formally assessing innovative stormwater management opportunities will help prepare Yale for an increased retention requirement that supports vegetation-based infiltration systems.

In addition, a series of projects will be formulated and implemented with a goal of reducing impervious surfaces on campus by 45,000 square feet collectively by 2020. This goal includes disconnected impervious areas, and projects include bioswales, downspout disconnections, porous pavement, and rain gardens. These and other examples of green infrastructure can lower flood risk, replenish groundwater reserves, reduce the urban heat island effect, lower building energy demands, protect water resources, limit erosion, and reduce stress on municipal sewer systems.22 More details on green infrastructure options are listed in Appendix B in the Yale Sustainable Stormwater Management Plan 2013–2016. A Yale planner and project manager will be assigned to direct these activities.

Further, Yale plans to create opportunities for academic engagement in analyzing, monitoring, and implementing stormwater techniques on campus.

Strategy 4 ADAPT MANAGEMENT PLAN GOALS

Identify progressive stormwater management goals by 2020 in alignment with municipal, regional, and state priorities and share lessons learned.

As we improve our understanding of stormwater on campus, we will update our goals and strategies accordingly. Through academic research, we will have more applied knowledge for increasing the effectiveness of novel stormwater technologies on campus. Through local efforts and campus pilot projects, we will learn how to best implement and maintain green infrastructure, and measure long-term impact. Working closely with New Haven and surrounding cities, we will share priorities and lessons learned to the benefit of the region as a whole.

Moreover, the University intends to address stormwater management priorities in the Campus Resilience Plan as part of the Yale Sustainability Plan 2025. This series of documents will comprehensively address campus issues and preparation for climate change adaptation, including extreme weather events.

Conclusion

Yale is committed to enhancing human health, biodiversity, and environmental vitality by developing innovative approaches to land and water management. This plan serves as a guide for future academic and operational projects, and provides priorities for the establishment of Yale's High Performance Design Standards and Campus Resilience Plan. Yale will continue to align with local and regional efforts through an adaptive management approach, in an effort to reduce the impacts of its stormwater runoff.

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Acknowledgments

Team Leaders
Beata Fiszer, *Program & Communications Coordinator, Yale Office of Sustainability*
Julie Paquette, *PE, LEED AP BD+C, Director, Energy Management*

Contributors
Virginia Chapman, *AIA, LEED AP BD+C, Director, Yale Office of Sustainability*
Rupal Patel, *MEM, 2016*

Editorial Consultant
Joyce Ippolito, *Editor*

Design & Typesetting
John Gambell, *University Printer*
Maura Gianakos, *Graphic Designer, Office of the University Printer*

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Yale

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on the cover

This map delineates storm sewersheds at Science Hill. It takes into account topography, catch basin placement, and pipe layout. This is critical information for stormwater management.

Map by Aram Marks

First Printing, September 2013

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2013–2016

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Introduction

In 2010, Yale University's Office of Sustainability released the Sustainability Strategic Plan 2010–2013. This comprehensive sustainability planning document identified a variety of goals and projects related to campus systems, administrative systems, earth systems, education, and engagement that, once adopted, would enhance Yale's commitment to maintaining a sustainable campus. Included within the campus systems goals was a desire to move the university beyond a role of compliance toward proactive and responsible environmental management. As one aspect of Yale's focus on reducing its environmental impact, the task force established a goal to reduce the impact of stormwater runoff from the campus and Yale University's properties. Specifically, the plan set the goal of developing "a University-wide stormwater discharge reduction goal and strategy by 2013" by completing "a comprehensive assessment of campus stormwater runoff by characterizing and digitizing watershed surface conditions and features that lead to flow characteristics (i.e., pavement, grass, garden)."

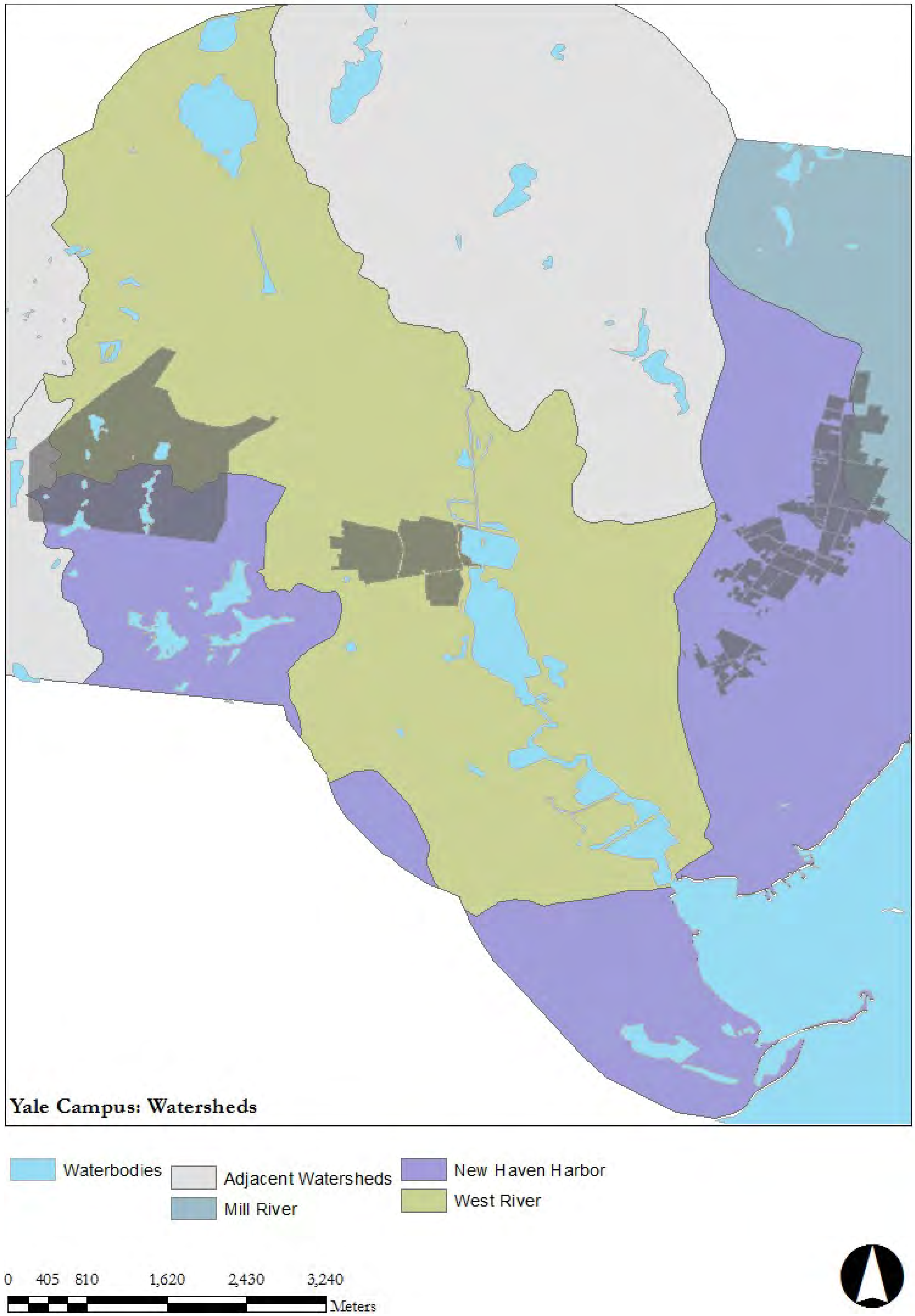
The Sustainable Stormwater Management Plan of 2013 is the response to the Sustainability Strategic Plan goal and will serve as the first step toward a campus that comprehensively manages stormwater through the use of green infrastructure. For the purposes of this plan, the term *green infrastructure* is defined as any tactic or system that slows and/or reduces the flow of stormwater into a sewer system. Included in this definition are both engineered vegetated landscape systems that temporarily store, treat, and/or infiltrate stormwater into the ground as well as more structural techniques such as disconnecting direct connections to the sewer system and decentralized stormwater storage through rain barrels and cisterns. The Sustainable Stormwater Management Plan presents an overarching vision for campus design and operations and defines interim strategies for activities that position the university to address proactively this growing environmental and public health issue.

The Importance of Mitigating the Stormwater Impact in New Haven

Yale University's 1,046-acre campus includes academic, residential, and administration buildings, laboratories, green spaces, sports fields, and a golf course. Within its boundaries are more than five million square feet of roof area that, along with other paved surfaces on campus, cover 55 percent of Yale University's total property.[1] When rain falls onto these roofs, roads, walkways, and parking lots, the surfaces create an impervious barrier that prevents rainfall from infiltrating into the ground and instead transforms it into stormwater runoff that flows off these surfaces and into the city of New Haven's sewer system.

Because the campus is spread across the city of New Haven, portions of the stormwater runoff from the campus drain to New Haven's two different sewer systems. Some portions of New Haven's sewer system contain areas where the sanitary and

Figure 1: The Distribution of Yale University Across Watersheds



stormwater flow in one pipe, known as a combined system. Other areas within the city drain to a sewer system where sanitary flows and stormwater flows are separated into two pipes, known as a separate storm sewer system.

In addition to being spread across different types of sewer systems, Yale's property lies within four watersheds: Mill River, West River, Beaver Pond, and New Haven Harbor, as shown in Figure 1. The stormwater runoff from Yale University's property that drains to the separate system areas flows into the stormwater sewers and discharges directly into one of the four waterways without treatment. The stormwater runoff draining to the combined sewer system in New Haven will generally drain to the Greater New Haven Water Pollution Control Authority (GNHWPCA)'s East Shore Water Pollution Abatement Facility for treatment and eventual discharge into the Long Island Sound. However, under certain storm events that create greater stormwater volumes, the runoff will overload the conveyance system, causing the combined sewage to overflow into one of the waterways through structures called combined sewer overflows (CSOs).

Because of these CSOs, each year, 257 million gallons of combined sewage containing chemicals, heavy metals, and human waste flow into these waterways, with a negative effect on the health of the ecosystems and the potential for public recreation (GNHWPCA 2012). Even without the CSOs, the untreated stormwater that drains to waterways through the sewers in the separate storm sewer system carries with it the contaminants of the impervious surfaces it flowed over before entering the sewers, as summarized in Table 1. The contamination in the waterways is the direct result of stormwater runoff from the city's impervious surfaces, including the campus's impervious areas, overloading the city's combined and separate storm sewer systems.

Table 1: Sources and Impacts of Stormwater Pollutants

pollutant	source	effects
Trash	Plastic bags, six-pack rings, bottles, cigarette butts	Can choke or cause physical damage to aquatic animals and fish
Sediment	Construction, unpaved areas, erosion	Increases turbidity, making it difficult for aquatic plants to grow
Metals, Pesticides, Solvents	Vehicle parts, emissions, and fluids; household products	Toxic to aquatic organisms; can accumulate in sediments and fish tissues
Nutrients	Vehicle emissions, atmospheric deposition	Creates algal blooms that decrease aquatic oxygen available to organisms
Bacteria	Exposure to sewage in combined sewer systems	Human health hazards, often making beach closures necessary

Sources: Lukes and Kloss (2008); U.S. Environmental Protection Agency (2013).

Because the City of New Haven and the GNHWPCA own the underground network of sewers, the roadways throughout campus, and the associated catch basins, Yale University's authority for reducing its environmental impact associated with stormwater issues at this point will likely not include changes or upgrades to the sewer systems. Instead, Yale has the opportunity to leverage its extensive property to look for potential ways to manage stormwater. The opportunity for Yale to reduce its environmental impact through stormwater management is instead to implement green infrastructure systems that slow or reduce the runoff from its surfaces in the first place.

The Approach to Stormwater Mitigation in the United States and Connecticut

Mitigating the impacts of stormwater runoff is not only an issue in New Haven—green infrastructure is being implemented more and more as a solution throughout the United States. In recent decades, the U.S. Environmental Protection Agency (EPA) has increased its enforcement of regulations to protect U.S. waterways from the impacts of CSOs. As part of this work, cities across the United States are being required to substantially reduce and/or eliminate their CSOs. The traditional response to managing CSOs has been to incorporate immense storage tanks and tunnels to temporarily store combined sewage until a treatment plant can treat the water or to separate combined systems. These tactics are often referred to as "gray" infrastructure. For the scale necessary to meet EPA's current requirements, these system solutions require both underground construction and extensive space, requiring enormous capital to construct.

To reduce the expense of upgrading current systems to respond to these regulations, many cities have looked for more cost-effective alternatives to reduce the amount of gray infrastructure needed while achieving the same result. Substituting green infrastructure for gray infrastructure has been found to cost less per gallon of stormwater treated by providing the benefit of temporarily storing, treating, and infiltrating stormwater where it falls, resulting in less stormwater entering the sewer systems. Cities including New York City, Philadelphia, and Washington, DC, have all negotiated with the U.S. Environmental Protection Agency (EPA) to adapt their CSO management plans, called Long Term Control Plans, to include significant investment in green infrastructure. These plans and further information on the current state of stormwater management in the United States and Connecticut are described in Appendix A.

Cities are also finding that these green infrastructure systems offer additional benefits beyond their ability to manage stormwater. In general, the green infrastructure techniques that include natural landscapes have been shown to increase the resiliency of cities against the anticipated effects of climate change by reducing urban temperatures and cleaning the air. The techniques also increase infiltration, which can replenish groundwater reserves (U.S. EPA 2013). There are several social benefits to green infrastructure as well. Trees and green space increase property values, calm tra∞c, and reduce crime (U.S. EPA 2013). By incorporating green infrastructure into the urban fabric, cities and universities can take advantage of the opportunity to drive revitalization, improve quality of life, and reduce environmental risk (U.S. EPA 2013).

Within New Haven, GNHWPCA's CSO management approach includes both sewer separation and treatment plant expansion to increase storage capacity for combined sewage. The authority that enforces the U.S. EPA's CSO management regulations, the Connecticut Department of Energy and Environmental Protection (DEEP), provides funding for these tactics and in so doing incentives GNHWPCA's current CSO management approach. Like cities across the United States, it is likely that New Haven will continue to be pressured to improve its CSO management, and these approaches may not be enough. As New Haven's largest landowner, Yale has the opportunity to meet its goal of reducing its environmental impact while serving as a leader in the community and assisting the City of New Haven in moving toward its goals for CSO management.

Sustainable Stormwater Management Principles

Yale University envisions a campus where stormwater runoff is reduced sustainably through green infrastructure. To move toward this vision, this plan advocates for investment in green infrastructure in a comprehensive manner throughout Yale's campus. The following principles, adapted from Pennsylvania's Department of Environmental Protection (Pennsylvania Department of Environmental Protection 2006), will guide Yale's approach to sustainable stormwater management on campus and are intended for both the initial phases of understanding stormwater on campus as well as the future goal setting and strategies to be defined in 2016. Further, they support the sustainability values reflected in Yale's Sustainability Strategic Plans and are in alignment with the Planning Principles stated in the 2013 Sustainability Supplement to the Framework for Campus Planning. The Sustainable Stormwater Management Principles are as follows:

Recognize Stormwater as a Resource

Stormwater has great impact on the health and economic vitality of the campus, the region, and the environment. Yale shall manage stormwater as a resource in order to enhance its positive effects on the environment and to reduce associated risks to Yale assets and infrastructure.

Prioritize Restoration of Watershed Function

Watershed function is restored with low-impact stormwater management strategies, including natural features, landscapes, and green infrastructure systems. Yale shall implement stormwater management strategies following a fundamental order of priority: first infiltration of stormwater where it falls, then storage for infiltration or reuse, and finally temporary detention and gradual release of stormwater to New Haven's combined and separate storm sewer systems.

Promote Stormwater Research

Sustainable stormwater management offers and necessitates robust research and educational opportunities for students and faculty. Yale shall encourage university-wide participation and stewardship of stormwater management strategies on campus.

Incorporate Adaptive Management

Data gathered by surveying campus infrastructure, monitoring stormwater discharge, and modeling campus performance provide a foundation for future goal setting. Yale shall commit to collecting data, sharing data, and using an iterative decision-making process for ongoing stormwater management.

With a vision of moving the campus away from compliance and toward reducing the campus's stormwater runoff impact using green infrastructure techniques, Yale University intends to set a specific quantitative goal similar to the green infrastructure goal set by New York City in 2010 (NYC Department of Environmental Protection, n.d.): "Capture the first inch of rainfall on 10% of the impervious areas in combined sewer watersheds through detention or infiltration techniques over 20 years."

To achieve the New York City goal at Yale, the university would need to manage approximately one million gallons of stormwater runoff from its impervious surfaces[2] or, for example, the first inch of rainfall from 1/3 of its 5.2 million square feet of roof space. At this point, little is known about the level of work and capital necessary to achieve a goal of this magnitude. Before committing to a goal that at this time may be unachievable, Yale must build its understanding of green infrastructure techniques on campus, and with that knowledge set a goal in 2016.

Creating this knowledge base can be accomplished through the implementation of a combination of engineered, vegetated landscape techniques that include rain gardens, bioswales, enhanced tree pits, and green roofs or through the structural techniques that include downspout disconnection, rain barrels, cisterns, blue roofs, infiltration trenches, and pervious pavement. Descriptions of these potential green infrastructure techniques and information on their associated design considerations are included in Appendix B.

This plan advocates for an adaptive management approach for stormwater management. Each phase of the stormwater runoff mitigation effort beginning with this plan's strategies is intended to build off the previous phases' work. The intent of this plan is to serve as the groundwork for sustainable stormwater management on campus with subsequent plans incorporating the knowledge gained over the next three years. The recommended process to achieve this adaptive management approach is further explained in Appendix C.

Previous Analysis for Stormwater Planning at Yale

This plan is the result of multiple years of analysis, including significant effort during the 2012–2013 academic year, to create the necessary information and understanding for completing the first sustainable stormwater management plan for Yale University.

Summary of Previous Analysis

For the past several years, students, faculty, and staff have investigated stormwater from various perspectives. That analysis both helped in the creation of this plan and has potential for informing future efforts on stormwater management on campus and in New Haven. Figure 2 provides an illustration of the individuals and highlights their contributions.

Of particular note, during the spring semester of 2013, thirteen graduate students in the Yale School of Forestry and Environmental Studies master's program participated in a seminar class focused on creating the necessary analysis to finalize portions of this plan. The class served as the second iteration of an examination of Yale's campus for a capstone project class, where in 2011 the first class examined the campus through the lens of ecosystem services. Through the study of cities pursuing green infrastructure as a response to combined sewer and stormwater management, members of the class provided important insights and recommendations on project ideas, maintenance, monitoring, university design standards, and potential for partnerships in the development of a green infrastructure implementation program for Yale. That analysis is included as the appendixes to this plan.

Baseline Analysis of Stormwater Runoff on Campus

To better understand the relationship between stormwater and the campus, a stormwater runoff model was developed during the 2012–2013 academic year to represent and estimate, at a basic level, the impact of stormwater runoff from Yale's campus. For this effort, Yale's property was divided into basins representing the areas draining to specific sewers. The small spatial scale of these areas, called subcatchments, allows for a better representation of stormwater runoff in a given area by including the various differences in surface characteristics (slope, area, and percent imperviousness) from parcel to parcel.

For the purposes of this initial estimation effort, Yale University chose EPA's Storm Water Management Model (SWMM) Version 5.0 as the modeling software due to its simplicity and reliability. For each of the 63 total subcatchments constituting the campus, surface characteristics including slope, area, and percent imperviousness are used to estimate the volume and flow rate of runoff into a storm drain for a given rainfall event. Additionally, a representation of the conveyance system (either combined or separate storm sewers) was modeled to give insight into the runoff capacity and vulnerability to flooding at various points in the network. Figure 3 illustrates the subcatchments that make up the campus. The specific type of sewer

Figure 2: Summary of the Previous Analysis and the Associated Contributors

yale university student research

Student Stormwater Research

Stormwater Analysis of Yale University Campus—Aram Marks (M.Arch and M.E.M. 2010)

Stormwater Management Using Vacant Lots in New Haven, CT—Hazel Scher (B.S. Environmental Studies 2011)

Closing the Loop: Alternative Land Management Practices at Yale—Emily Stevenson (M.Esc. 2011)

"Sustainable Stormwater Management" (presentation)—Valerie Fuchs (Postdoctoral student 2010–2011) and Joan Suris Miret (Office of Sustainability Summer Fellow)

Examining the Efficacy of Connecticut Constructed Wetlands as an Urban Stormwater Best Management Practice—Lisa Weber (M.Esc. 2013)

2011 Payments for Ecosystem Service Class Reports

Aesthetics and Ecosystem Services at Yale

Ecosystem Services and Water at Yale

The Role of Ecosystem Services and Campus Climate at Yale

Pursuing Biodiversity as an Ecosystem Service: A Guiding Framework for Yale

An Ecosystem Service Plan for Yale's Central Campus

Ecosystem Services Plan: Yale University School of Medicine Campus

Science Hill: Managing for Ecosystem Services

yale university operations

Office of Facilities

- Grounds Maintenance
- Utilities & Engineering
- University Planning
- Sustainable Initiatives

Office of Sustainability

Environmental Health and Safety

yale university research centers

Center for Green Engineering
Julie Zimmerman and Paul Anastas

Hixon Center of Urban Ecology
Colleen Murphy-Dunning and Gaboury Benoit

Urban Ecology and Design Lab
Alex Felson

Anisfeld Lab
Shimon Anisfeld

Class on Payments for Ecosystem Services
Mark Ashton and Bradford Gentry

yale university initiatives

Urban Meadows, No Mow Zones

Stormwater Credits Achieved Through LEED Building

Campus Tree Inventory (Fall 2012)

Initial Assessment of the Yale Swale (September 2012)

Campus Tree Management Plan (2013)

new haven initiatives

Green Infrastructure Feasibility Scan for New Haven and Bridgeport, CT (January 2012)

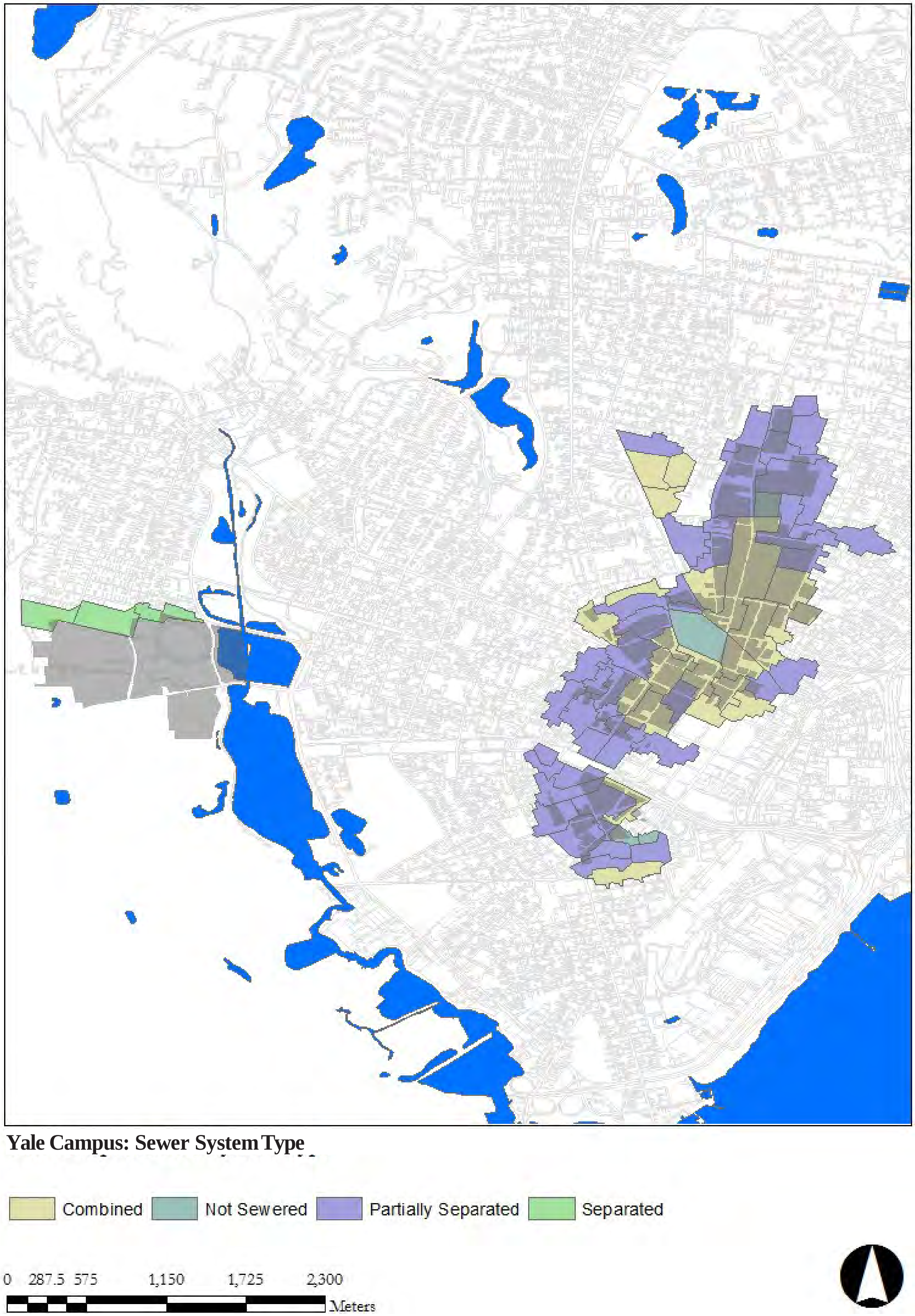
Connecticut Fund for the Environment's Save the Sound

City of New Haven

Greater New Haven Water Pollution Control Authority

Hazen and Sawyer

Figure 3: Campus Division into Subcatchments by Sewer Drainage Type



system that each subcatchment drains to is also shown. The partially sewered areas indicate that the combined sewers have been separated into storm and sanitary sewers but that the roof downspouts still are connected to the combined sewers. With a representation of Yale's campus and the associated sewer data, the model was run with a design rainfall event to represent a typical storm event that this area might experience during the year. Preliminary results were obtained from these runs to help understand the areas of campus that cause the greatest runoff.

Figure 4A and Figure 4B show two maps. Figure 4A illustrates the relative slope of the subcatchments compared with each other. As expected, the slopes found in the subcatchments that contain Science Hill are greater compared with the rest of campus. These higher slopes would likely cause greater runoff because of stormwater more quickly moving down the slopes. Figure 4B shows the preliminary results of the model, through an illustration of relative runoff volume associated with each subcatchment. The model results are largely based on how impervious each subcatchment is. The subcatchments that have greater impervious areas tend to result in more runoff. As expected, both Central Campus and the Medical Campus, which are both heavily paved, have the highest relative runoff from the subcatchments associated with them.

The SWMM software is not spatially oriented and does not integrate directly with GIS. Additionally, the current model simplifies many of the surface and subsurface characteristics of the stormwater runoff system. Although the model represents runoff dynamics on Yale's campus at a basic level, without use of a software that is spatially oriented and properly calibrated, results at this time are unlikely to have a high level of accuracy. Though the results do not accurately estimate runoff at this point, what is important to note is that it is likely that Science Hill's steepness and Central Campus's and Medical Campus's imperviousness have the greatest contributions of stormwater runoff to the sewer system. It is recommended that initial efforts be focused on one of these areas to have the greatest impact. A summary of the current model and recommendations on how to improve its accuracy are included as Appendix D.

Documenting Yale University's Existing Stormwater Assets

Though this plan serves as the development of a first comprehensive stormwater strategy, Yale has already taken steps toward managing its stormwater through various green infrastructure systems, including incorporating stormwater management into new building construction and landscapes. It is important to document existing green infrastructure already on campus as Yale continues to expand its portfolio of green infrastructure systems. The systems currently in place include stormwater storage tanks, green roofs, no-mow zones, drywells, vegetated filter strips, a bioswale, a preserved wetland area referred to as the Yale Swale, and the Yale Sustainable Food Project, which is included because of its urban agriculture component. Each feature contributes in some way to using or storing the stormwater that falls on campus.

Figure 4A: Relative Runoff Volume by Subctachment

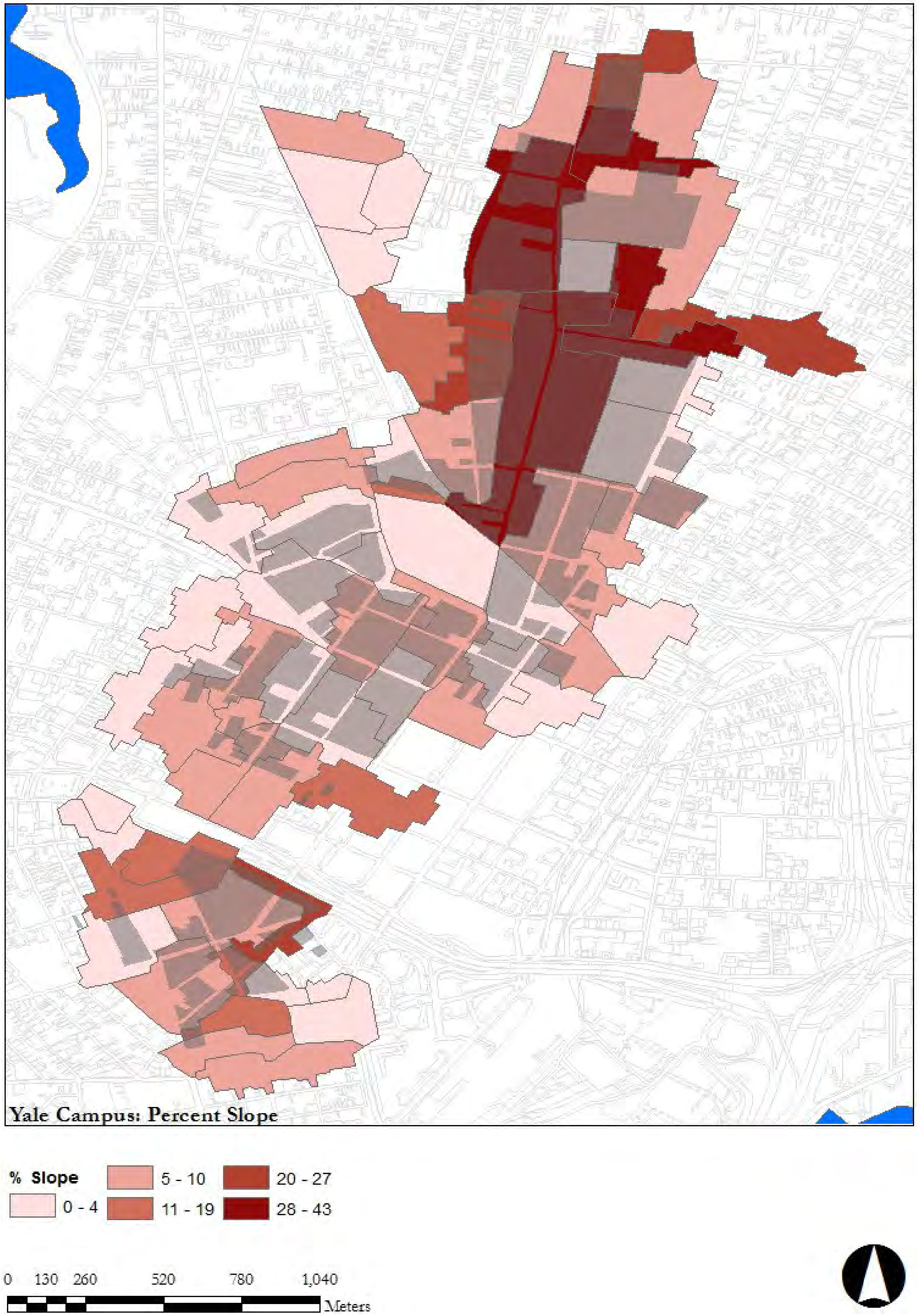


Figure 4B: Relative Runoff Volume by Subctachment

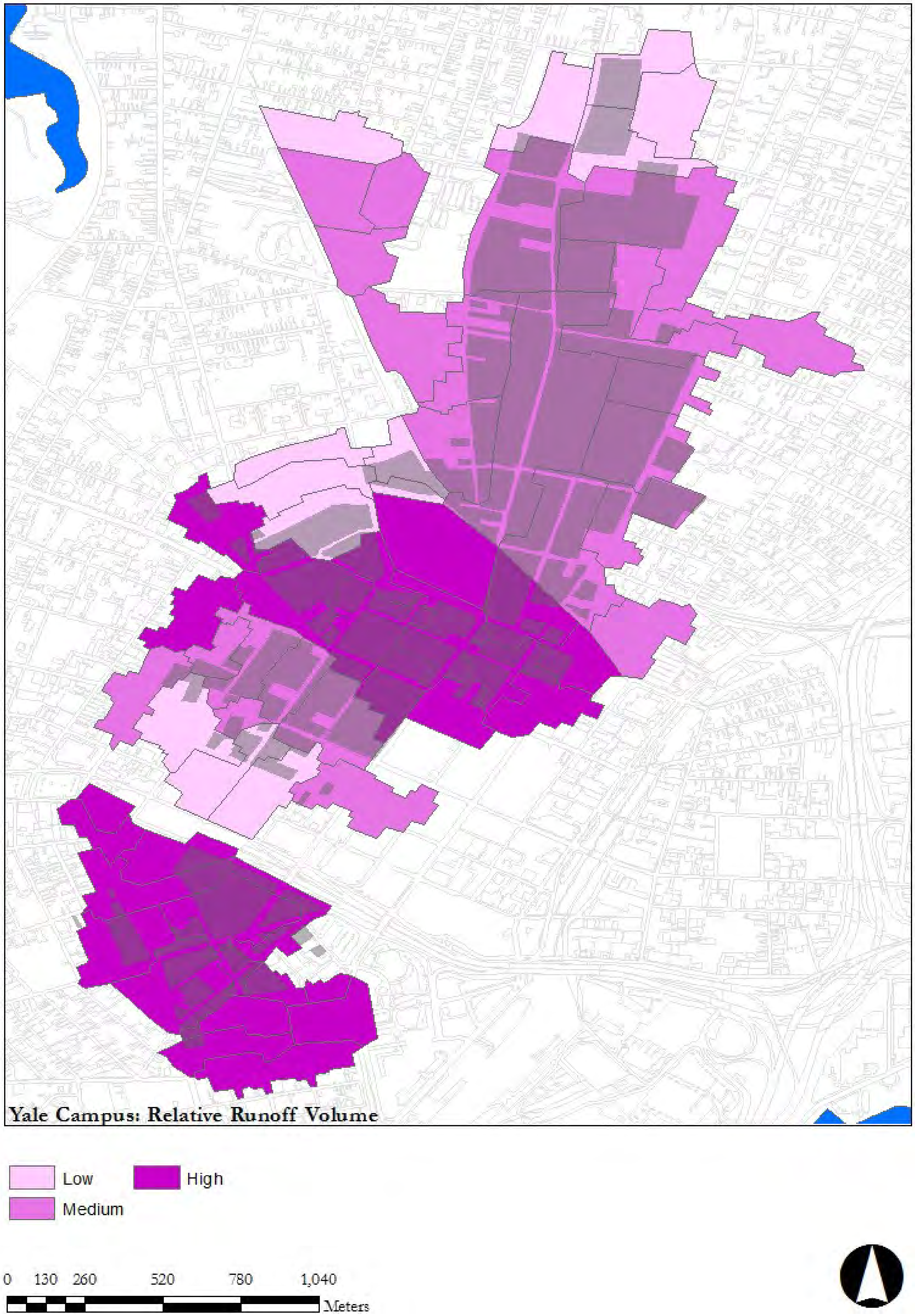


Figure 5A: Approximate Locations of Yale University's Stormwater Assets (Central and Medical Campuses)

Source: Yale University LEED Building Submittal Database. Viewed May 2013.

Figure 5B: Approximate Locations of Yale University's Stormwater Assets (Science Hill and Divinity Campuses)

Source: Yale University LEED Building Submittal Database. Viewed May 2013.

Figure 5A and Figure 5B show the specific types and the approximate locations of each of these systems. As part of Yale's planning efforts, these assets should continue to be maintained and monitored to learn more about each asset's contribution to managing campus stormwater in a comprehensive and responsible way.

Based solely on the known volume attributed to the storage tanks, Yale currently has 42,500 gallons of storage volume used to prevent stormwater from entering the sewers each year.

Beyond the structural and engineered systems that Yale has put in place, Yale maintains over 2,000 trees on its campus. Using the results from a tree survey conducted in fall of 2012 by the Urban Resources Initiative, it is estimated that the trees found on Yale's campus help prevent over seven million gallons of stormwater from entering the sewer system each year.[3]

Sustainable Stormwater Management Strategies

From the work thus far in the development of this plan, we do not yet have a complete understanding of the volume of stormwater runoff from campus property created from storm events and how it can be managed. Without this understanding it is di∞cult to set an informed quantitative reduction goal. To move toward setting this type of goal, this plan identifies actionable strategies to investigate stormwater impacts on the campus. These strategies are intended to educate university staff and position the university to confidently define a reduction goal in 2016. The goals and strategies will be revisited at regular intervals as part of an adaptive stormwater management approach described in Appendix C. This adaptive approach creates flexibility to make adjustments as greater knowledge is gained.

The following lists the strategies for 2013–2016 that will help Yale establish an improved understanding of the potential for green infrastructure on campus and allow the university to comprehensively manage its stormwater in the future:

Strategy 1 Establish an improved baseline understanding of stormwater on campus.

Strategy 2 Investigate the potential of green infrastructure techniques on campus.

Strategy 3 Integrate sustainable stormwater management into Yale University's design and planning standards.

Strategy 4 Develop the management plan goal(s) using information gathered through the 2013–2016 plan.

The following further describes these strategies.

Strategy 1 Establish an improved baseline understanding of stormwater on campus

Improve the current stormwater runoff model to create a baseline of the quantity of stormwater runoff on campus. Measure the impact of the existing green infrastructure on campus.

To understand the quantity of stormwater runoff from the campus that needs to be managed, the initial strategy for this management plan is to create a baseline of the stormwater existing conditions in terms of runoff and its management on campus. This strategy will focus on the following two tactics:

Tactic A Update the stormwater runoff model to include all of Yale University's properties and calibrate the model with sewer system flow-monitoring data.

Tactic B Install monitoring equipment to monitor the existing green infrastructure projects on campus and collect data to understand their impact.

The stormwater runoff model developed in the 2012–2013 academic year served as a first step toward estimating the stormwater volume created by the impervious surfaces on campus. The effort helped identify gaps in data and identify current high-runoff-creating areas of campus. Though this was an important first step, a more comprehensive and accurate model will be needed in the next phase of the management plan to help Yale University create a reduction goal.

With the pilot project work of Strategy 2, performance data on green infrastructure can be incorporated into the model to use it as a planning tool to estimate how the implementation of green infrastructure in a comprehensive way will influence the baseline. Before the model can be used in this way, however, the stormwater runoff model should be improved to help plan stormwater management at a campus level. In the coming years, the model should include all of Yale's properties to lead to an improved understanding of the stormwater baseline. It is recommended that Yale invest in model software that is integrated with GIS to spatially and more accurately estimate the runoff quantities associated with each area. Additionally, the model should be calibrated with real sewer flow data to check that the model simulates the conditions found during rain events. More specific information on recommendations for improving the current model is included as Appendix D.

The baseline model should include the projects on campus that have already been implemented, including the stormwater assets described above. To include these, the projects will need to be monitored to understand the quantity of stormwater reduced by each project. Monitoring equipment should be installed and data collected to understand how stormwater is reduced by these projects. The data should be incorporated into the baseline.

Strategy 2 Investigate the potential of green infrastructure on campus

Implement a green infrastructure piloting program to collect data on the performance of the projects on campus. Survey and document campus roof drains by June 30, 2014. Create a plan that will phase implementation of projects that disconnect campus roof drains incorporating green infrastructure technologies.

Before comprehensively implementing green infrastructure on campus, Yale must understand if the investment in green infrastructure will result in significant reductions in stormwater runoff. This strategy will be approached with the following tactics:

Tactic A Create a pilot program to implement green infrastructure, monitor its progress, and understand its maintenance needs.

Tactic B Survey roof downspouts from buildings on campus and create a plan to disconnect the downspouts and incorporate pilot green infrastructure projects, when possible.

Because the performance of green infrastructure techniques is site- and region-specific, Yale University will need to pilot green infrastructure projects on campus to demonstrate the potential for the systems. To that end, Yale will create a pilot program that tests an array of technologies on campus. Analysis and recommendations for the locations and types of potential green infrastructure projects are included as Appendix E.

Yale seeks to manage the runoff from its impervious areas on campus. To achieve this, Yale will investigate how to manage stormwater runoff from one of the campus's main impervious surfaces, the roofs of Yale's buildings, while simultaneously testing potential green infrastructure options. Many of the roof drains at Yale are directly connected to New Haven's sanitary and combined sewer system, posing a risk for CSOs even in areas where the storm sewers have been separated from the sanitary sewers.

Identifying and disconnecting downspouts where direct drainage to a sewer is not necessary will reduce Yale's stormwater footprint and provide opportunities for capturing and using stormwater for irrigation purposes. Recommendations and analysis on how to implement such a program, including conducting a downspout survey and prioritizing disconnections, are included as Appendix F. Constructing green infrastructure pilot projects, as part of the downspout disconnection strategy and the pilot program, will reduce potential for runoff to create new problems as well as help identify effective site-specific green infrastructure technologies.

Once the pilots are constructed, the projects should be monitored to better understand the predicted performance. During the design of these pilots, consideration should be given to the methods and instrumentation for monitoring the sites once the projects are in place. Recommendations on how this type of monitoring program could be organized are provided as Appendix G. During design, consideration should also be given to how the pilot projects and future projects will be maintained. Appendix H offers ideas on how maintenance of green infrastructure can be incorporated into the operations of Yale's campus, through both current grounds maintenance and the further development of Yale's campus as a living laboratory, where students and faculty can use the campus for research.

Strategy 3 Integrate stormwater management into Yale's design and planning standards

Develop campus design standards and maintenance policies that specify preference for green infrastructure and reductions in stormwater runoff.

As part of implementing sustainable stormwater management on campus, future projects should consider how the development of the project site can be used to achieve enhanced stormwater management, including any renovation projects. The incorporation of sustainable stormwater management techniques and practices into the design standards and maintenance of Yale's campus will ensure stormwater mitigation is addressed in new and current project development. Recommendations and analysis for how these goals might be achieved are provided as Appendixes H and I.

Strategy 4 Adapt management plan goals using information gathered

Identify next progressive stormwater management goal by June 30, 2016.

The Sustainable Stormwater Management Plan is designed to initiate an adaptive and iterative process to reduce the impact of stormwater on Yale's campus. As sustainable stormwater management principles are incorporated into the university's management strategy, it will be important to periodically assess and revise stormwater management goals, as part of the recommended adaptive management process. In 2016, with a comprehensive understanding of stormwater on campus, Yale University will be ready to set an informed campus stormwater management goal.

Next Steps for Sustainable Stormwater Management

As Yale moves forward with this vision and the associated strategies, it is important to consider how to look for opportunities to improve its campus-wide knowledge of stormwater management. In the development of this plan, much of the current information is associated with Central Campus and Science Hill. More knowledge and information must be gathered about the landscapes and buildings at the Medical Campus, the athletic facilities, the golf course, and West Campus. During part of the next three years, a special effort should be put toward gathering information to include these areas.

Beyond a campus understanding, individual and group engagement should be incorporated into the continued stormwater management process. Because Yale University operates through the work of many individuals and departments and interacts with an assortment of students, faculty, staff, and visitors as well as the City of New Haven and its residents, it is important to consider the need to engage stakeholders as this program moves forward. Many of these individuals and groups may need to participate in the maintenance and monitoring of these projects. Other individuals may directly benefit from their construction in the first place, as may be the case for the City of New Haven.

Partnerships will be extremely important to the success of this effort, and engaging individuals who could be affected by this work early in the design process and throughout the implementation phase will only help in that success. Appendix J highlights the potential partnerships that could be established through this work and how Yale University can play an important role in helping green infrastructure succeed throughout New Haven, the region, and the United States.

Conclusion

Yale has chosen to reduce its environmental impact through mitigating its stormwater runoff. With this decision, Yale has the opportunity to be a leader in sustainable stormwater management among universities and within this region. This plan serves as a first step and sets the stage for an adaptive management approach that will gradually build on the knowledge gained during each phase of the management effort. With each stormwater planning period, further progress will be made toward a campus that reduces the impact of its stormwater runoff on the environment.

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Notes

1 Information taken from "Bldgs_ACADEMIC.shp" and "ImperviousArea.shp." Yale University GIS File.

2 Estimate based on approximated runoff from the Stormwater Management Model (SWMM), 2013.

3 Estimate based on 2013 Yale University Campus Tree Survey data run with U.S. Forest Service's I-Tree Streets Software.

Appendix A

Stormwater Management Drivers and the Green Infrastructure Trend

Contents

Introduction

Faced with stormwater and wastewater management concerns from environmental regulations, budgetary and capital restrictions, aging infrastructure, and runoff-producing impervious land cover, cities are looking for less expensive alternatives to the traditional approach of large-scale sewers and storage tanks, or gray infrastructure. Instead, cities are turning to green infrastructure, or tactics and systems that slow and/or reduce the flow of stormwater into a sewer system for its ability to reduce the cost of gray infrastructure while effectively and sustainably managing stormwater. This shift in planning and design away from large, intensive, and invasive gray infrastructure projects to lower-impact "green" development techniques stems from a number of drivers and trends that fall into three distinct categories:

Regulatory A result of federal, regional, state, or local policies to protect the integrity of our nation's waters.

Economic Bridging the gap between the costs of effective stormwater and wastewater management, and limited financial resources.

Social An outcome of the urban renewal movement to improve community livability.

Moreover, when evaluating the overarching drivers and trends associated with implementing green infrastructure, it is necessary to evaluate the time, scale, and scope of the project.

The shift from the traditional reliance on gray infrastructure to the emergence of green infrastructure is critical due to the pervasiveness of gray infrastructure in most cities, especially as nearly 80% of Americans live in urban areas often characterized by poor public health, economic downturn, and lack of access to recreational amenities and green spaces (American Rivers et al. 2012). With urban population centers continuing to expand, new infrastructure becoming a necessity to handle additional flows, and old infrastructure in need of repair, turning to green infrastructure techniques has become the new stormwater management frontier. The purpose of this appendix is to discuss the reasons why cities and campuses across the country are incorporating green infrastructure in their efforts to sustainably manage stormwater.

Regulatory Drivers for Increased Stormwater and Combined Sewer Management

Regulation acts as a cornerstone driver for municipal stormwater management, and as such provides the foundation for many of the subsequent drivers and trends that lead to current green infrastructure practices.

The major statute governing water quality in the United States is the Clean Water Act (CWA) of 1972. The goal of the CWA is to "restore and maintain the chemical, physical, and biological integrity of our nation's waters."[1] To address the deleterious effect municipal stormwater has on water quality in receiving water bodies, in 1987 Congress added section 402 to the CWA. Section 402 established the National Pollutant Discharge Elimination System (NPDES), permitting programs for stormwater (National Research Council 2008). A NPDES permit is the main regulatory action available to lawmakers to ensure that any point source discharge,[2] in this case stormwater discharge from municipal pipes, does not exceed the water quality standards outlined in the CWA. In 1990, the U.S. Environmental Protection Agency (EPA) enacted section 402 when it issued the Phase 1 Stormwater Rules. This required NPDES permits for operators of municipal separate storm sewer systems (MS4s) serving populations over 100,000 and for runoff associated with industry, including construction sites five acres and larger (National Research Council 2008). Nearly a decade later, the EPA issued the Phase II Stormwater Rules, expanding the requirements for NPDES permits to small MS4s and construction sites ranging from one to five acres (National Research Council 2008).

In response to the water quality concerns from municipal stormwater, the EPA created several avenues through which regulators can operate.

Combined Sewer Overflow Control

The EPA initiated the National Combined Sewer Overflow Control Policy in 1994. This policy contains guidance on how to make combined sewer overflow (CSO) control as cost effective as possible and outlines a flexible approach to CSO management. This policy also led to the creation of long-term control plans. The plans are updated on a regular basis and are a means to ensure that cities are making steady progress toward compliance with CWA regulations (U.S. EPA 2002). Nearly 800 municipalities across the nation are required by the CWA to reduce and control CSOs.

Municipal Separate Storm Sewer Systems Permits

Polluted stormwater runoff is also commonly transported through MS4s, and often this municipal runoff is discharged, untreated, into local water bodies. In order to prevent harmful pollutants from washing into an MS4,[3] the operators must obtain an NPDES permit and develop a stormwater management program (SWMP) (U.S. EPA 2012). Phase I MS4s (serving over 100,000 individuals) are covered by individual permits, whereas Phase II MS4s are covered by a general permit to reduce the contamination of stormwater runoff and prohibit illicit discharges.

Total Maximum Daily Loads

The CWA requires total maximum daily loads (TMDL) be developed for those water bodies identified as impaired by a state, territory, or tribe. Waters are designated as impaired because they are too polluted, or otherwise degraded, and do not meet the quality standards set by the state, territory, or tribe. The TMDL sets the maximum amount of a pollutant that the water body can receive and still meet applicable water quality standards, as defined under CWA section 303d (U.S. EPA 2013). Essentially, the TMDL is a science-based plan to ensure the water body will attain and maintain water quality standards.

Green vs. Gray

The alternative to the innovative "green" examples seen in Philadelphia, Washington, DC, and Baltimore has been to continue with the traditional gray infrastructure approach to stormwater management. One prominent example is the City of Chicago, which adopted the Tunnel and Reservoir Plan (TARP) in 1972 to comply and meet federal water quality regulations. After major storm events, pumping stations dewater the vast underground system for treatment before discharge into Lake Michigan (Metropolitan Water Reclamation District of Greater Chicago 2013). In design and construction for over 30 years and still not complete, TARP had cost $3.5 billion as of 2008; this number has continued to rise as the project progresses (The Robbins Company 2008).

In conclusion, cities like New Haven face two types of regulatory drivers — one focusing on reducing CSOs, and one focusing on improving the overall quality of the municipal stormwater being discharged into the receiving water bodies. One option is to make considerable capital investments to separate the combined sewer systems or use traditional gray infrastructure, like deep tunnels and cisterns, to handle the additional wet weather flows in order to meet these regulatory requirements. However, as detailed above, sustainable stormwater management, focusing on using green infrastructure to mimic natural processes, has emerged as a cost-effective, low-impact approach to handling additional flows and mitigating the deleterious water quality impairments described in the next section on economic drivers.

The Economic Analysis of Stormwater Infrastructure

Cities face financial limitations when managing stormwater systems to meet regulatory requirements for a variety of reasons. The decisions surrounding the implementation of green versus gray infrastructure projects as means of stormwater management therefore often include funding, capital investment, and operating cost considerations. The economic framework behind stormwater management, as it pertains to green infrastructure, can be broken down at the macro level into funding opportunities (carrots) and cost mitigation (sticks), in both short- and long-term outlooks.

Cost-Mitigation Strategies

Gray infrastructure is expensive. On the system level, whether assessing the investment required for new pipes and storage units to handle increasing flow, separating combined sewer systems, or maintaining depreciating, already installed assets, many municipalities have di∞culty procuring the capital necessary to bring structures up to regulatory standards. On the granular level, actions to reduce flow from individual properties, such as disconnecting stormwater drainage into sewers, can be costly and cumbersome; proper disconnection estimates in New Haven can range as high as $18,000 per property.

Table 1

	gray	green
installation costs	High raw materials and production costs (concrete, heavy machinery, etc.) Opportunity cost of residential/ commercial disruptions Environmental degradation from installation	Relatively smaller installments, spread across various sites Competing contractors workforce Fewer residential/commercial disruptions Environmental improvement
maintenance costs	Little to no maintenance done until absolutely necessary, causing large expenditures when repairs needed Repair costs considered when repair occurs Maintenance needs to be done by trained professionals	Maintenance required regularly, causing smaller but more frequent expenditures Repair costs considered ahead of time—service contracts Under certain conditions, public, nonprofits, and other untrained professionals can maintain Improper maintenance reduces functionality
long-term/ social costs	Gray assets depreciate over time Long-term environmental degradation Stormwater management removed from public discourse—assets are "buried" in the ground	Green assets appreciate over time Co-benefits of green assets help offset other costs Public made aware of and educated about stormwater management

Table 1 helps further define all of the costs associated with green versus gray infrastructure projects.

The resulting trends from the costs associated with gray versus green infrastructure vary in approach, and Philadelphia is a great example because it embodies the full scale of these approaches in one city. On one end of the spectrum, Philadelphia is very planned and calculating in the ways it utilizes green infrastructure—making a concerted effort to maximize the value of its already installed pipeline system by using green infrastructure to reduce flow into the system, thereby reducing depreciation and maintenance costs. On the other end of that spectrum, Philadelphia employs an opportunistic approach to deciding where it will actually install green infrastructure assets—it's cheaper to make installations where the ground is already ripped up, so the Philadelphia Water Department (PWD) will place retention basins where other city agencies are breaking ground with the hope that enough installments will reach their higher-level goals.

Such approaches allude to more general trends across cities—a trial-and-error approach to determine which designs work best at which sites and to what extent they are effective, and a "leap of faith" approach that assumes the expenditures cities are making now will be su∞cient to reach the end goals of higher water quality:

- The PWD acknowledges it has turned to green infrastructure because the cost-prohibitive nature of gray infrastructure requirements leaves it no other choice.
- The New Haven Water Authority is weary of green expenditure investments without further evidence behind the effectiveness of green infrastructure.
- New York has already gone through several iterations of bioswale installments and only now is gathering robust data on effectiveness.
- Washington, DC, has put forth a plan to meet regulation by green infrastructure means, but contingent on the EPA granting a timeline extension for proper pilot projects to gauge effectiveness.

Funding Opportunities

It is left up to the cities to develop and implement mechanisms to finance their investments in green infrastructure. From water bills through state revolving funds (SRF) to stormwater utilities, cities can choose from a variety of options to raise capital. Because each city is unique in its stormwater management profile and overall issues, it will require different solutions and approaches to comply with the regulations.

In Philadelphia, for example, a meter-based billing system has been in place since 1968. Using this method, commercial properties' stormwater fees are based on the "property's potable water usage as measured by the size of the water meter on the parcel" (Levin and Valderrama 2012). A key disadvantage of the meter-based measuring is that there is little correlation between the stormwater fee and the volume of runoff generated by the property (e.g., a parking lot may have a small water bill, but the magnitude of burden imposed on the municipal stormwater infrastructure by the runoff generated from the surface is significant).

To solve this issue and raise adequate funds to support the investment in stormwater management, in 2010 the PWD transitioned from a meter-based to a parcel-based fee structure. Under the new fee structure, all publicly and privately owned properties are billed based on the property's gross area and impervious surface area—"a figure that is directly correlated to the volume of stormwater runoff that the parcel generates." The surface-based billing system allows commercial properties with smaller meter bills but large impervious surfaces to pay significantly higher fees. A study by the National Resources Defense Council (NRDC) focused on the effect on the new billing system on large property owners. According to the study, "The Philadelphia airport, which uses very little water but is almost entirely paved, will see its monthly stormwater fee raised by $126,000 per month, while the relatively unpaved University of Pennsylvania campus, which uses a large amount of water owing to its hospital and other campus facilities, will save approximately $11,000 per month on stormwater fees, as compared to the meter-based fee structure." The equation below is used to calculate the stormwater charge in Philadelphia (Philadelphia Water Department, n.d.):

Stormwater Charge = (Gross Area Rate × Gross Area of Property) + (Impervious Area Rate × Impervious Area of Property)

Another source of funding for the PWD is government funding and loans. The American Recovery and Reinvestment Act (ARRA) of 2009 provides funding for water and wastewater treatment projects to states through existing state revolving funds. In Pennsylvania, these SRF programs are administered by the Pennsylvania Infrastructure Investment Authority (Pennvest). The PWD has submitted projects worth $241.4 million to Pennvest and has received an additional $199.7 million on non-ARRA low-interest loans for water and sewer piping, water treatment, and green infrastructure. Approximately $30 million will go toward green infrastructure projects in different neighborhoods in Philadelphia.

Baltimore is another example of a city looking for an appropriate and acceptable mechanism to finance stormwater management projects. While Philadelphia's main objective is managing the CSO problem, Baltimore's efforts are focused on improving the quality of the water in the Chesapeake Bay. The city has separate storm- and wastewater systems, but the infrastructure is getting old and causing leakages and water pollution.

In the past couple of years, the city has developed a stormwater management program (SMP) that will "assure a high quality of life for citizens and continued compliance with applicable laws." A key element of the program is a separate stormwater fee for funding that is now required by Maryland State Law HB 987. In 2012, the residents of Baltimore approved the development of Stormwater Utility, which will manage the stormwater utility fee. As of July 2013, however, the fee had not been fully developed and implemented. Government o∞cials and stakeholders are working on structuring the fee and preparing to meet any public and institutional opposition. Similarly to the Philadelphia fee, the proposed stormwater fee will be charged to property owners within Baltimore based on the amount of impervious surface area on their property. The proposed rates are as follows (Clean Water Baltimore, n.d.):

customer	quarterly Fee
Tier 1 Residential	$11.88
Tier 2 Residential	$18.00
Tier 3 Residential	$36.00
All other Properties	$18.00 / ERU

Note: ERU = Equivalent Residential Unit (1,050 sq. ft. of impervious surface)

As is the case in many states, state- and municipality-owned properties are exempt from these fees. This is one reason why the projected fees above are higher than they would be if all properties were subject to the stormwater fee. Some large property owners, like Johns Hopkins University, for example, have been proactive and taken measures to reduce the impervious surfaces on their properties or install infrastructure that will reduce the runoff generated from them or allocate to pay a certain amount to the city in lieu of stormwater fees.

Yet a different approach is applied by the City of New York. Under PlaNYC's Green Infrastructure Plan launched by Mayor Bloomberg in 2010, projects focusing on reducing CSOs installing green infrastructure will receive grants and funding from the city. In March 2012, the Department of Environmental Protection in New York City signed an agreement with the New York State Department of Environmental Conservation to incorporate the New York City Green Infrastructure Plan into Clean Water Act compliance (NYC.gov 2012). As a result of the agreement, "the City will invest approximately $187 million over the next three years and an estimated $2.4 billion in public and private funding over the next 18 years in green infrastructure technologies. Of the $2.4 billion investment, $1.5 billion will come from public funds while $900 million is expected from new development. In total, the agreement will save $3.4 billion through elimination or deferral of gray infrastructure investments while still achieving equivalent water quality benefits. By shifting from the exclusive use of gray infrastructure to green infrastructure, the City will reduce combined sewer overflows by more than 12 billion gallons per year by 2030, a 40 percent reduction" (NYC.gov 2012).

The examples above illustrate the variety of approaches cities take to provide funding to support their stormwater management efforts. Driven mainly by the possibility of meeting regulatory requirements less expensively, cities are looking for innovative, effective, and site-fitting mechanisms to raise capital for green infrastructure projects. It is evident that cities are realizing the benefits of green infrastructure in their strategies to stay in compliance with the regulators. New Haven is staying behind the trend of investing in green infrastructure and taking a closer look at what other cities are doing before developing and implementing its own strategy.

The Private Side

Green infrastructure investments are also encouraged by involving nonmunicipal groups such as private landowners and nonprofits in ways that save public entities both time and money, and provide financial incentives to participants. In Washington, DC, on the local level, citizens receive incentives in the form of rebates and payments for green installations, which are in turn coordinated and administered by nonprofits and implemented by independent contracts. On the district level, market-based solutions such as a credit-trading exchange for stormwater retention are currently being planned. In Baltimore, citizens whose properties extend to the grounds of a river restoration project formed a local alliance to help clean and regulate the area.

Updating Building and Zoning Codes

The implementation of stormwater management measures is directly influenced by an array of overlapping and conflicting building codes, standards, and regulation. Due to their importance to the advancement of green infrastructure (GI) tools, zoning, building codes, and engineering and infrastructure standards and practices are currently going through some significant changes that will affect the future of sustainable stormwater management. Examples of revised standards include separate ordinances for new and infill development, integrated stormwater and management growth policies, unified development codes, and design review incentives to speed permitting.

Zoning

- Due to its nature and the codes that govern it, zoning can have a significant effect on the amount of impervious area in a development and on what constitutes allowable stormwater management.

- As a result of changes in urban planning thinking, fluctuations in legal constraints, and shifts in political views and priorities, zoning codes have evolved and adjusted over the years.

- Example: Landscaping ordinances apply to certain commercial and institutional zoning categories and specify that a fixed percentage of site area be devoted to landscaping or screening. These codes may require as much as 5% to 10% of the site area to be landscaped, but not often reference opportunities to capture and store runoff at the source, despite the fact that the area devoted to landscaping is often large enough to meet some or all of their stormwater treatment needs (U.S. EPA 2010).

Building Standards

- Building codes define minimum standards for the construction of virtually all types and scales of structures.

- Except for a few areas (geotechnical design standards, for example), building codes have limited direct impact on stormwater management.

- Geotechnical design standards do not facilitate the use of landscape stormwater management tools like porous pavement, bioinfiltration, and extended detention.

- The City of Los Angeles is in the process of updating its building codes to facilitate easier implementation of green infrastructure, but it is not clear if it will cover the use of some low-impact design practices such as on-site infiltration. As it is, the 2002 Building Code now in use requires builders to remove water away from the building using concrete or another "non-erosive device" (U.S. EPA 2010).

Engineering and Infrastructure Standards and Practices

- Engineering standards and practices for public rights-of-way complement building and zoning codes that control development on private property. They list requirements for public utilities such as stormwater and wastewater, roadways, and related basic services.

- Changing engineering and infrastructure standards and practices is a di∞cult and complicated process. Specific types of equipment, maintenance protocols and procedures, and the need for extensive training further discourage changes in established standards and procedures.

- Traditional drainage codes can often conflict with effective approaches to reducing runoff volume or removing pollutants from stormwater. Examples of such codes include requirements for positive drainage, directly connected roof leaders, curbs and gutters, lined channels, storm-drain inlets, and large-diameter storm-drain pipes discharging to a downstream detention or flood-control basins.

Despite the difficulties associated with updating and changing zoning and building codes and standards, a number of innovations have been introduced to make them better suited for stormwater management.

Separate Ordinances for New and Infill Development

Stormwater planning can include the development of separate ordinance for new development, redevelopment, and infill. Wisconsin provides a helpful illustration for developing separate ordinance. For a new development, the requirement is to reduce total suspended solids (TSS) by 80%, maintaining the pre-development peak discharge for the two-year, 24-hour storm, infiltrating 90% of the pre-development infiltration volume for residential areas, and infiltrating 60% of the pre-development infiltration volume for nonresidential areas. For redevelopment, the only difference from new development is that the TSS requirement is less, at 40% reduction. Requirements for existing developed areas in incorporated cities, villages, and towns do not include peak flow reduction or infiltration performance standards, but the municipalities must achieve a 40% reduction in their TSS load by 2013 (U.S. EPA 2010).

Integrated Stormwater Management and Growth Policies

An example from San Jose, California, illustrates an innovative approach to link water quality and development policies that emphasize higher density infill development and performance-based approaches to achieving water quality goals. The city's strategy encourages stormwater practices such as minimizing impervious surface and incorporating swales as the preferred means of conveyance and treatment. In urbanized areas, the policy goes on to define criteria to determine the practicability of meeting numeric sizing requirements for stormwater control measures, and identifies alternative measures for cases where on-site controls are impractical.

Unified Development Codes

A unified development code (UDC) consolidates development-related regulations into a single code that represents a more consistent, logical, integrated, and efficient means of controlling development. Examples of UDC development standards are circulation standards that address how vehicles and pedestrians move, including provision for adequate emergency access.

Design Review Incentives to Speed Permitting

To motivate property owners to reduce their on-site stormwater runoff, municipalities often offer financial incentives like discounts, credits, and development rebates, providing property owners with the option to either improve and retrofit their existing properties or implement and incorporate on-site green infrastructure. Such improvements help lessen the burden on public infrastructure for dealing with stormwater management.

The Social Benefits of Green Infrastructure

Co-Benefits

Unlike gray infrastructure assets that serve limited, specific purposes, green infrastructure assets produce multiple benefits, the values of which help offset installment costs and provide a platform on which to bring together multiple constituencies.

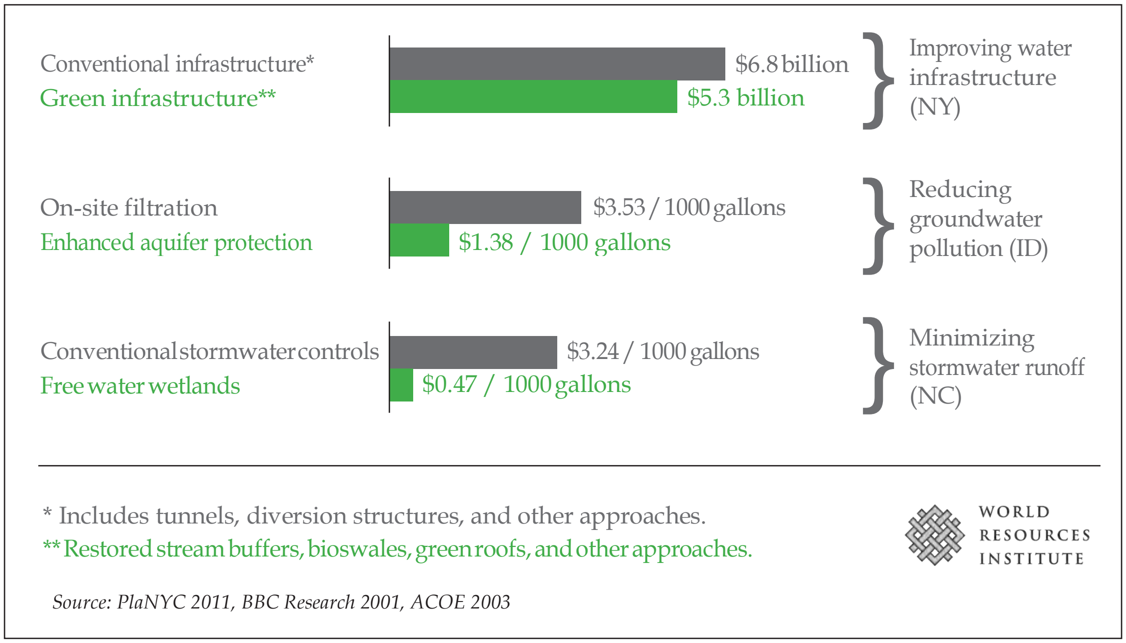
Climate Resilience Planning and Flood Control

Investments in green infrastructure are not driven only by the presence of regulations and the need to be in compliance. Green infrastructure reduces flood-related damages by reducing the amount of stormwater that enters the public system via increased infiltration and retention rates. Poor stormwater management can play an important role in localized flooding events and damages to property and public infrastructure. According to the American Rivers report *Banking on Green*, the "Federal Emergency Management Agency (FEMA) estimates that 25% of the $1 billion in annual damages from caused by flooding are linked to stormwater" (American Rivers et al. 2012).

Flooding as a result of climate change has significant economic effects as well. While larger flood events that lead to catastrophic damages are rare, smaller but frequent events may create serious economic burden on affected communities. The traditional approach to reducing the impacts of flooding has been to capture, convey, and release runoff with an emphasis placed on large storm events. Among some of the common green infrastructure tools used to target flood management are green roofs, bioretention, water quality swales, and infiltration basins and trenches. These tools are used to restore the hydrologic function of an area as well as improve and enhance water quality. As the EPA's *Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure* reports, "Because a significant portion of the flood losses is associated with small, frequent storms, green infrastructure is well-suited to manage these flows, and therefore provides significant flood loss reductions on an average annual basis" (American Rivers et al. 2012).

On-the-ground case studies from a variety of locations across the country have also documented the effectiveness of green infrastructure not only to reduce runoff volumes and provide water quality treatment, but also to help address flooding impacts in a cost-effective manner. A study by the World Resources Institute looked at the savings cities would incur by using green infrastructure over gray. In the case of New York City, for example, the green infrastructure option results in a cost savings of more than $1.5 billion. Similar results have been observed by government o∞cials in North Carolina and Idaho as well (Talberth and Hanson 2012):

Figure 1: Examples of Green vs. Gray Infrastructure Costs



Aesthetics and Community Enhancement

Green infrastructure not only reduces stormwater runoff, but also can enhance community livability if well designed and maintained. Green infrastructure can aid in the transformation of deteriorated or abandoned spaces from urban eyesores to community assets such as parks and small urban farms. In addition, several studies indicate that increased green space leads to sizable economic gains from avoided medical expenses. Finally, incorporating greenscapes across the urban area not only mitigates the water quality problems, but also improves the social and economic composition of communities.

Key findings from research indicates that green infrastructure has multiple benefits to improve community livability:

- Reduced crime
- Increased property values
- Reduced rates of mental and behavioral illnesses
- Additional "green" jobs
- Enhanced air quality
- Improved biodiversity
- Carbon sequestration
- Reduction of the urban heat island effect

Federal Initiatives and Partnerships

In response to the increased demand for federal support when implementing green infrastructure, federal agencies have created collaborative efforts to promote and provide technical and financial assistance for sustainable stormwater management techniques.

- U.S. EPA's Urban Waters Federal Partnership
- Department of Housing and Urban Development, U.S. EPA, and Department of Transportation's Partnership for Sustainable Communities
- President Obama's America's Great Outdoors Initiative

Nonprofit and Educational Partnerships

Cities and universities are forming innovative and interdisciplinary collaborations in order to advance sustainable stormwater management practices, including green infrastructure. Often, these partnerships are between universities, nonprofits, local and state governments, and the private sector. These collaborative efforts help provide resources for implementation and monitoring, as well as innovative funding strategies. A salient example of this type of partnership is the work that the Parks and People Foundation is doing in Baltimore, Maryland. The Foundation is working with city agencies on greening vacant lots, greening schoolyards, planting street trees, and greening public housing. As Yale moves forward with the Sustainable Stormwater Management Plan, these innovative partnerships should be prioritized.

Case Studies

Baltimore, Maryland

The City of Baltimore is under regulatory pressure to preserve the integrity of the local rivers and streams, the Baltimore harbor, and the Chesapeake Bay. Under the Watershed Implementation Plan, the Maryland Department of the Environment mandated that all counties and Baltimore make specific reductions in phosphorus and nitrogen pollution. By 2020, Baltimore must reduce phosphorus loads by 48% and nitrogen load by 30% to achieve regulatory compliance. In order to meet the goals outlined in the various TMDLs that apply to the city, their management efforts will focus on implementing green infrastructure, including bioretention areas, green roofs, permeable pavement, and increased urban tree planting. This management effort involves multiple city agencies, as well as collaboration with other environmental initiatives, like the Growing Green Initiative and Urban Waters Partnership.

Source: Baltimore City Phase II (2010).

Philadelphia, Pennsylvania

The City of Philadelphia is faced with the problem of controlling combined sewer overflows, with nearly 13 billion gallons of untreated sewage mixed with polluted municipal stormwater runoff into the major city waterways annually. To achieve compliance with the CWA, the Philadelphia Water Department created the Green City, Clean Waters plan. The plan is Philadelphia's "25-year plan to protect and enhance our public waterways by managing stormwater with innovative green infrastructure" (Philadelphia Water Department 2013). Green City, Clean Waters set a goal to transform 10,000 acres of impervious area in its combined sewershed into "greened acres" over the next 25 years (a greened acre is one in which the first inch of rainfall from any given storm is managed on-site). This plan is helping the city meet the regulatory requirements while working to revitalize its neighborhoods by using green infrastructure for urban wet weather pollution control.

Source: Philadelphia Water Department (2013).

Syracuse, New York

The city is facing the problem of nearly 3,000 vacant parcels spread across the city. This raises concerns about liabilities, public safety, litter, property maintenance costs, and overall unappealing characteristics. The city has created a plan to add green infrastructure to eight to 12 lots per year as a means to mitigate the problem of abandoned land and help mitigate the excess stormwater runoff deteriorating Lake Onondaga.

Source: Atlantic States Legal Foundation (2012).

Villanova University

Established in 2002, the Pennsylvania Department of Environmental Protection (PA DEP) and Villanova University's Department of Civil and Environmental Engineering formed the Villanova Urban Stormwater Partnership. The mission is to advance the evolving field of sustainable stormwater management and to foster the development of public and private partnerships through research on innovative stormwater best management practices, directed studies, technology transfer, and education, and the partnership goal is to promote cooperation among the private, public, and academic sectors. The Partnership continuously monitors various green infrastructure pilot projects spread across Villanova's campus and contributes to the growing body of scientific literature on green infrastructure effectiveness.

Source: Villanova Urban Stormwater Partnership (2013).

Washington, District of Columbia

The District of Columbia ("the District") MS4 permit, operated by the District Department of the Environment (DDOE), integrates an adaptive management approach with enhanced control measures to address the complex issues associated with municipal stormwater runoff. DDOE's 2008 report to the EPA indicated serious water quality impairments in the surface waters in and around the District, making it out of compliance with the CWA. A key component of the District's EPA-approved MS4 permit is the use of green infrastructure as a stormwater control measure. The final permit includes performance requirements designed to increase the effectiveness of the "green" stormwater controls, which include green roofs, enhanced tree plantings, permeable pavers, and water harvesting, to ensure that they are reducing runoff volumes and pollutant loads. The District further justified the use of green infrastructure to manage stormwater runoff by using cost-benefit analyses to show that these practices were more cost effective because of the wide array of additional benefits that do not accrue with traditional approaches to stormwater management.

Source: District Department of the Environment (2011).

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Notes

1 Clean Water Act, 33 U.S.C., §§ 1251–1387. Available at http://www.epa.gov/npdes/pubs/cwatxt.txt.

2 A point source discharge, as defined by the EPA, is a source of pollution that can be attributed to a specific physical location—an identifiable end-of-pipe. The vast majority of point source discharges of nutrients are from wastewater treatment plants, although some come from industries.

3 As defined by the U.S. Environmental Protection Agency, an MS4 is a conveyance system used to collect or convey stormwater.

Appendix B

Green Infrastructure Options for Yale University

Contents

Introduction

Yale owns a unique array of commercial, residential, and academic properties throughout New Haven. This range of properties and their associated buildings and open space affords the opportunity to implement sustainable stormwater management practices on a wide spatial scale. Before examining the potential for implementing green infrastructure on Yale's campus, it is important to fully define what green infrastructure is and the specific approaches and options that could be used to reduce stormwater runoff and improve water quality throughout campus.

This appendix is designed to provide additional background on green infrastructure and describe the broad range of green infrastructure technologies, highlighting their design. The appendix presents this information in the form of fact sheets that briefly introduce each of the major potential green infrastructure options that are relevant for consideration by Yale. These fact sheets are meant to serve as a guide to the possible options for Yale's use, with the understanding that final design decisions will include site-specific considerations outlined in the "Considerations" portion of each factsheet.

What Is Green Infrastructure?

The EPA defines the term green infrastructure as the use of "vegetation, soils, and natural processes to manage water and create healthier urban environments." Often, for simplicity, the term is extended to not only the landscapes that are designed to manage stormwater above ground, but also to the necessary structural components included in the design to store stormwater as well as convey stormwater to and from the site. These practices are also often referred to by other terms, including: low impact development (LID) practices, stormwater best management practices (BMPs), high-performance landscapes, sustainable urban drainage systems (SUDS), and environmental site design (ESD).

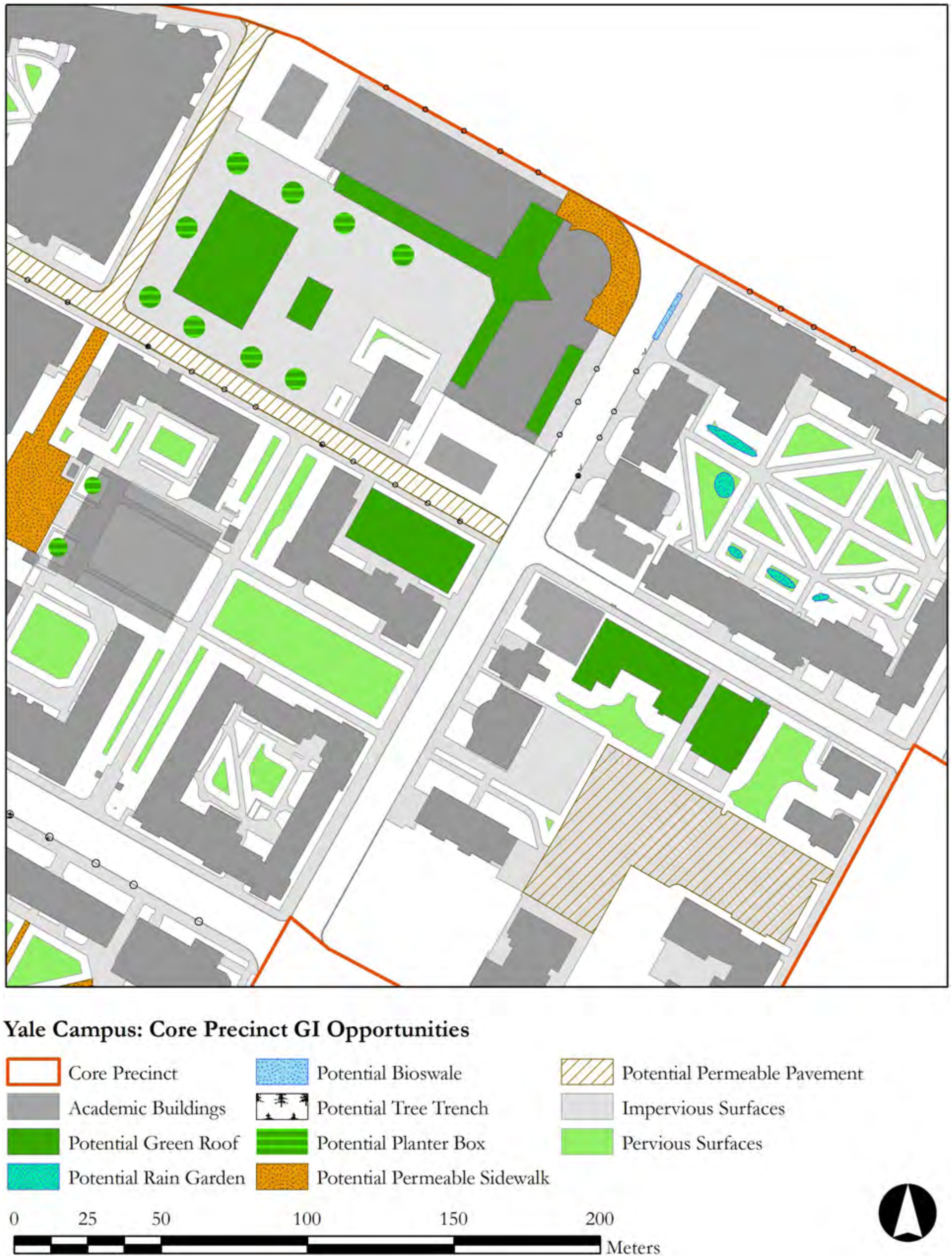
For the purposes of creating consistency in this document, the term *green infrastructure* will be used to refer to all potential practices, landscapes, and storage devices that can be used to slow the flow of stormwater, reduce stormwater volume, and improve stormwater quality before it enters the sewer system.

Opportunities for Green Infrastructure on Campus

It is important to identify the range of green infrastructure technologies that would offer Yale the best opportunities for reducing stormwater and improving water quality.

Figure 1 introduces a sample of the potential opportunities for green infrastructure placement on campus at the scale of a typical building site. These opportunities will be further explored in Appendix E.

Figure 1: Example of Opportunities for Green Infrastructure on Yale's Central Campus



Green Infrastructure Fact Sheets

With an understanding of the potential for green infrastructure on Yale's campus, the remainder of this appendix is composed of fact sheets for each technology depicted above. These fact sheets are intended to provide a description of each technology and its potential use on the Yale campus. The fact sheets are presented in the following order:

1. Green Roofs
2. Blue Roofs
3. Downspout Disconnection and Rainwater Harvesting
4. Bioretention—Bioswales
5. Bioretention—Rain Gardens
6. Bioretention—Enhanced Tree Pits
7. Constructed Wetlands
8. Subsurface Infiltration
9. Permeable Pavement

To briefly illustrate the key pieces of each technology's description, Table 1 summarizes some of the information found on the fact sheets. The fact sheets provided following the table include:

- A definition of each technology
- The different types of that technology
- Design considerations and technology components
- Locations for application
- Maintenance needs
- Cost of installation

Table 1: Green Infrastructure Technologies Matrix

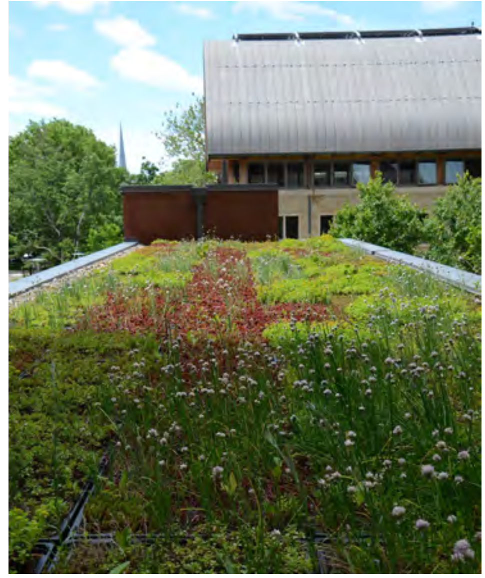
	types	applicability	cost	maintenance
1. green roofs	Shallow system Deep system	New construction Existing building retrofit Commercial, primarily	\$18–\$25/sq. ft.	Periodic roof membrane inspection Watering during first few yrs Weeding, as applicable
2. blue roofs	Permanent/modular tray system Shallow system (slows runoff) Deep system (stores runoff)	New construction Existing building retrofit Flat or moderately sloped roofs Commercial, primarily	\$5–\$8/sq. ft.	Periodic clearing of roof drains Waterproofing membrane inspections
3. downspout disconnection / rainwater harvesting	Downspout disconnection Rain barrel Cistern	New construction (esp. for rainwater harvesting systems) Existing building retrofit Commercial Residential	\$50 for downspout disconnection materials \$25–\$200 for rain barrel \$3,000–\$10,000 for rainwater harvesting system	Leaf removal from gutters/ downspouts 2x/yr. Inspect and clean pre-screening devices 4x/yr.
4. bioretention—bioswales	Dry swale (subsurface drainage) Wet swale (permanent pool) Grassed channel	Parking lots Road medians Sidewalks	\$0.10–\$20/sq. ft. \$200–\$4,000 for a 200-sq.-meter bioswale	Periodic inspection Sediment removal Weeding/vegetation care Trash removal, as needed
5. bioretention—rain gardens	Ground water recharge Raised planting bed	Parking lot medians Road shoulders Courtyards Downspout drainage areas Residential Commercial	From \$1.25/ sq. ft. in new construction to \$16.25/sq. ft. in retrofits	Occasional inspections, sediment removal Plant material inspections 2x/yr. Removal of dead plants Replacement of mulch Weeding, as necessary
6. bioretention—enhanced tree pits	Simple curb cut with inlet Highly engineered soils with underdrain system	Sidewalks Road medians Parking lot medians Residential yard/lawn Commercial yard/lawn Other green space	\$50–\$500/tree Maintenance: \$15–\$65/tree annually	Regular inspection of plants, structural components Regular cleaning of inlets/ outlets Occasional testing of soil and mulch for contaminants/ pollutants Biannual mulch replacement

	types	applicability	cost	maintenance
7. constructed wetlands	Wetland basin Pond/wetland combo Multi-cell wetland Multi-cell pond/ wetland combo	Almost anywhere with su∞cient space Ideal for locations with highly contaminated stormwater Not for ultra-urban zones	$0.90–$1.90/ sq. ft.	Mow embankment as needed Inspect vegetation biannually Replant vegetation as needed Inspect and remove trash/ debris from inlet/outlets as needed Monitor and control invasive species Dredge and dispose of sediment from pre-treatment chambers (annually), wetland areas (10 yrs.)
8. subsurface infiltration	Dry well Infiltration trench Gravel bed Perforated pipe Chamber system	Parking lots Alleyways Roadways Parks/fields/lawns (flat)	$5.70/sq. ft. average, but varies considerably based on type	Regular cleaning of catch basins, pre-treatment areas Filter replacement Biannual inspection and cleaning of components and connections Periodic evaluation of drain-down time Maintenance of above-ground vegetation
9. permeable pavement	Porous asphalt Porous concrete Interlocking pavers	New construction Retrofits Lightly used roads Alleyways Sidewalks/pathways Parking lots Driveways	Asphalt: $0.50–$1/sq. ft. Concrete: $2–$6.50/sq. ft. Pavers: $5–$10/ sq. ft. Maintenance: $400–$500/yr. for ½ acre parking lot	Occasional inspection of pores Concrete/asphalt: Vacuum sweep 3–4 times/year Concrete/asphalt: Repaving every 15–25 years, sooner in colder climates (Pavers): Mowing, as necessary

Sources: U.S. Environmental Protection Agency, Department of Water. 2013. "Green infrastructure." http://water.epa.gov/infrastructure/greeninfrastructure/index.cfm. Retrieved March 8, 2013.

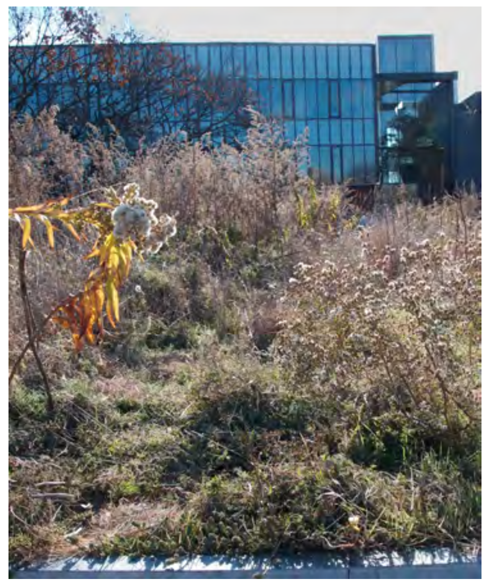
The 45,000-square-foot green roof on the PECO Energy Building in Philadelphia, Pennsylvania is a high-profile green roof that combines extensive and intensive technologies.

Flat to slightly sloping roofs that are visible from walking paths and other buildings are optimal candidates for green roofs. An example of a green roof with modular trays is visible on Science Hill.



The extensive green roof at the Sidwell Friends School in Washington, DC, is accessible to students and visitors and provides ecological as well as educational benefits.

The deep soil and diverse vegetation on the Yale Sculpture Gallery intensive green roof mitigates stormwater runoff, adds thermal insulation, provides urban wildlife habitat and helps extend the longevity of the roof membrane.



The intensive green roof on the Yale Sculpture Gallery resembles a small meadow. The sculpture gallery green roof is the site of ongoing ecological and performance monitoring by environmental researchers at the architecture firm of Kieran Timberlake in collaboration with the Yale University Office of Facilities and Office of Sustainability.

1. Green Roofs

Definition

A green roof is a living, vegetated water retention system. The soil and vegetation on a green roof help to retain and mitigate the flow of stormwater through absorption and evapotranspiration. Green roofs also help to filter and cool water as it passes through the soil and plant roots.

Types

Shallow Green Roof Also called "extensive" systems, shallow green roof systems include 2–4" of soil and shallow rooting plants such as succulents. Shallow systems can be modular (including trays or rolls of growing medium and vegetation) or permanent (or "loose laid" systems). Shallow systems weigh about 12–40 lbs. per square foot of roof area.

Deep Green Roof Also called "intensive" systems or roof gardens, deep green roof systems include 6–12" of soil and more deeply rooted vegetation than in "extensive" systems. Deep systems allow for greater plant diversity, variety, and creativity, and have a larger capacity for stormwater retention than shallow systems. Deep systems weigh about 80–150 lbs. per square foot of roof area.

Effectiveness

Extensive green roofs have an average stormwater retention rate of 56% (Gregoire and Clausen 2011). Nagase and Dunnet (2012) found that intensive systems that include grasses and other deep-rooted plants, however, are more effective at reducing stormwater runoff than systems with shallow-rooted plants (i.e., sedums). Many large-scale systems, such as the 45,000-square-foot green roof on the Philadelphia Energy Company (PECO) building in downtown Philadelphia, combine extensive and intensive systems to optimize reductions in peak stormwater flow (Miller 2013).

While both extensive and intensive roof systems are effective at slowing the rate and reducing the of stormwater runoff through interception, retention, and evapotranspiration, careful attention must be paid to the composition of growing media and fertilizers in the system in order to account for water controls (see Czemiel Berndtsson 2010). If composts and fertilizers are added to the soil matrix, for example, the green roof may contribute unwanted nutrients and metals (i.e., potassium, copper, and zinc) to stormwater runoff (Gregoire and Claussen 2011). In their study on modular green roof systems at the University of Connecticut, Gregoire and Claussen (2011) found that, although nutrient levels were slightly higher in green roof systems than in precipitation, nutrient levels were still significantly less than in the control. Green roofs may be effective at reducing both stormwater quantity and overall pollutant loading (Gregoire et al. 2011).

Design Considerations

Climate

Average rainfall

Solar exposure

Wind velocity

Load-bearing capacity of building

Waterproofing

Drainage

Plant selection

Roof slope

Components

Waterproofing membrane

Root barrier system

Drainage medium

Filter fabric

Soil/growing media

Vegetation

Applicability

Green roofs are appropriate for new construction and existing buildings, but application may be limited to flat or gently sloping roofs. Green roof designers and practitioners indicate that green roof installations are possible on roofs with a slope of up to 42 degrees (Miller 2013).

Maintenance

Periodic roof membrane inspection

Watering during first few years

Weeding in high-visibility areas

Cost

$18–$25 per square foot

References

Czemiel Berndtsson, J. 2010. "Green roof performance towards management of runoff water quantity and quality: A review." *Ecological Engineering* 36(4):351–60.

Gregoire, B. G., and J. C. Clausen. 2011. "Effect of a modular extensive green roof on stormwater runoff and water quality." *Ecological Engineering* 37(6):963–69. doi:10.1016/j.ecoleng.2011.02.004

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Nagase, A., and N. Dunnett. 2012. "Amount of water runoff from different vegetation types on extensive green roofs: Effects of plant species, diversity and plant structure." *Landscape and Urban Planning* 104(3–4):356–63.

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U.S. Environmental Protection Agency. 2012. *Green roofs in the semi-arid West.* http://www.epa.gov/region8/greenroof/pdf/GreenRoofsSemiAridAridWest.pdf.

Both blue and green roof technologies are present on the roofs of the Accelerator Lab and the Wright Laboratory on Science Hill. The gravel that covers the blue roof helps to store rainfall and slow stormwater runoff.

2. Blue Roofs

Definition

A blue roof is a non-vegetated rooftop water retention system, used for energy regulation, water storage, or stormwater detention. Rather than using vegetation to slow the flow of water, blue roofs incorporate a series of weirs and flow-restriction devices to help store runoff during peak rainfall events. Blue roofs often double as water catchment systems for secondary water uses.

Types

Permanent or modular tray systems
Shallow systems with drains may slow runoff
Deeper systems that may act as catchment and water storage systems

Effectiveness

A blue roof is effective at slowing the rate of peak stormwater runoff through retention and storage (Ohio Water Environment Association 2012). More research is needed in order to identify the precise rate of blue roof effectiveness under varying conditions. A current pilot project at P.S. 118 in New York City includes blue roof and green roof systems and will measure and compare costs and benefits "under similar environmental conditions" (New York City Department of Environmental Protection 2013).

Design Considerations

For stormwater mitigation purposes, blue roofs are largely consistent with green roof design.

Components

Waterproofing membrane
Drainage medium
Structural analysis of building
1" water adds 5 lbs. per square foot

Applicability

Blue roofs are applicable where water retention is desired on a flat or moderately sloped roof, but green roof installation is cost prohibitive. Applicable for existing buildings and new construction.

Maintenance

Periodic clearing of roof drains
Waterproofing membrane inspections

Cost

$5–$8 per square foot

References

King, Jason. 2008. "From the rooftop: Varietals." LANDSCAPE + URBANISM blog, http://landscapeandurbanism.blogspot.com/2008/03/from-rooftop-varietals.html.

New York City Department of Environmental Protection. 2013. "Blue roof and green roof pilot project *PlaNYC.* http://www.nyc.gov/html/dep/html/stormwater/green_pilot_project_ps118.shtml.

New York City Department of Environmental Protection. 2012. *Rooftop detention* [Pamphlet], http://www.nyc.gov/html/dep/pdf/rooftop_ detention.pdf.

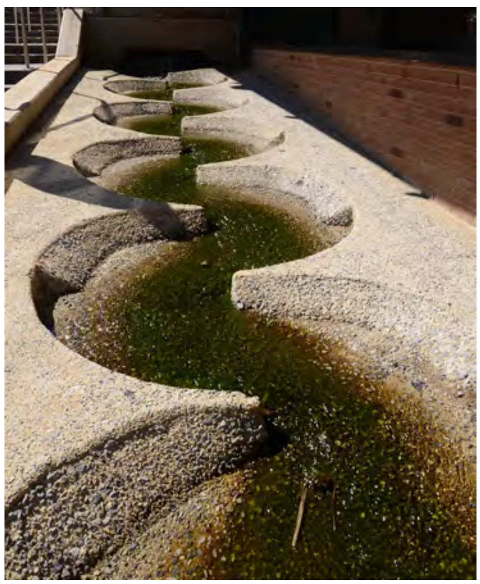
Ohio Water Environment Association. 2012. "Performance evaluation of blue roofs to mitigate CSO impacts for NYC DEP" http://www.ohiowea.org/docs/Th1100Storm_Perf_ Eval_Blue_Roofs.pdf.

Depending on the site and the amount of roof area being drained, downspout disconnection may require minimal intervention and additional infrastructure. For this academic building on Hillhouse Avenue, the splash guards help to protect the ground from erosion and divert water away from the building into the adjacent garden.

Stormwater from downspouts may also be stored in cisterns for reuse. The cistern behind the Washington, DC, Engine No. 3 fire house, for example, holds rainwater that has been diverted from the buildings' downspouts. The rainwater supplements the potable water required to wash the fire trucks.

There are many ways to implement downspout disconnection. This sculpture is a part of a rainwater collection and recycling system at the Sidwell Friends School in Washington, DC.

Some downspout disconnection projects may require additional infrastructure, such as rain barrels and rain gardens. Rain barrels are often effective tools for collecting downspout discharge at the residential scale.



3. Downspout Disconnection and Rainwater Harvesting

Definition

Method of slowing the flow rate and reducing the volume of rainwater into the sewers by disconnecting the roof drains when they are directly connected to the sewer system. In the simplest approach, the roof drain is disconnected and the discharge is allowed to flow onto the adjacent surfaces where it can infiltrate into adjacent pervious area or flow over surfaces until it enters the storm system through a catch basin. This approach often includes the construction of an adjacent rain garden or infiltration trench to encourage infiltration.

An alternative approach includes connecting the roof drain to a rain barrel or cistern, allowing for storage and use of stored stormwater. This approach is referred to as rainwater harvesting and can include the replacement for the potable water use associated with flushing toilets or landscape irrigation.

Types

Downspout disconnection

Rain barrels—smaller storage tank for discharge from the downspout Cisterns—larger storage tank for discharge from the downspout

Effectiveness

From a study conducted in Portland, Oregon, roof drain disconnection was shown to reduce inflows by between 5% and 10%, or 800 million gallons per year (Juza et al. 1996). When the reliability curves developed are used to size rainwater harvesting (RWH) systems to flush the low-flow toilets of all multifamily buildings found a typical residential neighborhood in the Bronx, rooftop runoff inputs to the sewer system are reduced by approximately 28% over an average rainfall year, and potable water demand is reduced by approximately 53% (Basinger et al. 2010).

Design Considerations

Roof size

Intended use for the water (irrigation versus toilet flushing)

Protection from freezing temperatures

Method for moving water (gravity versus pumping)

Diversions when storage tank becomes full

Available space for storage tank

Filtering of stormwater before it enters storage tank

Components

Components for downspout disconnection (D), rain barrels/cisterns (B), and rainwater harvesting (R):

Gutters and downspouts—D, B, and R

Leaf screens—B and R

Roof washers—B and R

Storage tanks—B and R

Delivery systems—B and R

Purification/treatment—R

Roof runoff must be discharged 5 feet from the building to avoid excessive water near the building foundation.

Gutters should be screened with a mesh to remove leaves and other large debris.

Rain barrel inlet should have a fine screen to restrict mosquitoes from entering.

Applicability

New construction and retrofits for older buildings.

When using the stormwater as gray water indoors—that is, for toilet flushing—the building's plumbing will need to be reworked or designed to allow stormwater to flow only to toilets.

Maintenance

Remove leaves from gutters and downspouts twice yearly.

Inspect and clean out pre-screening devices four times yearly.

Cost

Variable and dependent upon the scale of the project.

Approximately $50 for downspout disconnection materials.

$25–$200 for a rain barrel.

$3,000–$10,000 for a rainwater harvesting system, as described above.

References

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4. Bioretention—Bioswales

Definition

A type of bioretention system, also called a vegetated swale, biofilter, or bioretention swale, intended to convey water and serve as an alternative to a typical underground stormwater pipe. Bioswales are linear, gently sloping, open channels that sometimes contain an underdrain layer and are planted with hardy and native plants that filter water to improve water quality while reducing stormwater quantity as the water moves along the slope.

Types

Infiltration bioswale—Unlined; if it contains an underdrain system, it will partially infiltrate
Flow-through bioswale—Lined, with an underdrain system

Effectiveness

In a New York City Parks and Recreation pilot of two bioswales within a median along North and South Conduit Avenues, the preliminary data from 2011 indicate that for storm events less than two inches, the bioswales achieve a 100% volume retention (NYC Department of Environmental Protection 2012).

Design Considerations

Drainage ability of the soils
Importance of nutrient control
Sediment and floatable loads
Mechanism for energy dissipation of flows coming into bioswale
Groundwater location relative to the surface
Exposure to excessive shade
Slope—flat sites or sites with slopes of greater than 5% are not recommended

Components

An inlet structure to slow flows and collect floatables and sediment
An outlet or control structure should be included to convey high flows
The shape should be parabolic or trapezoidal shape with side slopes no steeper than 3:1
The bottom of the swale should be 3 feet above the groundwater level
The channel should be between 2 and 8 feet wide with a slope of 1–2%
If the soils do not drain well, soils can be replaced with a soil/sand mixture and a drainage layer should be included in the design.

Applicability

Commonly used in parking lots, road medians, and along roads, but can be used as a replacement for traditional underground stormwater pipe.

Bioretention refers broadly to any system that utilizes the natural properties of plants and soils to remove pollutants from stormwater and encourage infiltration. Examples of bioretention systems described in this appendix include bioswales, rain gardens, and enhanced tree pits but may also include enhanced planter boxes.

Penn Park, a 24-acre urban park and recreation site on the University of Pennsylvania campus in Philadelphia was once an industrial brownfield. This bioswale is one of many green infrastructure features at Penn Park that helps the university mitigate stormwater runoff and protect water quality in the Schuylkill River and the Delaware River estuary.

Though the fundamental principles are similar, the design and appearance of bioswales may differ on a site-by-site basis. This bioswale, designed by Casey Trees, features curb cuts, which allow water from the road to flow into the deep gravel bed, native grasses and a raised overflow pipe.

New developments and sites undergoing renovation should be considered for green infrastructure implementation. This bioswale in Washington, DC creates green-space and receives stormwater runoff from the right-of-way in a new commercial district.

This vegetated bioswale at Kensington High School for the Arts and Performing Arts in North Philadelphia helps to filter runoff from the adjacent parking lot and also receives overflow from nearby improved tree pits. Importantly, bioswales help to capture stormwater and other sediment and debris that would otherwise pollute nearby rivers and streams.

Maintenance

Periodic inspection (especially after major storm events)
Sediment removal
Weeding and vegetation care
Trash removal (if located in a high tra∞c area)

Cost

Approximately $0.10–$20 per square foot.
Between $200 and $4,000 for a 200-square-meter bioswale.

References

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Shoemaker Green on the University of Pennsylvania campus in Philadelphia features a large rain garden with subsurface infiltration and a 20,000 gallon cistern. Rainwater collected on the site is used to irrigate the surrounding lawn.

This rain garden and swale collects and stores stormwater from downspouts and a parking lot at the Casey Trees facility in Washington, DC. Hydrophilic trees and native grasses help to soak up and transpire stormwater that would otherwise flow into the area's combined sewer system.

5. Bioretention—
Rain Gardens

Definition

Rain gardens are bioretention systems designed to utilize the natural properties of plants and soils to remove pollutants from stormwater runoff and encourage infiltration. Rain gardens are designed to mimic natural hydrology, and thereby slow water velocity and improve groundwater recharge. Rain gardens can range in from 2 to 5 feet in depth and can utilize a base layer of infiltrative material. Water may collect during heavy storm events, but is moved through the system completely within 48 hours. Native plants are planted to maintain soil structure and encourage filtration and absorption. Unlike bioswales, which generally include a gentle slope to convey water in a single direction, rain gardens emphasize infiltration in situ, with no conveyance feature.

Types

Groundwater Recharge Rain Gardens—base layer of porous material to encourage infiltration.

Raised Planting Beds—Planting areas above ground level that have perforated bottom to allow water to seep into the ground below.

Effectiveness

In a New York City Parks and Recreation pilot of five rain gardens in a neighborhood development in the Bronx, the systems achieved an 80–100% volume reduction for most storms less than 1 inch (NYC Department of Environmental Protection 2012).

Design Considerations

Drainage ability of the soils
Slope (not advisable for slope >20%)
Water table height (not advisable for area with water table within 6 feet of surface)
Climate (freezing may prevent infiltration)
Size (rain garden area should be 5–7% of the drainage area, multiplied by the runoff coe∞cient for the site)
Typical rainfall volume (maximum drainage area determined by the sheet flow associated with a 10-year storm)
An outlet or control structure should be included to convey high flows
Mechanism for energy dissipation of flows coming into bioswale

Components

3–5 feet of depth
Grass buffer strip on either side
Porous underdrain discharge pipe (optional)
Gravel blanket at the base
Pea gravel mixture above
Planting soil: mixture of sand and soil
Native plants, trees
Protective layer of mulch

Applicability

Parking lot medians/islands
Road shoulders
Courtyards/downspout reception areas

Maintenance

Occasional inspections and removal of sediment.
Inspections of plant material twice per year
Removal of dead plants
Replacement of mulch to prevent erosion
Occasional weeding

Cost

Range from $1.25/square foot for installation at a new development to $16.25/square foot for retrofitting existing development (i.e., removing concrete, etc.). Maintenance strategies are similar to regular landscaped areas, and while variable across projects, have been estimated to be 1% of installation cost.

Limitations

Not ideal for filtering water coming from area greater than 1 acre
Limited to areas with surface slopes < 20%

References

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6. Bioretention—Enhanced Tree Pits

Definition

Tree pits collect stormwater runoff from small areas such as portions of parking areas or stretches of roads. Stormwater filters through the tree roots and surrounding soil mix, trapping sediment and pollutants before infiltrating into the soil or flowing to a piped stormwater system. Planting and maintaining trees in urban settings is a common green infrastructure practice with multiple benefits for resilience, adaptation, and even climate mitigation.

Effectiveness

A study in Tucson, Arizona, has shown that savings in stormwater management calculated at $0.18 per tree per year (Dwyer et al. 1992). Runoff estimates for an intensive storm event in Dayton, Ohio, showed that the tree canopy reduced potential runoff by 7% and an increase in canopy cover reduced runoff by nearly 12% (Dwyer et al. 1992).

Design Considerations

Proximity to the buildings to allow for proper crown and root development
Proximity to utility lines; select a small species at least 5 feet below the wire
At least 12 feet from a major underground utility for large trees
Knowledge of land ownership and regulations
Evaluation of social influences by installation of tree pits
Maintenance possibilities

Components

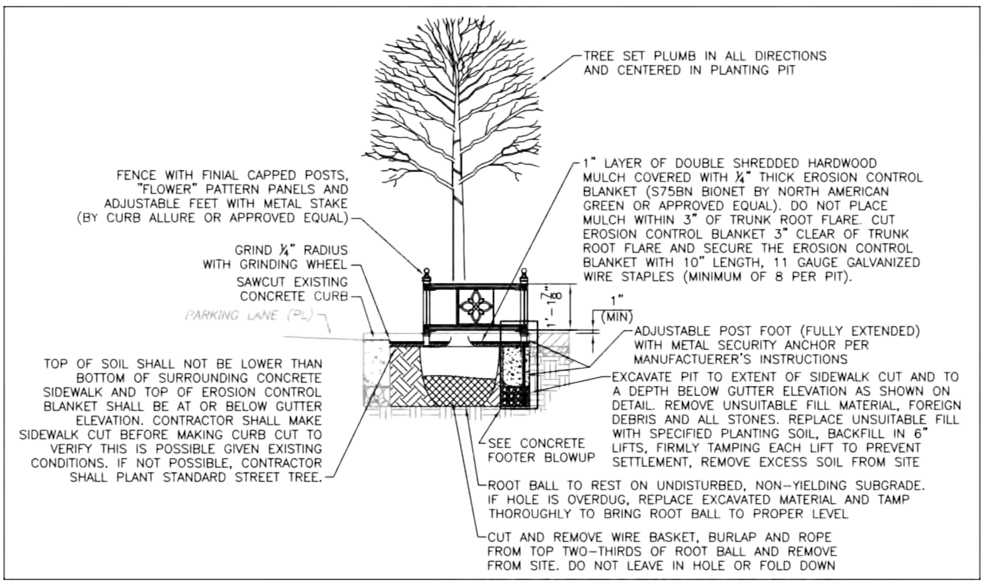
Curb/channel—stormwater flows from road or surrounding hard surface to tree pit
Curb inlet—large opening to direct stormwater to tree pit
Plant covers: structure at base of tree trunk to protect roots
Plants: large shrub or tree to help collect and filter stormwater
Ponding area
Mulch layer
Plant soil—mix of sand, topsoil, and compost to drain stormwater well
Root barrier such as geotextile fabric to line tree pit (if required)
Waterproof lining (if required)
Connection of tree trenches to storm water drain (if included)

Applicability

Right of way
Streets
Residential front yard
Residential back yard
Parking lot
Community gardens
Community spaces

Enhanced tree pits reduce impervious surface, provide green space, and mitigate stormwater runoff. Enhanced tree pits in New York City feature curb cuts, a gravel strip, and additional vegetation to help capture stormwater, sediment, and debris that would otherwise clog sewer systems and pollute urban waterways. Subsurface infiltration and storage in enhanced tree pits provide a reservoir of water for trees to absorb and transpire.

This diagram from the Philadelphia Parks Department provides details for curb cuts and enhanced tree pit installation.



Maintenance

Regular inspection of plants and structural components

Regular cleaning of inflow and outflow mechanisms

Regular testing of mulch and soil for collection of pollutants that may be harmful to the plants

Biannual replacement of mulch

Cost

Approximately $10,000 per tree

References

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The constructed wetland next to Kroon Hall on the Yale University campus uses aquatic plants to help filter stormwater from the building's roof and grounds for re-use for flushing toilets and irrigation.

Constructed wetlands may filter stormwater as well as wastewater. This subsurface constructed wetland in the courtyard of the Sidwell Friends School in Washington, DC, utilizes soil and deep-rooted vegetation to filter and recycle wastewater from the buildings' septic system.

7. Constructed Wetlands

Definition

Constructed wetlands are manmade systems designed and constructed to treat wastewater using natural processes. These natural processes are provided by a combination of wetland plants, soil, and microbial life. As stormwater is held in the wetland, particles settle out and wetland plants take up nutrients. Constructed stormwater wetlands reduce peak flows and also reduce overall stormwater runoff volume to surface waterways through evapotranspiration. However, they do not recharge a significant amount of water into the ground as groundwater.

Types

Constructed wetland basins A single cell (including a forebay) with a uniform water depth.

Pond/wetland combination design A wet pond cell in parallel with constructed wetland cells designed to convey small storms through the wetland cells while diverting the storm runoff into the wet pond cell.

Multi-cell wetland and multi-cell pond/wetland A combination of those listed above. It is highly effective in moderately to highly urban areas where space is at a premium and providing adequate surface area or grade drop is di∞cult.

Effectiveness

A study conducted on constructed stormwater wetlands on the Villanova University campus near the headwater of a high-priority stream outside of Philadelphia shows that the average base flow travel time (retention time) through the wetland is 58 hours (Wadzuk et al. 2010). In all seasons, water flowing out of the wetland showed a statistically significant (=0.05) decrease in concentration of total phosphorus (TP), total nitrogen (TN), total suspended solids (TSS), and copper (Cu) from the runoff flowing in (Wadzuk et al. 2010).

Design Considerations

Adequate water balance
Contributing drainage area
Space requirements
Available hydraulic head
Steep slopes
Minimum setbacks
Depth to water table
Soil types

Components

Impermeable layer or barrier to prevent infiltration of wastes into groundwater
Gravel layer or root zone where water flows and dentrification takes place
Above-ground layer containing vegetation

Maintenance

Mow embankment as needed
Inspect vegetation biannually
Re-plant vegetation as necessary
Inspect and remove debris/trash from inlet and outlet structures
Monitor and control invasive species
Dredge and properly dispose of sediment from pretreatment chambers (annually) and wetland areas (every 10 years)
Maintenance cost is $780–$1,640 for a one-acre wetland

Applicability

Constructed wetlands are applicable everywhere except highly urbanized and arid areas. The best location is the place that produces highly contaminated stormwater.

Construction Cost

Approximately $39,000–$82,000 for one acre of wetland.

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8. Subsurface Infiltration

Definition

Subsurface infiltration refers to systems designed to detain water underground such that it can eventually seep into the underlying soil. Subsurface infiltration can take many forms, including dry wells, infiltration trenches, gravel beds, perforated pipe systems, and chamber systems. The primary difference between subsurface infiltration types is the method of underground water storage. For example, gravel beds provide water storage via voids between the rocks, whereas perforated pipe systems provide storage both within the pipe and in the surrounding gravel.

Types

Dry wells
Infiltration trenches
Gravel beds
Perforated pipe systems
Chamber systems

Effectiveness

In a study within the South Washington Watershed District in Minnesota, where numerous infiltration trenches were installed and monitored starting in 1997, drainage rates during spring snow melt are documented as high as 4 inches per hour and during summer rainfall events as high as 6.8 inches per hour (Ackerman and Stein 2008).

Design Considerations

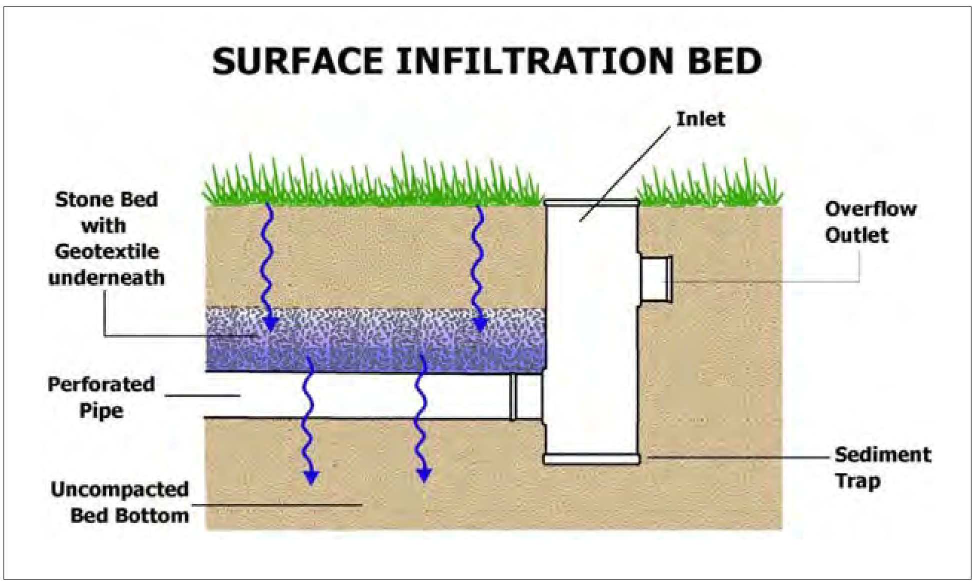
Hydrology and soil characteristics
Storage capacity
Drainage
Typical rainfall volume
Proximity to building foundations
Proximity to groundwater or bedrock
Vehicle tra∞c
Cannot be located in areas with unstable or contaminated soils and high groundwater table (areas where permanent or seasonal groundwater rises within 10 feet of bottom of trench)

Components

Vegetation
Positive overflow outlet
Stone-filled trench
Perforated piping
Geotextile
Observation well (optional)
Outflow pipe

Subsurface infiltration may involve a permeable substrate such as gravel, perforated piping, or both.

Water infiltrates through the surface and gravel substrate and is conveyed through the perforated pipe into a larger cistern, dry well, or other storage chamber.



Applicability

Both new construction and repaving or repair of existing surfaces. Opportunities for increased subsurface infiltration exist where largely impervious surfaces currently dominates, such as in parking lots, alley ways, and roadways. Improved infiltration techniques may also be applied to recreational fields, parks, and other lawns to help mitigate stormwater flows.

Maintenance

Regular cleaning of gutters/catch basins
Filter replacement and cleaning out pre-treatment areas
Biannual inspection and cleaning of components and connections
Periodic evaluation of system drain-down time
Maintenance of vegetated areas above storage medium as needed

Cost

Varies considerably depending on specific type of system used. $5.70/sq. ft. is the average cost of subsurface infiltration for excavation, aggregate (2 feet assumed), non-woven geotextile, pipes, and plantings.

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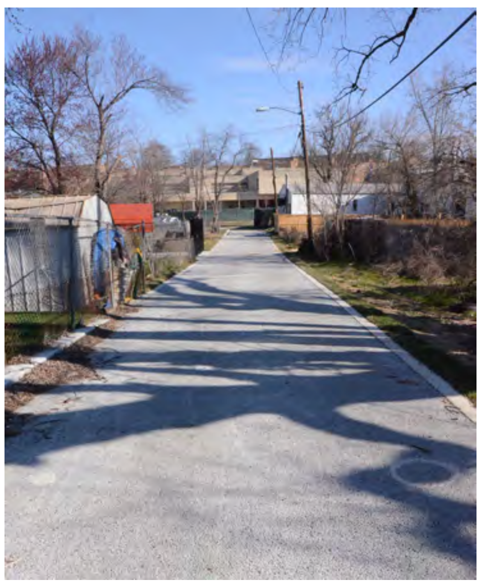
Permeable pavers in front of Kroon Hall at Yale University rest on a bed of gravel and sand, which allow stormwater to infiltrate rather than quickly run off.

Robert Traver at Villanova University uses his campus as a living lab for green infrastructure projects. This university parking lot features a pilot site to test the infiltration and performance of pervious asphalt and pervious concrete. On a rainy day, there is little surface runoff compared with the adjacent impervious surfaces.

In Washington, DC, the District Department of Transportation (DDOT) and the District Department of the Environment (DDOE) have teamed up to reduce stormwater runoff from the right-of-way. This Green Alley in the Anacostia River watershed improves the appearance and function of the alley while reducing impervious surface and combating CSOs.

Canal Park is a reclaimed industrial space and new urban park in Washington, DC. Pervious pavers and permeable pavement, tree pits, and rain gardens help to capture stormwater and direct it to underground storage cisterns. Water is then recycled into non-potable sources, such as toilets, ponds, and a seasonal ice rink.



9. Permeable Pavement

Definition

Permeable pavement is asphalt or concrete that is mixed with fewer fine particles to create more air space, which in turn allows water to percolate through it. An underlying layer of fine sediment filters the water, and a sub-base of uniform-grade stones stores the water as it infiltrates into the ground. Interlocking pavers function in a similar way, but instead of a consistent layer of asphalt or concrete, these are modular systems with interlocking pieces. The holes between pieces are filled with sand and/or soil, which allows water to percolate through to the subsurface. Depending on the specific system and location, most permeable paved areas capture 70–80% of annual rainfall that lands on its surface.

Types

Porous concrete (more expensive)
Porous asphalt (least expensive)
Interlocking pavers (most expensive, but most common and usually also designed to provide aesthetic benefits)

Design Considerations

Vehicle tra∞c
Average slope of surface
Climate
Weight of vehicles and other objects/people using the surface
Drainage
Likelihood of spills or handling of hazardous material
Typical rainfall volume (most systems are designed to capture infiltration from at least a two-year storm)

Effectiveness

Porous concrete A large pervious concrete plaza installed at Villanova University, which takes runoff from adjacent standard concrete areas, several rooftops, and grassed areas, has successfully captured and infiltrated runoff from all storms 5 cm or less since its installation (Kwiatkowski et al. 2007).

Porous asphalt A 1999 study in France concluded that on average, 96.7% of stormwater volume infiltrated into the soil below a 61-cm thick crushed stone reservoir installed in the section of a street (Legret and Colandini 1999).

Interlocking pavers Studies conducted in 2003 in Washington, DC, of two different interlocking paver products calculated negligible surface runoff from both products over the entire six-year study period. Water quality was also improved, as copper and zinc concentrations in infiltrate water were significantly lower than in concentrations in runoff from an adjacent asphalt lot (Brattle and Booth 2003).

Requirements

Interlocking pavers

- Top layer of interlocking pavers, porous asphalt, or porous concrete
- Permeable joint material (sand/soil) to go between pavers (interlocking pavers)

Open-graded bedding course (interlocking pavers)

Open graded crushed stone base reservoir

Open graded larger stone sub-base reservoir

Underdrain (as required)

Geotextile under sub-base (as required)

Uncompacted subgrade soil

Applicability

Both new construction and repaving of existing surfaces

Parking lots

Sidewalks

Road shoulders

Driveways

Maintenance

Vacuum sweep 3–4 times/year (porous asphalt/concrete)

Occasional inspections of pores to test permeability

Mowing, if necessary (interlocking pavers)

Re-pavement necessary every 15–25 years, especially in colder climates

Cost

Porous concrete: \$2–\$6.50/sq. ft.

Porous asphalt: \$0.50–\$1.00/sq. ft.

Interlocking pavers: \$5–\$10/sq. ft.

\$400–\$500/year per half-acre parking lot in maintenance costs

Limitations

High installed cost/volume reduced ratio

Not intended to collect stormwater from other areas

Substantial maintenance requirements

Challenges in cold climates

Limited to areas with surface slopes < 20%

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pp. 70 Top: New York City Department of Parks and Recreation; Diagram: Philadelphia Water Department and Philadelphia Department of Parks and Recreation

Appendix C

Implementing an Adaptive Stormwater Management Approach at Yale University

Contents

Introduction

Because using green infrastructure as a means for stormwater management is still a new trend, information on its potential performance is still largely lacking, especially in the New Haven area.

Adaptive management is an iterative process structured so that the actions to meet management objectives simultaneously provide information needed to improve future management goals and actions. The approach emphasizes management experiences as a source of learning that informs the next set of actions. It has been proven applicable across a range of resource sectors, including agriculture, water resource management, and fisheries, especially in the presence of uncertainty (Stankey, Clark, and Bormann 2005).

This appendix describes why this adaptive management approach is suitable for Yale's Sustainable Stormwater Management Plan. It explains the detailed steps for strategy implementations, assessment, and goal setting, and the flow of actions that shall be taken to apply an adaptive approach for developing future plan iterations utilizing the knowledge gained from the current plan.

The incremental design of a Sustainable Stormwater Management Plan (SSMP) has the ability to lead to a more robust and widespread implementation of green infrastructure while having a long-term positive impact on campus water management.

This plan aims to shift the mindset of Yale stakeholders from stormwater as *waste* product on campus to storm water as a *resource*. Learning, step by step, through an iterative process, will allow green infrastructure practices to be continually evaluated by annual performance monitoring, improved operations upgrades, accurate documentation, assessment, modeling, and adapting to fundamental fluctuations in the water management process (Alshuwaikhat 2008). The ultimate objectives are to:

- Improve the understanding of the volume of stormwater runoff on the campus properly and its impact on the combined sewage overflow for the city of New Haven.
- Provide information to set a reduction goal in 2016 that can be achieved through green infrastructure interventions.

The initial phases of the plan will have the ability to affect multiple stakeholders directly or indirectly by virtue of its actionable items and stormwater interventions that mitigate the quantity and quality of water flows on campus.

Suitability of Adaptive Management Approach for Sustainable Stormwater Management

Applying an adaptive management strategy during sustainable stormwater planning can enable subsequent performance monitoring to inform a responsive, effective, and e∞cient practice. A number of characteristics of stormwater make performance monitoring critical:

- Wet-weather events are responding nonlinearly to climate change (Mohammed 2005).
- Runoff behaves very differently depending on the magnitude of precipitation event.
- Modular and decentralized green infrastructure practices are still being optimized.
- Damages include both flooding of private property and degradation of public goods like ambient water quality.

As a result, traditional project management that sets fixed timelines and static milestones may be a good starting point for infrastructure improvement, but sustainable stormwater management requires more flexibility, responsiveness, and agility. Implementing green infrastructure without performance monitoring could result in a number of failure points:

- Engineers and architects deliver plans designed for very specific performance parameters.
- Contractors with little experience often make shortcuts in construction that render the as-built installations ineffective for the designed purpose.
- Maintenance is critical for continued performance of the vegetative practices and geo-engineered soils that provide the substantive value-added of green infrastructure.
- To obtain benefits under any future regulatory credit or incentive scheme, green infrastructure may need to prove catchment-specific effectiveness at attenuating runoff and/or improving water quality.

Other campuses have made significant progress identifying and implementing strategies and management practices for stormwater reduction, but may be vulnerable without an explicit adaptive management program. An analysis of comprehensive stormwater management plans on university campuses by Steven Gillard (2011) at the University of Pennsylvania suggests a common approach for:

- Creating inventory baseline
- Identifying best management practices
- Education and outreach
- On-schedule operation and maintenance

All of these points present challenges for budget-limited offices, which can lead to a preference for cutting operation and maintenance costs. However, our experience interviewing employees at the Philadelphia Water Department suggests that the long-term sustainability of stormwater management installations is directly dependent on proper maintenance.[1] Additionally, communication and collaboration between the designers and maintenance crews is an underutilized opportunity for reducing operational cost and improving installation effectiveness.

The University of Pennsylvania chose to contract with an environmental consulting firm to write its stormwater management plan. Yale University has an opportunity for leadership by integrating students, research faculty, and the broader community in its adaptive management plan. By continuing to develop the SSMP in-house, through an adaptive management process and the collaboration of the Yale Office of Facilities and research faculty, Yale can ensure that the as-built installations function as designed and serve the community well into the future.

Preparation for Setting Stormwater Goals in 2016

After implementing the four management strategies discussed in this plan, the next step in adaptive management is the development of goals and objectives. Goals contribute to the decision-making process and influence the selection of management actions, which are considered to be projects, programs, or initiatives undertaken in pursuit of achieving a management goal partially or entirely.

By adopting several stormwater management strategies, Yale University will generate a better understanding of stormwater's relationship with and function on the campus. This understanding will lead to the selection of several initial stormwater goals by 2016. In developing and reevaluating goals, it is necessary to consider that they should address the issue that initially motivated management and reflect the social, economic, and ecological values of the stakeholders (Williams, Szaro, and Shapiro 2009). Certain conditions and technical features should be met for a goal to be useful for decision making and evaluation:

Specific Goals should be clearly articulated, expressing the expected outcome of the management action implemented and the reasons for and benefits of accomplishing the goal. Specific goals for stormwater management are not to be general-purpose statements that reflect the interest of reducing and improving the quality of stormwater runoff. Instead, these should include target conditions that address the main problem, such as a reduction in stormwater runoff by a certain amount, reduction of the quantity of combined sewer overflow (CSO) events, establishment of specific guidelines for stormwater control to new developments, and so on.

Measurable Goals should contain elements that can be measured with success, so as to provide means to evaluate the effectiveness of the employed management actions. A measurable goal for stormwater management can be quantified with field monitoring and modeling information. For example, a goal that requires stormwater runoff to be reduced by a certain amount can be measured with modeling estimates to determine if the management action has resulted in the expected outcome.

Attainable Goals should be realistic and based on the capabilities of the system being managed, the conditions in which management occurs. Managers should consider their limitations as well as those of the system to reduce and treat stormwater. Realistic stormwater reduction goals should be developed with the use of baseline data and considering the resources available to execute the management plan.

Time-based Goals should indicate a timeframe for achievement. For a stormwater management adaptive strategy, the timeframe selected should be realistic and allow for reevaluation and adjustment. Depending on the case, timeframes can extend from several years to decades.

Results-oriented Goals should state endpoints and conditions that indicate their achievement.

Goal Performance Evaluation

Facilitate Goal Performance Monitoring

Before measuring goal performance, it is useful to meet certain conditions that facilitate evaluation. These are related to the measurability criteria of goals and objectives:

Measures of performance (or indicators) toward goals have been established Performance indicators are measurable conditions that can provide a quantitative basis for evaluating how well management actions are meeting the stated goals and objectives. Ways to evaluate the effectiveness of these actions should be considered throughout all stages of planning and implementation of the management plan. Performance indicators are the factors measured through monitoring and allow for continuous learning, broadening the understanding of how the system functions and responds to specific management actions. The criteria for the quantification of goal performance vary among goals and goal typologies. For example, quantitative goals can be measured by analyzing scientific data (e.g., flow, water quality parameters), while action or positional goals can be evaluated with information collected as a result of management efforts (e.g., area of land converted into green infrastructure).

Milestone goals have been established Within the context of stormwater management, it is common to develop long-term goals. Monitoring the progress toward long-term goals can be challenging because results can take significant time to materialize. To ensure that the management actions toward achieving these objectives are being effective and that the goal can be reached within the specified timeframe, milestones, or subgoals, should be specified during the goal-setting process. During the implementation period, evaluation of milestones provides information on how far the managers are into achieving the goal and on any lags in the expected response. For example, suppose that the established goal states that stormwater quantity should be reduced by a certain amount in the next 25 years. A strategy to achieve this goal could include the disconnection of impervious surfaces that discharge directly to the stormwater drainage system. Using existing models, the impervious surface area that needs to be disconnected to achieve this reduction can be determined. Consequently, a milestone goal for this management action could be to disconnect a certain area of impervious surface every five years until achieving the final goal in 25 years. This can provide information leading to the modification of the management action and will encourage evaluation of progress and continuous monitoring.

Measuring Goals

The process of measuring goal status involves the evaluation of data obtained from monitoring efforts. It is an analysis of the indicators of performance to answer questions about the response of the system to the implemented management action and an assessment of the effectiveness of the strategy, as illustrated in Figure 1.

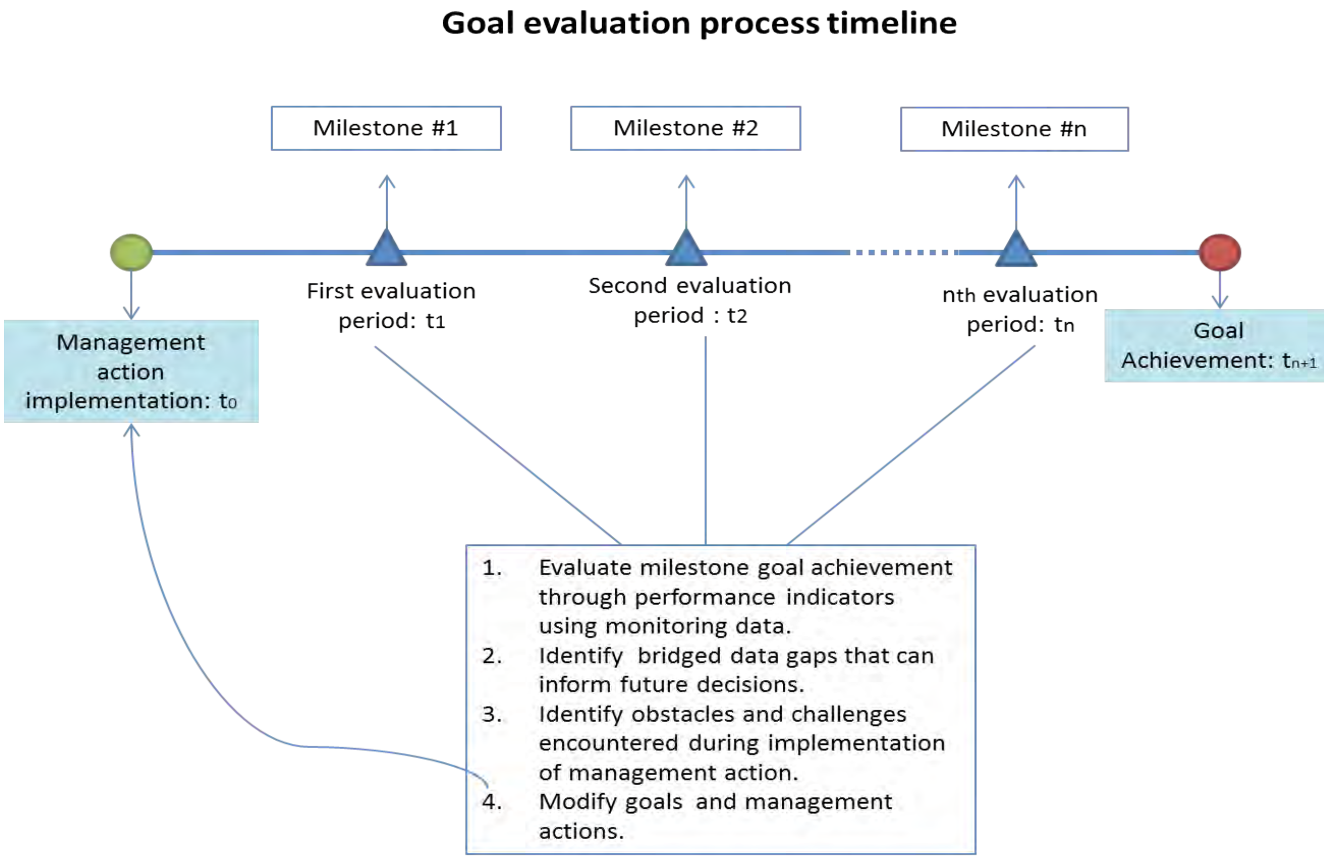
Using monitoring data to evaluate goal performance The monitoring program designed to assess the outcome of the SSMP should aim to obtain the information necessary to make management decisions and evaluate the results of individual management actions. In the adaptive management context, the purposes of monitoring are the following:

- Evaluate the progress toward achieving a goal through the current management strategy;
- Increase understanding of the system dynamics;
- Provide information to improve and develop models for decision making; and
- Provide data that can inform the development of future goals.

Monitoring involves obtaining data of the performance indicators throughout the duration of the project. These data would be used as input for models that apply to the system or statistically analyzed to determine success or failure of the management strategy. For the SSWP, two monitoring categories provide useful information for determining goal achievement:

Implementation monitoring Document the extent to which strategies have been implemented as well as to which regulatory actions proposed by the SSWP have been taken. This type of monitoring provides a basis for tracking the completed actions and is a way to monitor goals involving zoning, stricter stormwater standards for new developments, downspout disconnection programs, and so on.

Figure 1: Goal Evaluation Process Timeline



When implementing a management strategy, evaluation of performance throughout the duration of the project tracks progress toward milestones. These evaluations include the use of monitoring data to assess performance indicators and identifying bridged data gaps and obstacles and challenges encountered that might have led to failure in achieving the goal. This is the key process that leads to the modification of management actions and goals that characterizes adaptive management.

Outcome monitoring Addresses how effectively the SSMP meets the explicit objectives and conditions. This monitoring can relate to small projects and milestone goals as well as to the general outcome of the management strategies implemented and long-term goals (e.g., a reduction of stormwater volume reaching the drainage system).

Other uses of monitoring data Although monitoring data is essential to evaluate goal performance indicators, the data also provide information that can further inform decision making.

- The data provide new information about the system: An adaptive management strategy is usually necessary in systems where there is not su∞cient information to implement a fixed management action with certainty. Monitoring through the implementation process can fill these informational gaps, provide a clearer picture of the system being managed, and serve as a foundation for future management approaches. This information can also provide a different perspective of the situation that can lead to the reevaluation and modification of goals.
- Monitoring data helps to document and explain obstacles and challenges encountered: When goals are not met by the specified timeframe, monitoring information can help identify the cause of these challenges and provide insight on how to overcome them to accomplish the objective.

Goal Achievement Measurement Outcomes

The process of evaluating goal accomplishment is part of the setup phase and the iterative phase of adaptive management. It involves consistent monitoring throughout the implementation of the SSMP and encourages and maintains the decision-making process. In general, it provides the information that allows both management actions and goals to be dynamic.

Application of Adaptive Management to the Sustainable Stormwater Management Plan 2013–2016

This section will describe the steps that will take the strategies specified in the current plan through monitoring and assessment, and feed into the goal development in 2016. Since Strategy 1 requires continual improvement of the runoff model to achieve a baseline for stormwater on campus, the steps are distinct from Strategies 2 and 3, which directly address the reduction of stormwater on campus. For this reason, the approach for Strategy 1 is described separately from the approach for Strategies 2 and 3.

Approach for Strategy 1: Model and Data Development Process

Strategy 1 establishes that annually, the supervisor of the modeling effort will recruit one or more Yale students to oversee the model update process. The general procedure by which the model will be improved is described below. Specific information about the current status of the stormwater modeling effort can be found in Appendix D. The stormwater baseline for Yale University is being determined using the Environmental Protection Agency (EPA) Stormwater Management Model (SWMM). The model is described as follows in the SWMM handbook (Rossman 2010):

> SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps.

Model Evaluation Develop familiarity with current iteration of model and identify opportunities for improvement and operational shortfalls.

Each year when the model development cycle begins, the modeler(s) and supervisor shall assess the functionality, complexity, accuracy, and structure of the model. They will then prepare a list of potential improvements to the model that may include: change in software, additional/updated data, structural changes, intensified level of analysis (e.g., inclusion of water quality), or increased scale of analysis.

Workflow Prioritization/Software Selection Develop model improvement strategy by setting performance goals.

Once the model is evaluated, a number of performance goals will be chosen to address during the yearlong model development cycle. To preserve the integrity of the model, performance goals must be informed by previous work and represent an incremental improvement over previous iterations.

Data Retrieval/Model Update Incorporate new data and refine model components, parameters, and assumptions.

The majority of time and effort during the model development cycle will be dedicated to locating and incorporating new and up-to-date data, improving accuracy of the representational structures, tweaking hydraulic and hydrological parameters, and increasing complexity.

Calibration and Results Analysis Compare model results with monitoring data, and evaluate for management implications.

While the model improvement is ongoing, intermediate results from model runs shall be evaluated for accuracy through comparison to calibration data of flow and quality at specified junctions and outlets in the conveyance system. Depending on the level of similarity between modeled flow and calibration flow, different choices for parameters and model structure may be made. In Yale's case, altering slope, percent impervious cover, subcatchment width, depression storage, or other parameters may lead to more accurate results.

At the end of the model development cycle, a series of final runs will be produced to provide baseline analysis data for the management plan supervisors. The modeling team shall produce a report that analyzes the model results and recommends future steps.

Communication of Results Report findings to management planning team.

Along with the annual report analyzing the state of the model and stormwater baseline, the modeling team will also present their findings and recommendations to the management plan supervisors. In the presentation, the team shall address work completed, model accuracy, and implication of the model results. In addition, the modeling team shall participate in the goal-setting process when applicable.

Approach for Strategies 2 and 3: Stormwater Management Commitments

Decision Making/Implementation Identify management actions to address plan goals and commitments.

Upon adoption of the SSMP, the O∞ce of Facilities with input from the O∞ce of Sustainability will identify a course of action to address management Strategies 2 and 3 set out in the plan. Depending on resource availability, current understanding of the project, and guidelines described in the SSMP, decision makers will choose and initiate management actions to address guiding principles. Management actions may be initiated at any point during the three-year adaptive stormwater management cycle, but all must be subject to ongoing monitoring and review.

Tracking Progress/Monitoring Monitor and record progress of management action implementation toward achievement of management goals.

Immediately following the initiation of a management action, and during the period of active work, managers must record progress made and periodically inform supervisors regarding the state of completion. Collected data and progress updates shall be incorporated into a succinct living document known as the Management Action Report (MAR). For each management action installed, a corresponding section in the MAR will allow supervisors to track progress and assess effectiveness of the action.

For example, the downspout survey management action for Strategy 3 has several kinds of data that should be included in the MAR. A GIS file with downspout data, a report describing the downspout survey plan, images of downspouts on campus, and notes from downspout surveyors are all information that might be helpful to track progress. By increasing the degree to which information about projects is recorded, managers will have an easier time ensuring progress.

Assessment Periodic assessment of monitoring results and implementation progress, culminating in a final assessment report.

Once per year, supervisors of the SSMP will assess the level of effectiveness of any ongoing or completed management actions. Using the MAR as a guide, the plan supervisors will, based on the results of the MAR, choose one of the following outcomes for each management action:

Table 1: Descriptions of Potential Outcomes

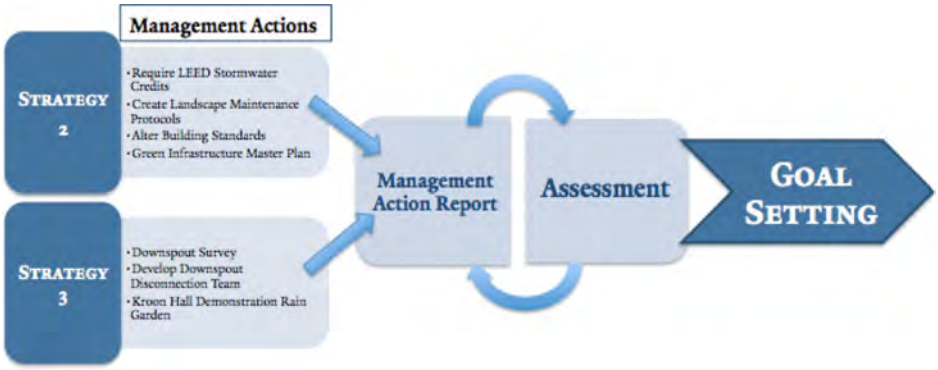
ongoing	completed
Continue Management action is showing effectiveness in addressing a goal.	**Progress** Management action achieved desired goal or part of goal.
Terminate Management action is not effective in meeting goal expectations, or is not an e∞cient use of resources.	**Re-implement** Management action still has potential to produce results for management plan.
Alter Management action will better address goal expectations with a change in strategy, implementation, or scope.	

Goal Setting and Plan Development Information gathered during management cycle informs goal evaluation and next-cycle management planning.

At the completion of the three-year adaptive stormwater management cycle, the goal-setting and plan-development process will begin. Supervisors will assess the information gathered during implementation of management strategies. Using the information and data gathered through the MAR, supervisors will establish a set of goals that address Yale's stormwater management ambitions, and incorporate the existing stormwater management capacity on campus.

The cycle of adaptive stormwater management occurring between plan development periods is designed to mirror at a smaller scale the larger goal-setting/strategy implementation cycle that will occur every three years. Under such a strategy, supervisors will be able to catch and correct ine∞ciencies before significant time and resources have been drained.

Example: Structure of Adaptive Management Process for Stormwater



Conclusion

An adaptive management approach provides an opportunity for effective results by learning, adapting, and improving management actions as new information is made available from monitoring efforts. Faced with uncertainties of stormwater events and optimal monitoring strategies, control technologies, and management practices for addressing the stormwater runoff, an adaptive management approach is suitable for Yale to most effectively manage stormwater in the long run. The adaptive management approach will help ensure that lessons from implementing the 2013 management plan are fully reflected in the 2016 plan.

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Note

1 From a conversation with G. Bright, Philadelphia Water Department, March 19, 2013.

Appendix D

Summary of the Stormwater Runoff Model

Contents

Introduction

This appendix describes the modeling approach taken during the initial stormwater management planning process. Descriptions of the software and data used, assumptions, and model results are included below. General suggestions for the next step of the modeling process are provided as well, though it should be understood that gradual refinement of the model is the ultimate goal.

EPA SWMM 5.0

Description of SWMM

The Environmental Protection Agency's Storm Water Management Model (SWMM), Version 5.0, was chosen as the modeling software for this initial attempt due to its simplicity, reliability, and free availability. SWMM is the basic platform upon which a majority of the commercially available stormwater modeling packages are based. But, because the software is not spatially focused and does not integrate directly with GIS, the current model simplifies many of the surface and subsurface characteristics of the stormwater runoff system. Although the model represents runoff dynamics on Yale's campus at a basic level, without proper calibration, and considering the simplification of system parameters, results at this time cannot be taken as fully accurate (Rossman 2010).

With this caveat, this appendix describes the system and some of the results from simulation to provide some insight into the functioning of Yale as an urban watershed.

SWMM was developed by the U.S. Environmental Protection Agency (EPA) in 1971 and has been updated several times since then. The latest version, SWMM 5.0, represents a complete rewriting of the previous FORTRAN code into the C programming language, allowing for an updated graphical user interface (GUI) and greater ease of use with the Windows operating system.

SWMM is a dynamic runoff hydraulic simulation model that incorporates rainfall, runoff, and subsurface components. Able to model both water quantity and quality, SWMM sets the basic standard for urban stormwater modeling approaches.

SWMM uses four major environmental compartments to model water and material flows. These compartments and their associated model components are:

Atmosphere Contains the precipitation and atmospheric pollutant components, which travel to the land surface compartment. A rain gauge object represents rainfall intensity/duration/structure within SWMM.

Land Surface Consists of subcatchment objects. Incident precipitation and pollutant deposits are transferred to the transport compartment or groundwater compartment depending on surface characteristics.

Groundwater Rainfall infiltrated from the land surface compartment enters the groundwater compartment, where a portion of the water is retained and the rest enters the transport compartment. Groundwater is modeled using aquifer objects.

Transport Consists of the conveyance structures that move water and materials to outfalls or treatment facilities. Node and Link objects move the inflows from the land surface and groundwater compartment.

Not all compartments must be included in a SWMM model (Rossman 2010).

Model Inputs and Assumptions

The rainfall component of SWMM converts precipitation to runoff using the surface and subsurface characteristics of subcatchment basins as defined by the user. The routing component then moves runoff through a series of pipes, channels, regulators, pumps, or treatment facilities to an outfall. A functional model system in SWMM must have the following components:

Subcatchments are polygons that represent contiguous areas that drain to the same point. Any incident precipitation on the surface of a subcatchment is either run off into the conveyance system or is infiltrated to groundwater. The proportion of water going to each is determined by the following surface characteristics:

- Area
- Characteristic width
- Slope
- Percent impervious
- Infiltration characteristics
- Depression storage characteristics
- Groundwater
- Routing
- Additional optional characteristics

Nodes serve as both connections between conduits (junctions) and outfalls. The runoff from subcatchments enters the conveyance system at junctions, and runoff exits the system into receiving waters at outfalls. Nodes are described in SWMM by the following characteristics:

- Invert elevation—the lowest elevation of the interior of a pipe or junction
- Additional optional characteristics

Conduits are the pipes, ditches, culverts, and drains that move water from one junction to another. SWMM requires that all conduits be connected to an upstream and downstream node and have su∞cient slope and capacity to establish regular gravity-driven flow, unless pumps are used. Conduits are described by the following characteristics:

- Shape
- Maximum depth
- Length
- Roughness
- Additional optional characteristics

Rainfall was represented by a single rain gauge with a two-year, 24-hour design storm for southern Connecticut, corresponding to 3.5 inches. A Natural Resources Conservation Service (NRCS) type III rainfall distribution was used to describe rainfall intensity for the study period (Kibler 1982; U.S. Department of Agriculture [USDA] 1986).

Data Sources and Process

Data generated in ArcGIS and collected from additional sources about the surface characteristics of Yale's campus, and the structure of New Haven's storm/sewer system, were input into the SWMM model.

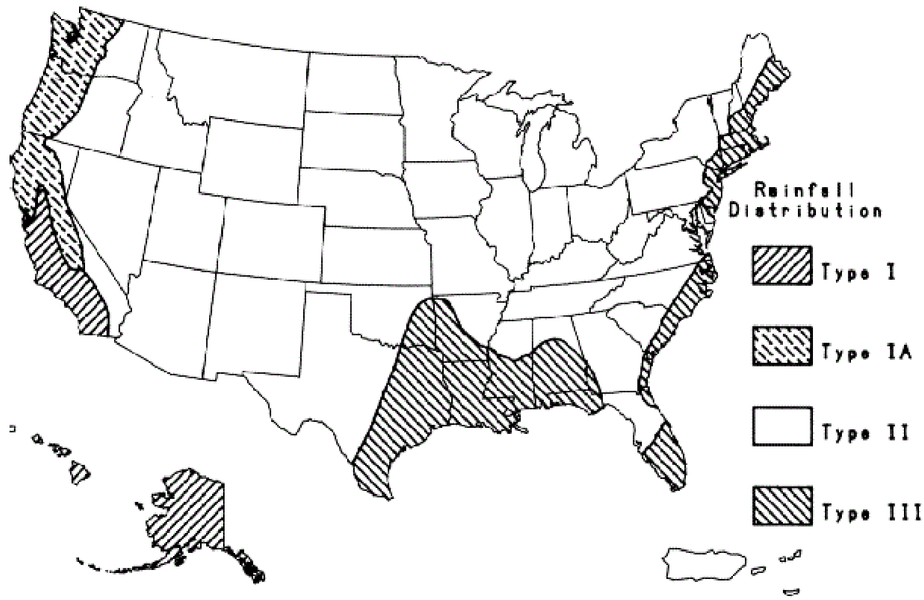
Initially, the data created by researcher Aram Marks for subcatchment shape, area, slope, impervious surface, and width were used. Later, though, these data were replaced with data collected by the engineering firm CH2MHill for the Greater New Haven Water Pollution Control Authority's (GNHWPCA) stormwater modeling effort.

To select the subcatchments corresponding to Yale's campus, a polygon shapefile was created in ArcGIS that represented an outline of all of Yale's real estate holdings in New Haven. Then, any subcatchment that overlapped at least 15% of its area with the Yale shapefile was included in the study. This resulted in 68 subcatchments that cover all Yale precincts except West Campus.

Information about the conveyance system structure and characteristics was gathered from the GNHWPCA GIS database. Because the GNHWPCA administrates both the sewer and storm systems in New Haven, it was assumed that these data represented the most up-to-date and accurate reflection of the system.

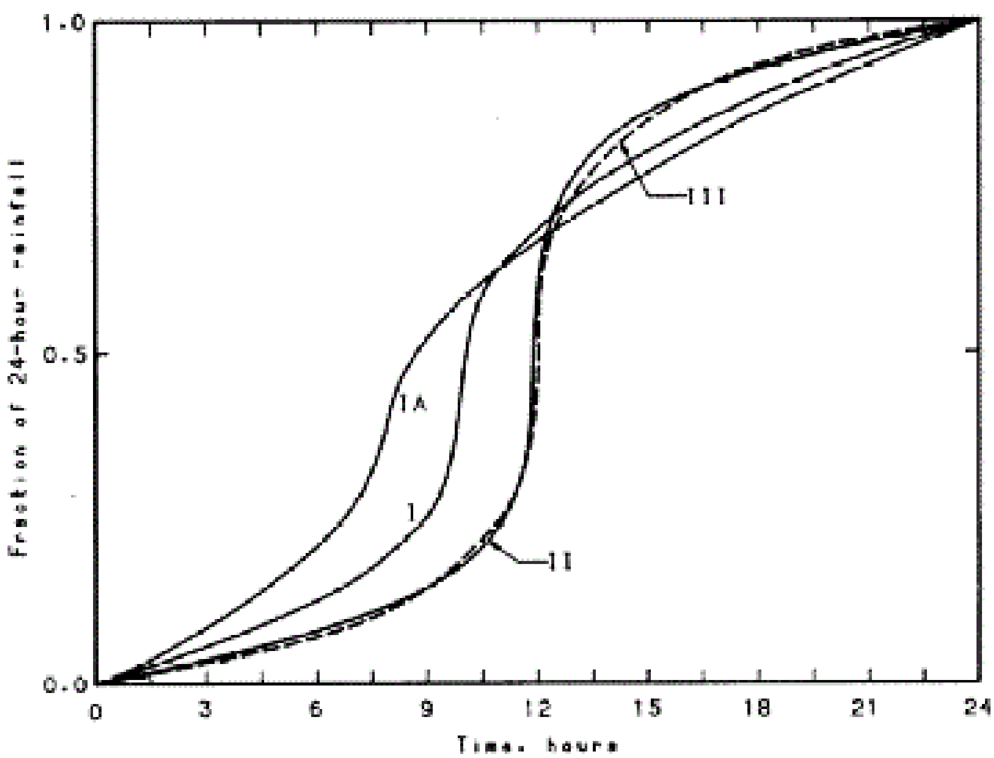
For each of the 68 subcatchment basins constituting the campus, surface characteristics including slope, area, and percent imperviousness were input based on the available GNHWPCA data file. These data are used to determine the volume and flow rate of runoff into a storm drain for a given rainfall event. Additionally, a representation of the conveyance system (either combined or separate storm sewer system) was modeled to give insight into the runoff capacity and vulnerability to flooding at various points in the network. In the Yale SWMM model, water volume is the main concern. All objects are described by a set of unique parameters or data, and connected in such a way to represent the runoff cascade from atmosphere to outfall discharge. Infiltration on a given subcatchment may be described by one of the following methods; Horton, Green-Ampt, or Soil Conservation Service (SCS) curve number. Water that does not infiltrate into the subsurface becomes runoff

Figure 1: Approximate Geographic Boundaries for SCS Rainfall Distributions



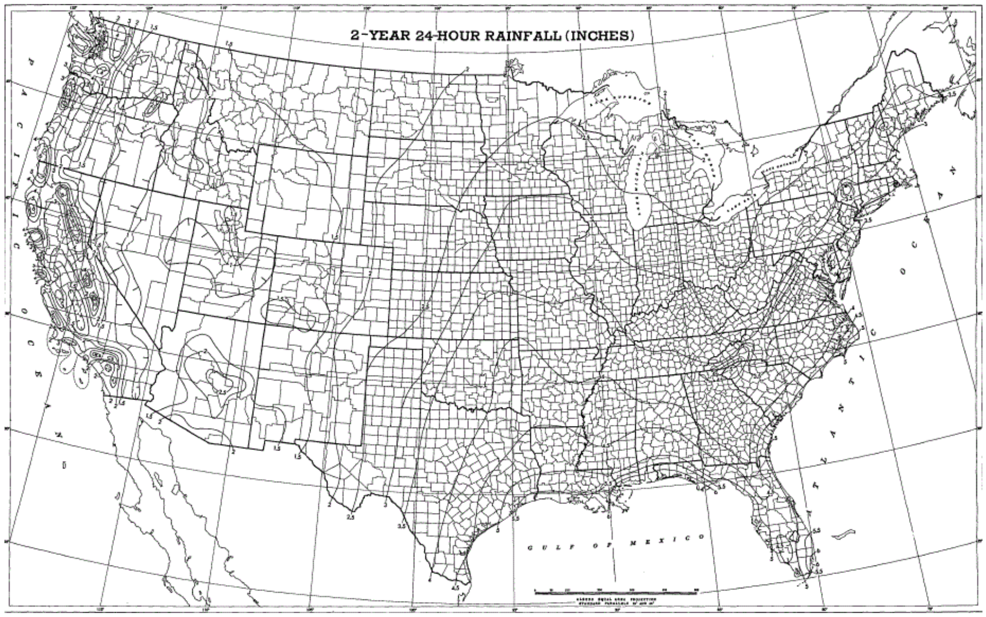
Source: USDA (1986).

Figure 2: SCS 24-Hour Rainfall Distributions



Source: USDA (1986).

Figure 3: Rainfall Amount for Two-Year, 24-Hour Storm Events (Inches)



Source: USDA (1986).

that travels through the transport system in a series of conduits and junctions eventually leading to an outlet. There are three options for flow routing in SWMM: kinematic wave, steady flow, or dynamic flow routing. In conduits, Manning's equation is used to describe the relationship between flow rate, area, hydraulic gradient, and slope (Kibler 1982; Rossman 2010; USDA 1986).

For rainfall, a two-year, 24-hour storm event based on a SCS type III rainfall distribution was chosen. SCS distributions approximate the characteristics of rainfall for different geographic regions in the United States. A type III distribution is the most common rainfall event for the northeastern Atlantic coast region. The two-year, 24-hour storm, which corresponds to 3.5 inches in New Haven, Connecticut, is a common benchmark for stormwater infrastructure modeling efforts (USDA 1986).

All object characteristics have been collected into an Excel file titled SWMM_Yale-SystemData. Contained within are detailed tables filled with the model inputs. For organizational e∞ciency, the different system components have been labeled specifically to identify the associated drainage basin, and in the case of conduits, the position in the conveyance chain. The labeling system is explained in Table 1.

Outputs

Once a functioning model has been constructed and rainfall data input, then the modeler may run a simulation. A variety of values are generated for the components of the model. The categories of results are listed below.

Subcatchment

- Total infiltration (inches)
- Total runoff (inches)

- Total runoff (10^6 gallons)
- Peak runoff (cubic feet per second, CFS)
- Runoff coe∞cient

Node

- Depth

Average depth (feet)
Maximum depth (feet)
Maximum hydraulic grade line (feet)
Time of maximum occurrence

- Flow

Maximum lateral/total inflow (CFS)
Time of maximum occurrence
Lateral/total inflow volume (10^6 gallons)

- Surcharge

Hours surcharged
Maximum height above crown (feet)
Minimum height below crown (feet)

- Flooding

Hours flooded
Maximum rate (CFS)
Time of maximum occurrence
Total flood volume (10^6 gallons)
Maximum ponded volume (10^6 gallons)

Outfall

- Loading

Flow frequency percentage
Average flow (CFS)
Maximum flow (CFS)
Total volume (10^6 gallons)

Conduit

- Flow

Maximum flow (CFS)
Time of maximum occurrence
Maximum velocity (feet per second)
Ratio of maximum flow to full normal flow
Ratio of maximum flow depth to full depth

- Surcharge
  Hours full: Upstream, Downstream, Both ends
  Hours above normal flow
  Hours of limited capacity

The results data associated with the Yale modeling effort are included in a data file titled SWMM_YaleSystemResults.

Current Results

Preliminary results from the modeling effort are shown in Table 1. For the design storm, a total of 38,304,000 gallons of stormwater runoff was produced. Subsewersheds O-3, O-4, O-5, and O-9/10 produced the greatest amount of runoff in comparison with the rest of campus. High runoff volume seems to derive from two overriding surface characteristics and one system characteristic. On the surface side, both impervious percentage and slope percentage are significant drivers of runoff volume. While subsewershed O-4 has a low impervious percentage, its largest and most upstream subcatchment has a significant slope that drives high levels of runoff. O-9/10, on the other hand, has minor slope percentage, but very high levels of impervious surface. This results in the highest volume of runoff of any subsewershed, almost 1.5 million gallons more than O-5, a subsewershed of comparable size, but lower impervious percentage. Subsewershed O-3, although relatively small in size, has both high impervious cover and high slope percentage, and the five million gallons of runoff it produces reflect these conditions.

The system characteristic driving runoff volume in this model is subsewershed size. The larger subsewersheds produce a higher proportion of stormwater runoff, which explains the contribution of O-5, the largest basin at 130 acres. When analyzing the subsewersheds for runoff produced per acre, a different picture emerges, with the second smallest, but highly impervious subsewershed O-8 having the largest per acre contribution to runoff: 77,000 gallons.

These preliminary model results are very rough estimations of the behavior of stormwater runoff on Yale's campus. Although the results do conform to anecdotal observations of runoff, more data need to be collected to improve model accuracy and calibrate the model to observed flows. Initial results such as these are helpful to identify areas of interest for campus managers and establish a basic working knowledge of stormwater dynamics.

Table 1: Flow Rates and Runoff Volume of Yale Core Campus Subsewersheds for Two-Year, 24-Hour Design Storm

outfall	avg. flow (CFS)	max flow (CFS)	total volume (10^6 gallons)	volume/acre (10^6 gallons)
O-1	2.60	34.20	1.615	0.051124
O-2	2.30	25.54	1.435	0.070759
O-3	7.80	79.82	4.874	0.060329
O-4	8.14	105.63	5.003	0.044361
O-5	9.63	117.56	5.900	0.045225
O-6	1.99	7.76	1.256	0.034658
O-7	5.51	65.26	3.454	0.059675
O-8	3.87	41.18	2.424	0.076855
O-9/10	11.88	126.69	7.290	0.066985
O-11	5.65	73.20	3.499	0.045757
O-12	2.47	32.30	1.554	0.047552
Total	61.83	697.96	38.304	Volume/Acre

Recommendations for Further Model Development

In consideration of these results and the expected future work associated with stormwater management at Yale, improvements to the modeling process should be implemented. This section outlines the required advancement in software and data to provide a clearer picture of stormwater behavior on campus.

Recommendations fall into one of three categories: Calibration, Input Data, and Software.

Calibration

A major di∞culty associated with computer modeling software is verification of the results. Typically, this is done by calibrating outputs with real-life data and tweaking input parameters until the modeled results and measured results converge. When modeling a large stormwater system, calibration can be especially di∞cult due to the large area modeled and high number of conduits, nodes, and drainage structures involved. For the stormwater modeling effort at Yale, calibration data are essential to ensure an accurate assessment of stormwater challenges, but collecting such data may prove especially di∞cult.

If possible, arrangement should be made to install flow meters within the stormwater conveyance system. Actual flow data can be compared with modeled flows to assess the accuracy of the modeling effort. Sites for flow monitoring must be carefully chosen in order to ensure that the drainage area above the monitoring site is equivalent to the drainage area modeled in SWMM. In addition, choosing a site as far "downstream" as possible, while still within the sewershed, will increase the reliability of calibration.

Due to the structure of the stormwater conveyance system, multiple monitoring sites are required to calibrate all the subcatchments on Yale's campus. Each subsewershed must have its own calibration data set because the subsewershed groupings all drain to different locations. Because of the large capital expense of installing in-stream monitoring equipment, it is assumed that full coverage may not occur, or will be implemented over an extended period of time. That being said, calibration should be a priority, and any data available to compare will improve modeling accuracy.

Input Data By using data from the GNHWPCA in the modeling exercise, we have ensured that results are based on the most accurate data possible. Still, the data are not 100% accurate or up to date, and data collection efforts should continue to improve understanding of the system. Part of this effort should involve maintaining communication with the engineers at GNHWPCA so that when new data are created, they are immediately shared with managers at Yale. In addition, the data shared by GNHWPCA should be verified and/or improved when more detailed data sources are available.

In this modeling effort only the basic characteristics of model components were used. There is significant potential for improvements to the model results by including additional characteristic data such as infiltration parameters, evapotranspiration, depression storage, alternative inflows, overflow parameters, and so on. Further investigation should be done to determine the appropriate values for these characteristics in each subcatchment.

Software In addition to improving data and calibrating model parameters, upgrading to more powerful modeling software can both increase accuracy of results and facilitate easier model improvement. There are several commercially available stormwater routing packages based on the SWMM platform that are used regularly to perform stormwater analysis. The most commonly used and most reliable software packages are:

- InfoWorks
- InfoSWMM
- HydroCAD

All three of these software packages have similar basic functionality, but should be evaluated based on expected need and functionality when the time comes to upgrade.

Conclusion

This appendix has summarized the stormwater modeling effort by describing the tools and data used, presenting high-level results and discussion, and making recommendations for further improvements to the process. This is a first step toward understanding the mechanics of stormwater on the campus of Yale University. Subsequent efforts to improve the quality of the model will provide managers with a valuable tool to prioritize stormwater mitigation efforts and identify opportunities. The incremental improvement of this model is essential for better management and should be considered a priority going forward.

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Appendix E

Spatial Decision-Making Guide for Green Infrastructure Implementation on Yale University's Campus

Contents

Introduction

To successfully manage stormwater using the practice of green infrastructure, the techniques must be implemented in a comprehensive manner across campus. In preparation for a future program of wide-scale implementation of green infrastructure, this appendix presents an analysis to determine site suitability and opportunities for green infrastructure on Yale's campus. Consistent with the definition used in the plan, green infrastructures refer to all potential practices, landscapes, and storage devices that can be used to slow the flow of stormwater, reduce stormwater volume, and improve stormwater quality before it enters the sewer system.

The analysis for this appendix was conducted using data from the Greater New Haven Water Pollution Control Authority, Yale University, Urban Resources Initiative, University of Connecticut, and Google Maps. This appendix focuses on the six primary management precincts of Yale University's campus: Upper Prospect, Science Hill, Hillhouse, Core, Broadway/Tower Parkway, and the Medical Campus. This appendix is meant to help identify high-priority areas for stormwater runoff and to provide guidance for green infrastructure implementation on the Yale Campus.

The maps on the following pages represent campus-wide approximations of site suitability for green infrastructure implementation. Recommendations for green infrastructure opportunities are based on the following:

- Volume of water runoff per subcatchment and per management precinct
- Slope of subcatchment
- Direction of flow for surface water runoff and areas of high water accumulation
- Amount of pervious and impervious surface
- Visual assessment of building roof slope and other site conditions

These data were incorporated to identify high-risk areas, where surface water is likely to accumulate in a storm event, and to provide a scale of site suitability from least to most suitable for green infrastructure implementation. Areas of greatest suitability include pervious surfaces located within subcatchments that generate a high volume of stormwater runoff. In order to encourage onsite water management while limiting the potential for damage to infrastructure, sites were prioritized to include pervious surfaces at least 10 feet away from existing buildings.

General information on geology, hydrology, and soils was considered, but not incorporated into this analysis. The underlying bedrock is arkosic sandstone, and soils from this parent material are characterized as sandy loams with moderate drainage capacity. Characteristics vary depending on location, as soils in the city of New Haven are highly disturbed anthropogenic soils that contain fill material of variable quality. Fine-grained data on soil permeability, depth to bedrock, and depth to water table should be considered on a site-by-site basis and incorporated into future analysis as these data are made available. This information will be an important component of determining site suitability for green infrastructure implementation.

Where infiltration is not possible, permeable surfaces with under-drains, such as parking areas, sidewalks, and tree trenches, will help attenuate the flow of rainwater runoff and should be considered. Recommendations for permeable pavement presume these conditions.

A visual assessment of tree canopy cover was conducted based on the 2012 Urban Resources Initiative Yale Campus Tree Survey. Though the campus tree survey is comprehensive, there are still several gaps in the data, including a tree inventory for the Upper Prospect Precinct and Mansfield Street on Science Hill. Though data from the tree survey are not represented in this appendix, canopy cover, species, age class, and condition of campus trees should be considered when prioritizing green infrastructure implementation.

Current and future New Haven sewer separation projects were also identified in order to consider possibilities for future collaborations between Yale and New Haven.

Information regarding buildings that flooded during the August 2012 storm event was incorporated into the precinct-level maps to help identify problem areas. Neither the New Haven projects nor storm-damaged buildings were included in the scale of site suitability; rather, they provided guidance for green infrastructure site selection.

Existing buildings on the Yale campus were assessed for their green roof potential using Google Maps satellite imagery. Flat to slightly sloped roofs with minimal mechanical infrastructure were considered to be optimal candidates for green roof installation. No structural analysis was completed, nor were site visits or inspections conducted in order to verify green roof potential. Potential green roofs indicated in the following maps represent candidates for further green roof investigation.

Based on existing data, including runoff contribution, slope, and percentage of available impervious surface, the Upper Prospect Precinct and Science Hill Precinct are high-priority candidates for green infrastructure pilot projects.

In order to develop a more robust assessment of green infrastructure for stormwater management on the Yale campus, a block-by-block on-the-ground assessment should be conducted within each management precinct. Data from the Yale Bowl, West Campus, and other Yale properties must be incorporated into the green infrastructure decision-making guide.

Campus-Scale Map Summaries

Runoff

- Based on runoff volume contribution from each subcatchment.
- The dark blue color represents the areas of high runoff volume.
- Surface runoff from these regions flows toward areas of high accumulation.

Slope

- The dark green color represents areas of high slope percentage.
- The slope of individual subcatchments within this zone ranges from 5% to 12%, which is suitable for many types of green infrastructure.
- The lower the slope, the higher the flow accumulation and the higher the concentration of problem areas.
- Precincts upslope of areas of high accumulation should be targeted for green infrastructure implementation in order to reduce/mitigate stormwater runoff.

Areas of High Water Accumulation

- A flow-direction map is created based on topography.
- The red represents the areas of high accumulation, which are subject to flooding in a peak storm event.
- Problem areas may be best managed by implementing green infrastructure upstream to reduce runoff contribution downstream.

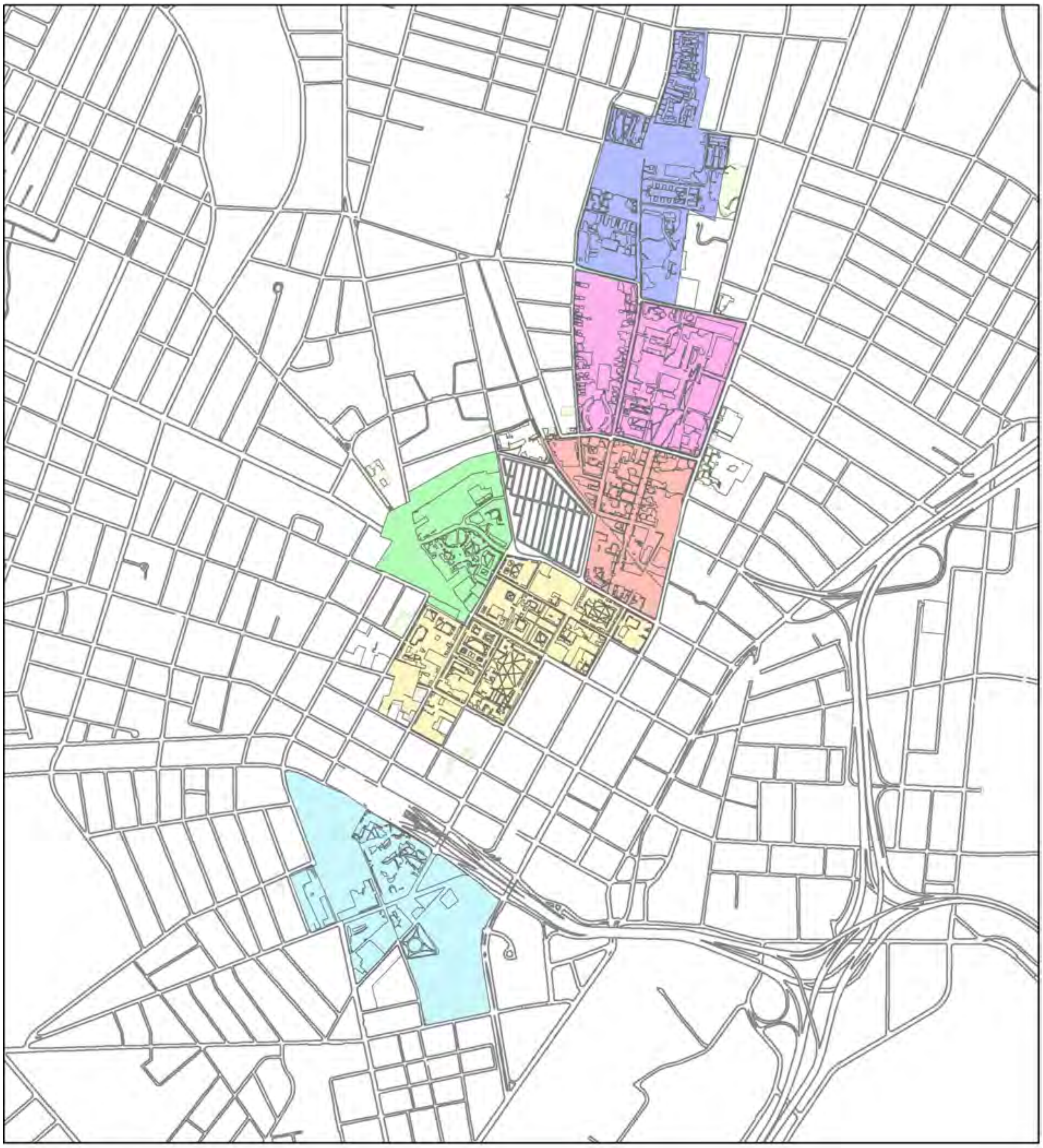
Site Suitability

- The green represents the pervious areas that are most suitable for green infrastructure implementation.
- These areas have higher opportunities to capture and infiltrate runoff to reduce its impact downstream.

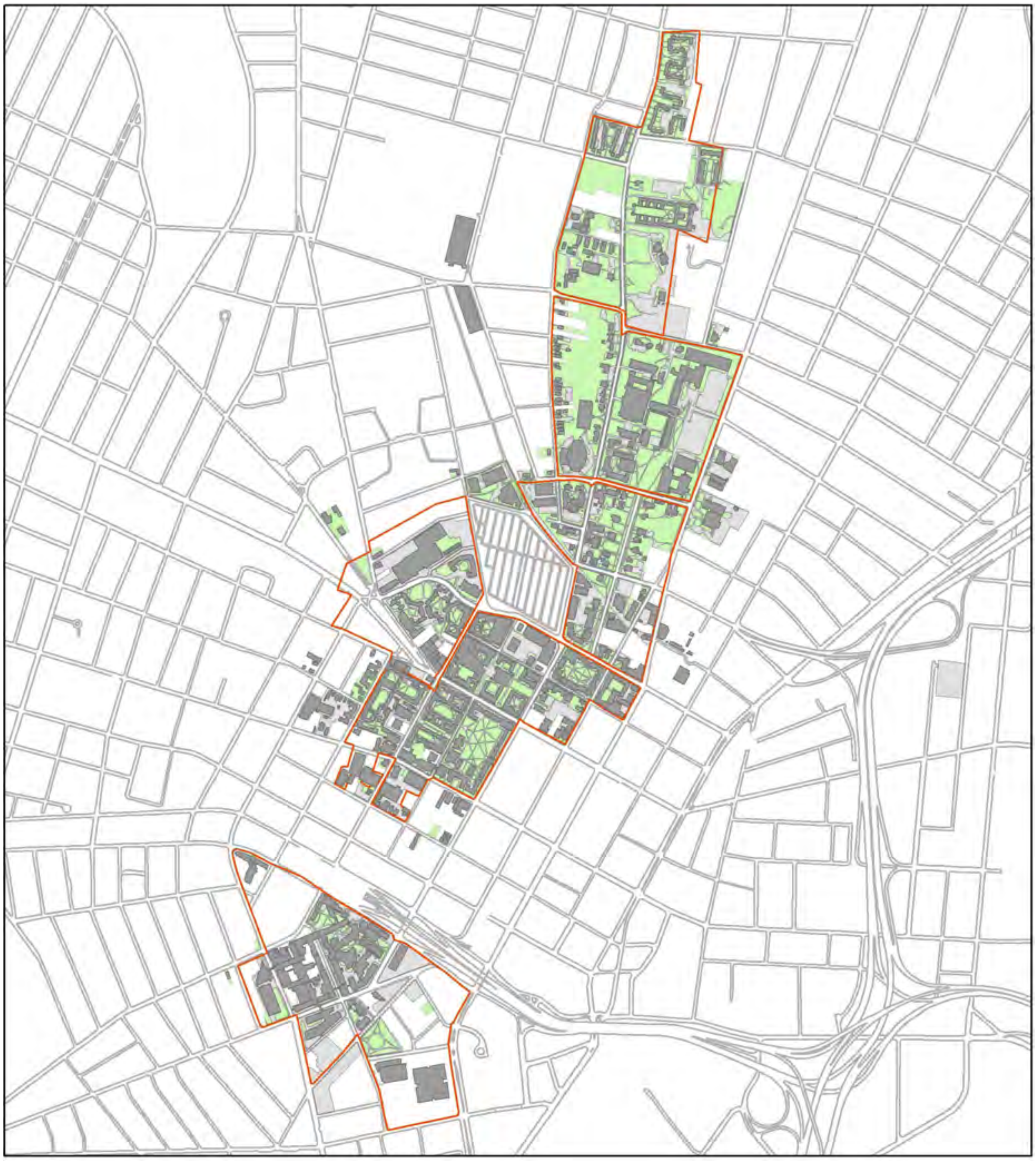
Site Suitability/Target Areas

- This site suitability map was refined from the previous site suitability map in order to consider on-site management of runoff from campus buildings and only include sites that are within 50 feet of existing buildings.

Maps: Yale Campus Priority Areas for Stormwater Management



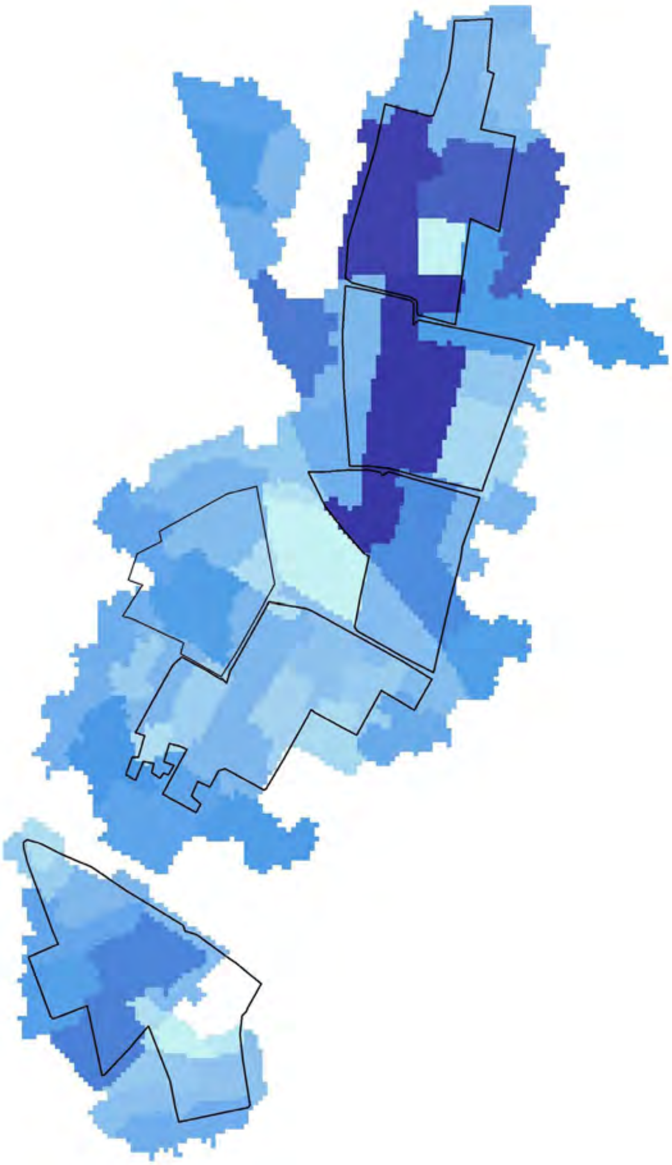
Yale Campus: Primary Precincts



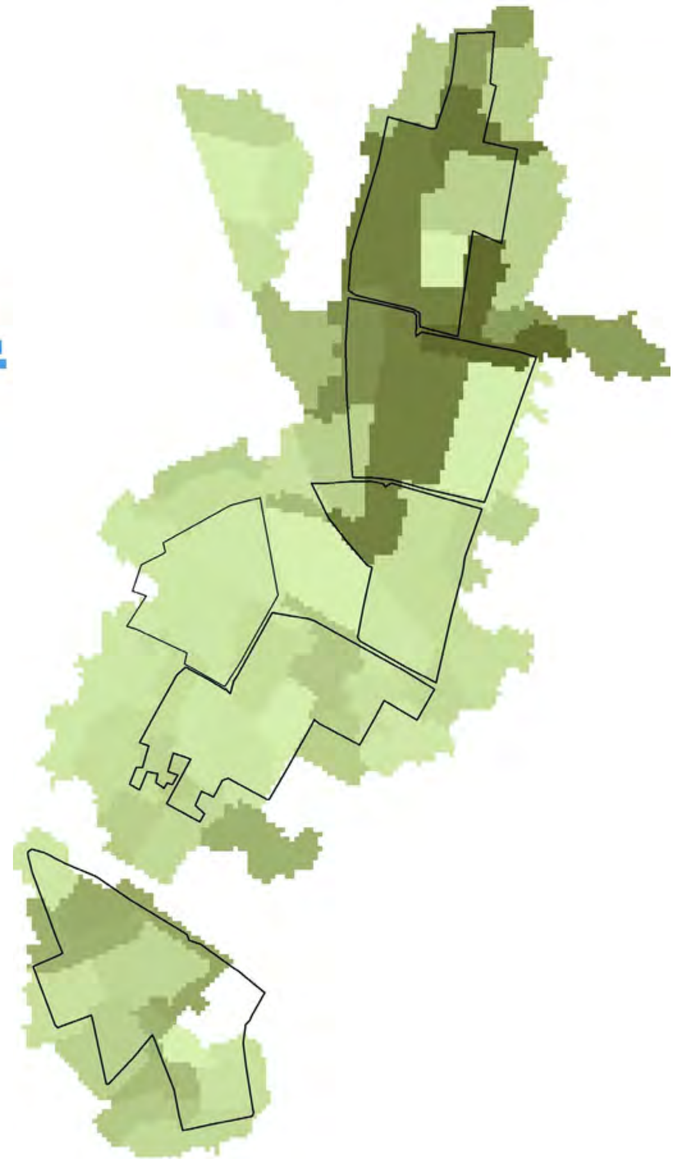
Yale Campus: Pervious and Impervious Surface

Yale Campus Buildings   Pervious Area   Impervious Area

0 250 500 1,000 1,500 2,000 Meters



Yale Campus: Subcatchment Runoff Volume



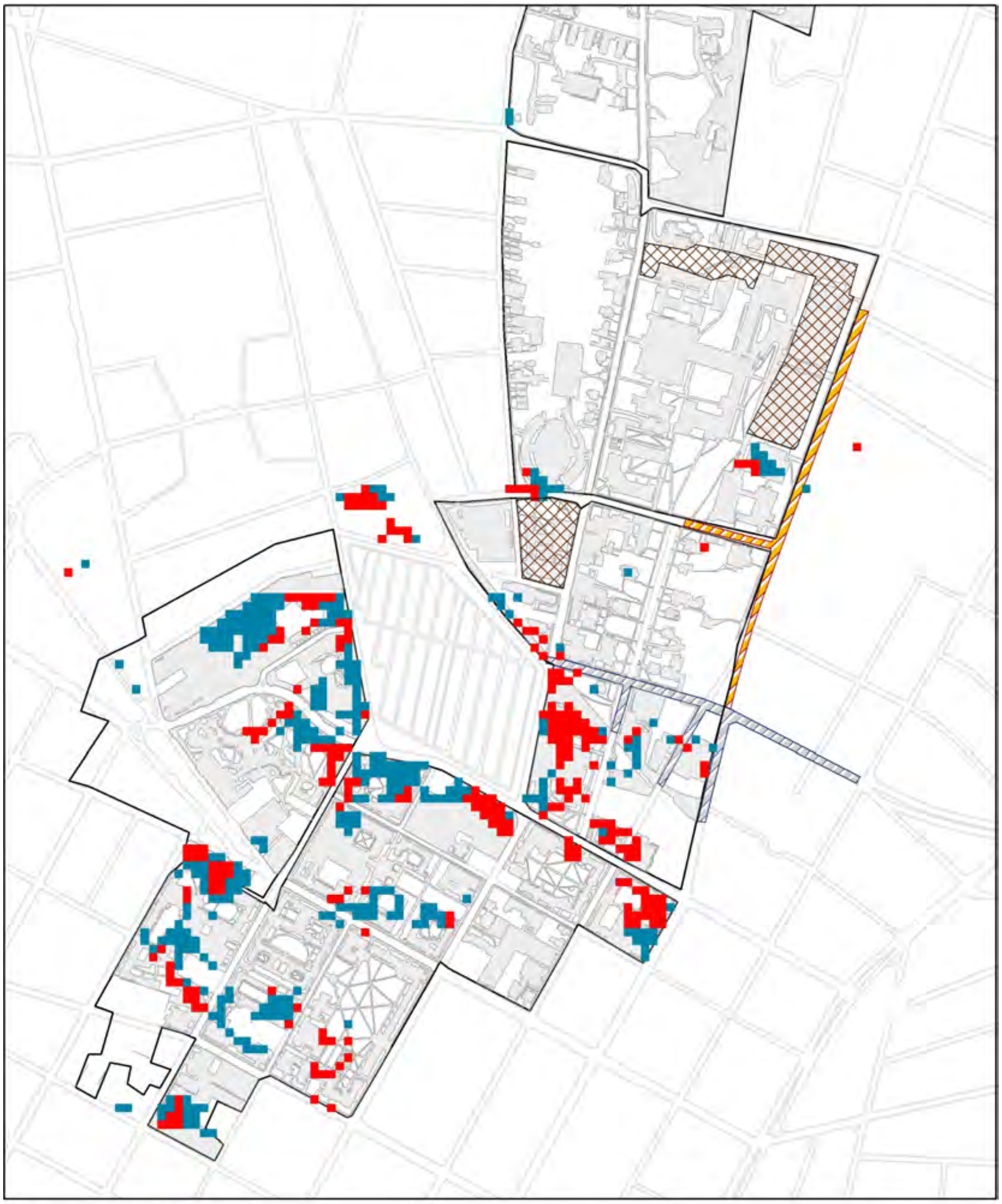
Yale Campus: Subcatchment Slope Percentage

Yale Campus: Areas of High Water Accumulation

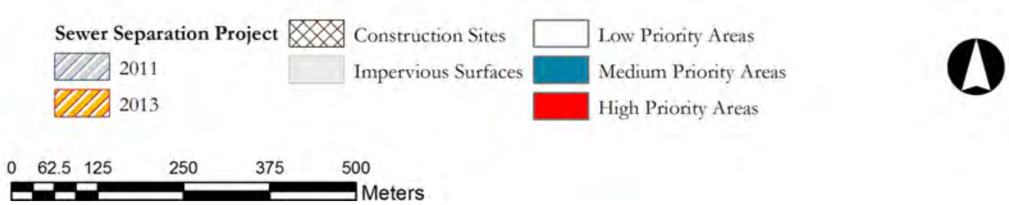
Low priority
High priority
Medium priority
Impervious Surfaces

Yale Campus: Site Suitability

Most Suitable
Least Suitable
Moderate



Yale Campus:High Priority Areas and New Constructions

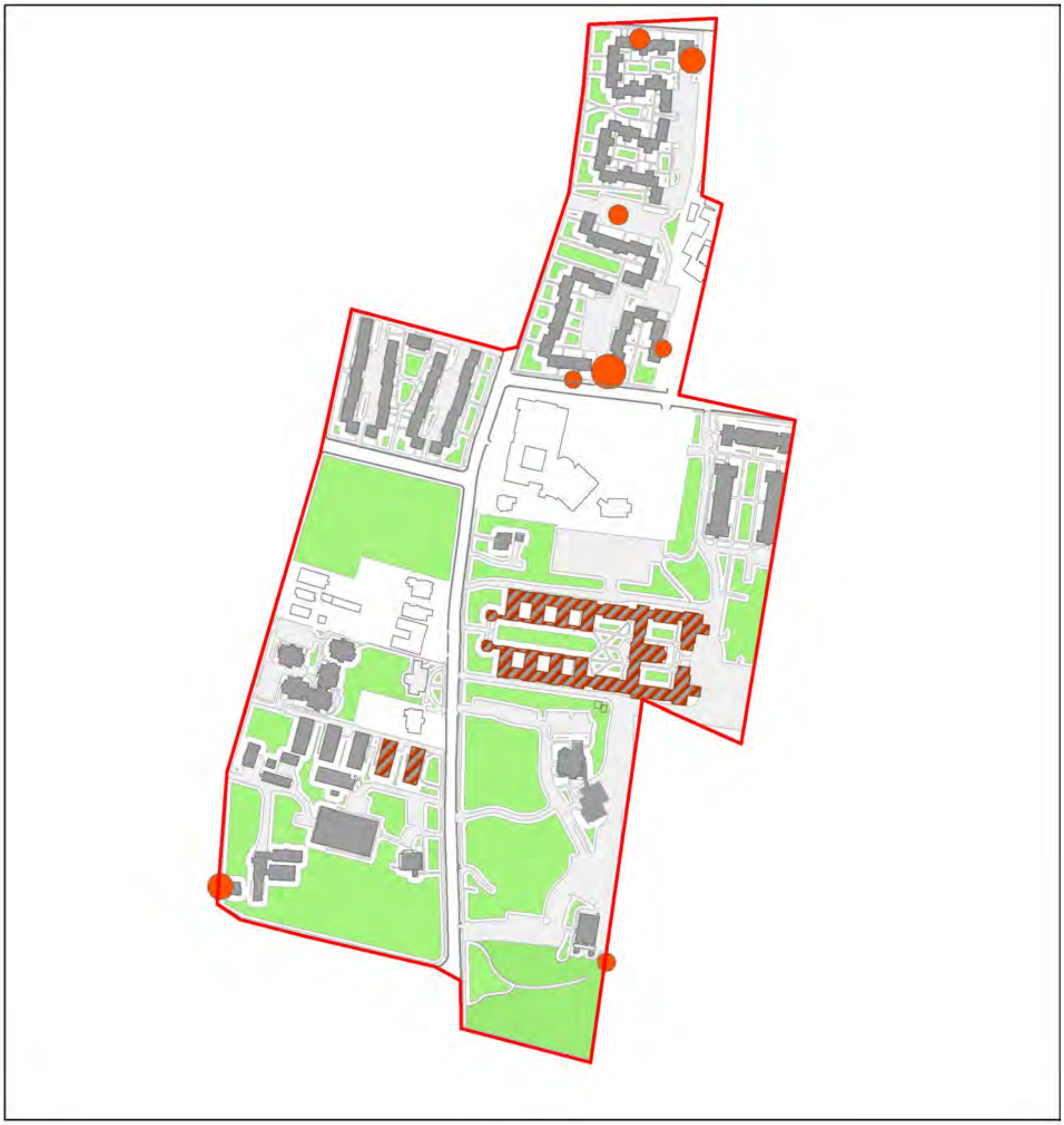


Yale Campus: Site Suitability and GI Target Areas

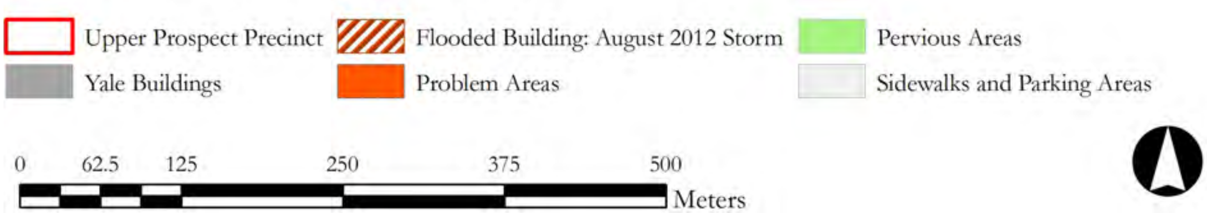
Maps: Green Infrastructure Opportunities at the Precinct Level

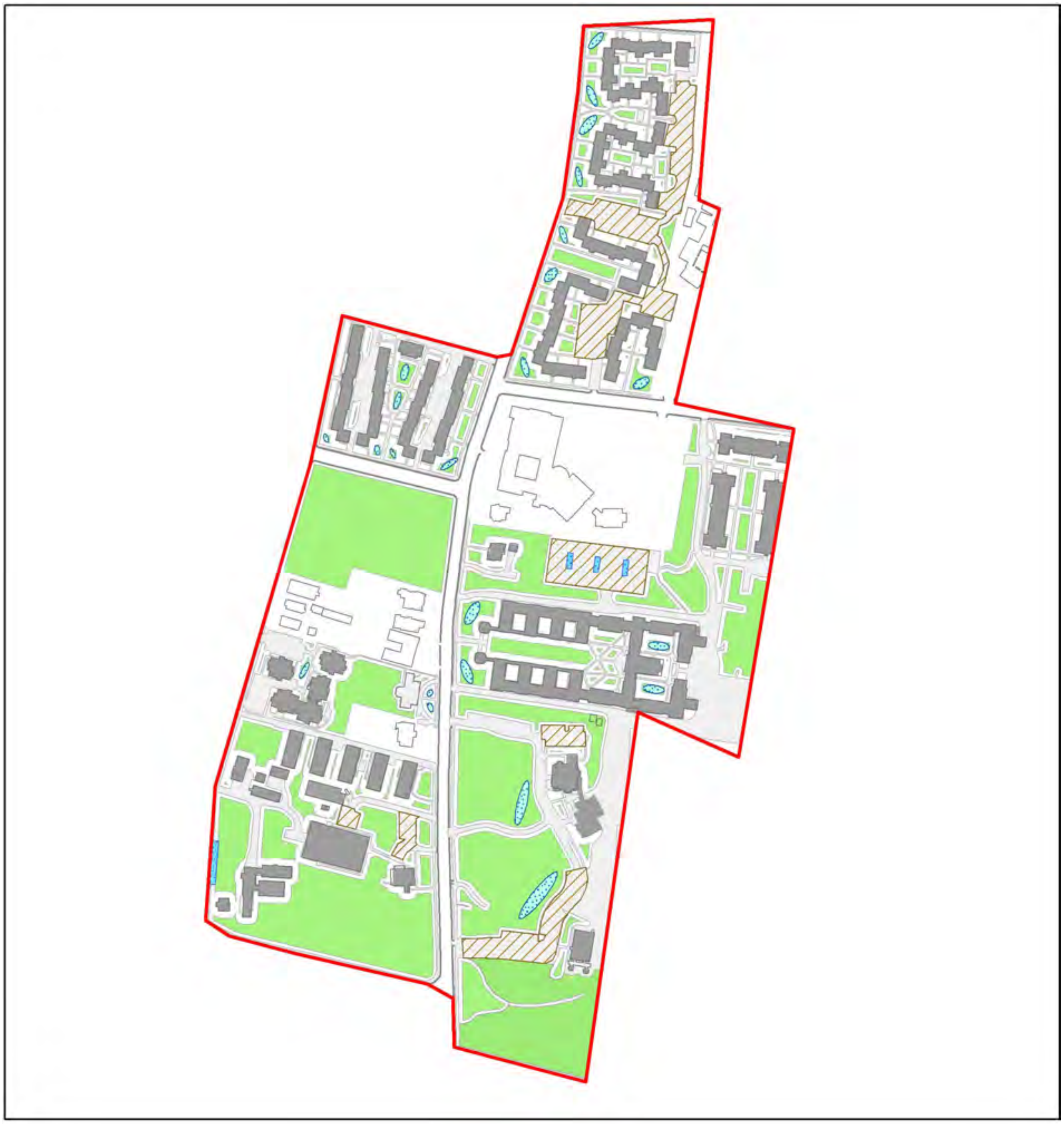
Yale Campus: Potential Green Roofs

Possible Green Roof
Other Yale Buildings
ImperviousArea
PerviousArea



Yale Campus: Upper Prospect Priority Areas





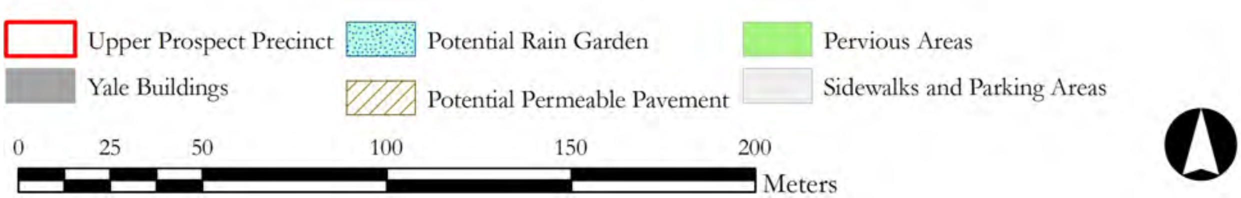
Yale Campus: Upper Prospect GI Opportunities

Yale Campus: Upper Prospect GI Opportunities – Close Up I

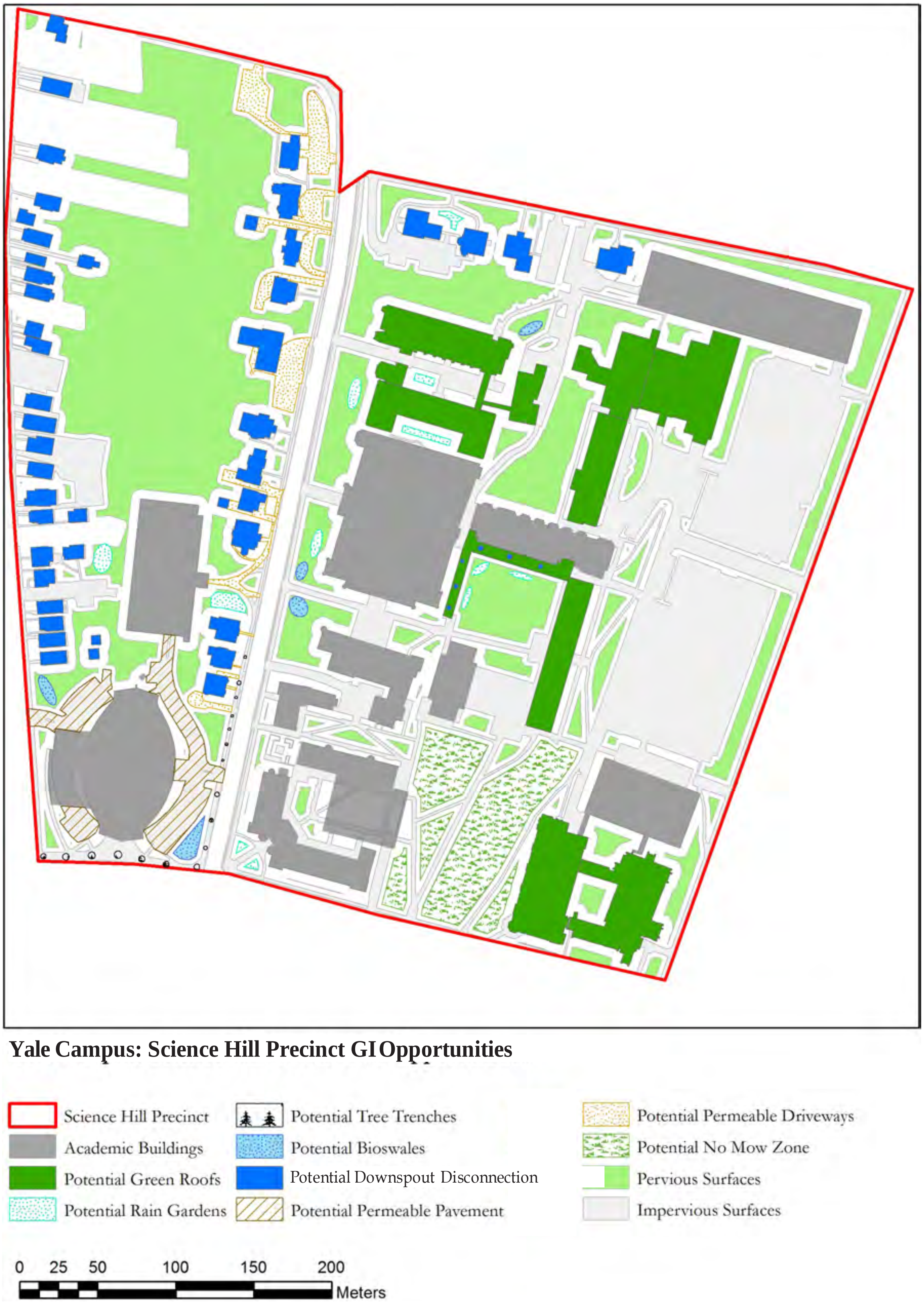
Upper Prospect Precinct	Potential Rain Garden	Pervious Areas
Yale Buildings	Potential Bioswale	Sidewalks and Parking Areas
Potential Green Roof	Potential Permeable Pavement	

0 25 50 100 150 200 Meters

Yale Campus: Upper Prospect GI Opportunities – Close Up II



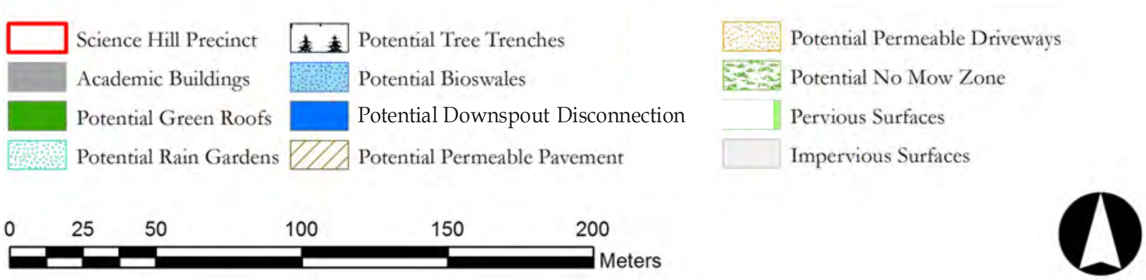
Yale Campus: Science Hill Precinct Priority Areas



Yale Campus: Science Hill Precinct GI Opportunities

Yale Campus: Science Hill Precinct GI Opportunities – Close Up I

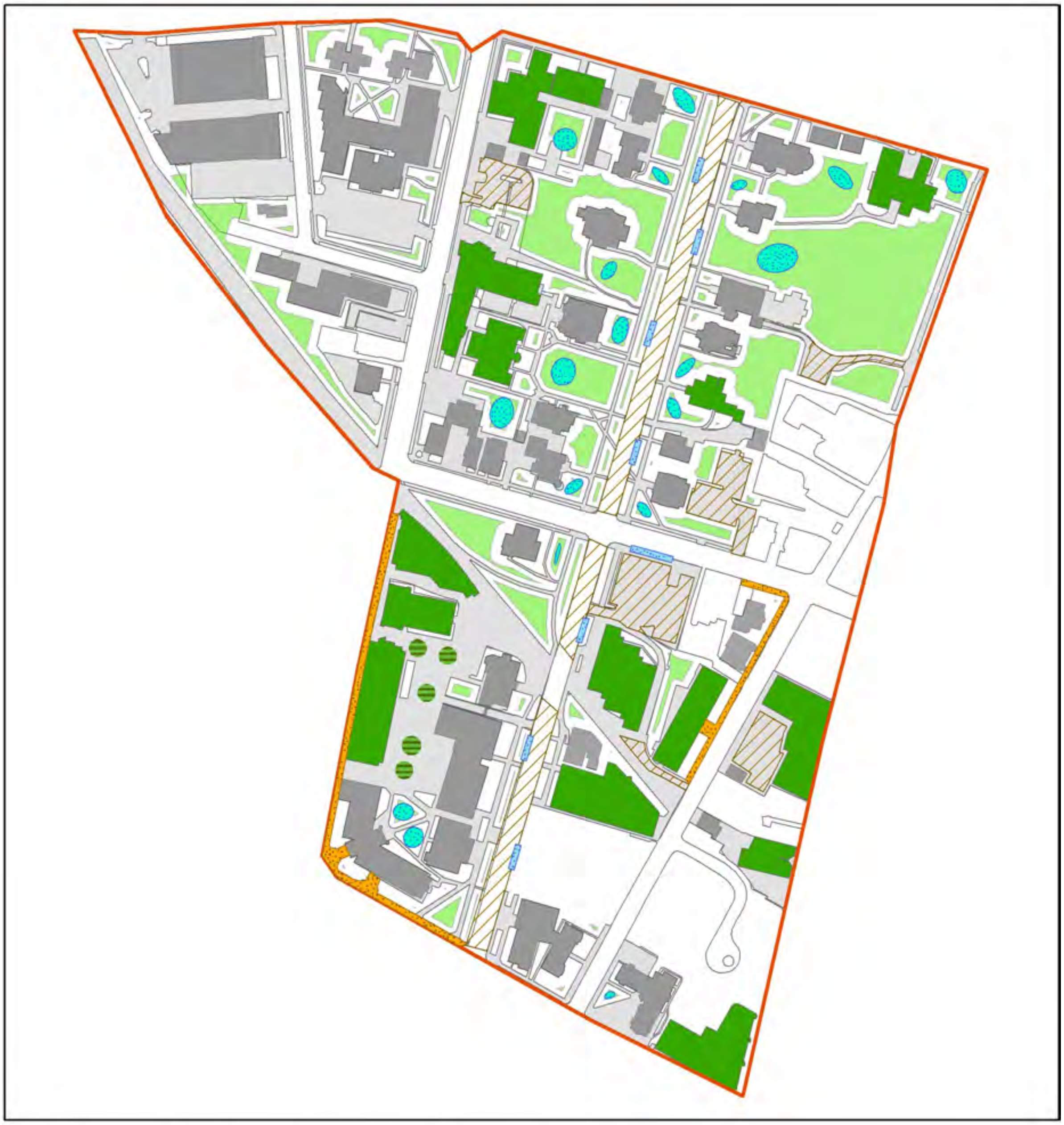
Yale Campus: Science Hill Precinct GI Opportunities – Close Up II



Yale Campus: Hillhouse Precinct Priority Areas

Hillhouse Precinct
Flooded Building: August 2012 Storm
Pervious Surfaces
Academic Buildings
Areas of High Water Accumulation
Impervious Surfaces

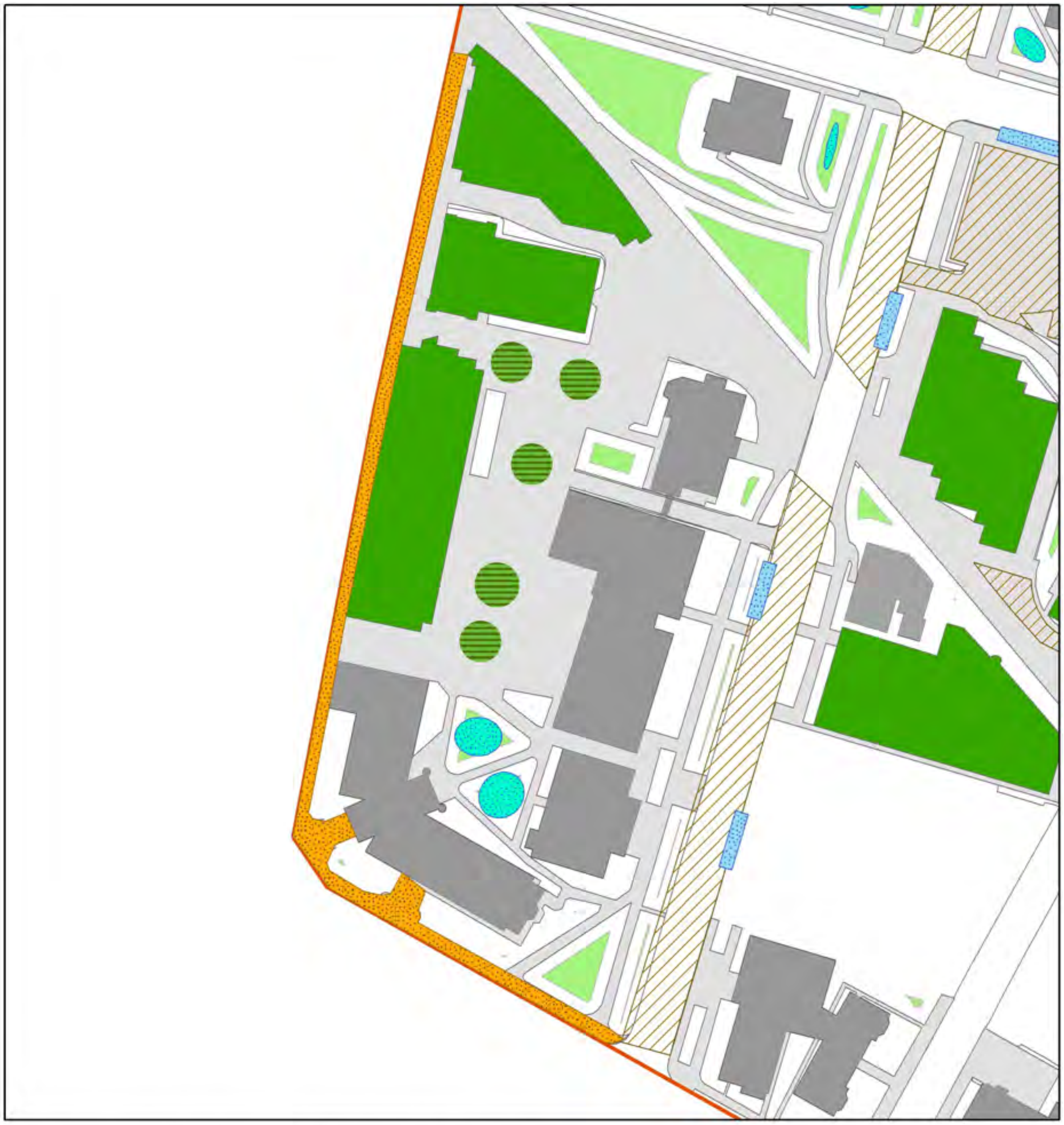
0 25 50 100 150 200 Meters



Yale Campus: Hillhouse Precinct GI Opportunities

Hillhouse Precinct
Academic Buildings
Potential Green Roof
Potential Rain Garden
Potential Raised Planter Boxes
Potential Bioswale
Potential Pervious Pavement
Potential Permeable Sidewalk
Pervious Surfaces
Impervious Surfaces

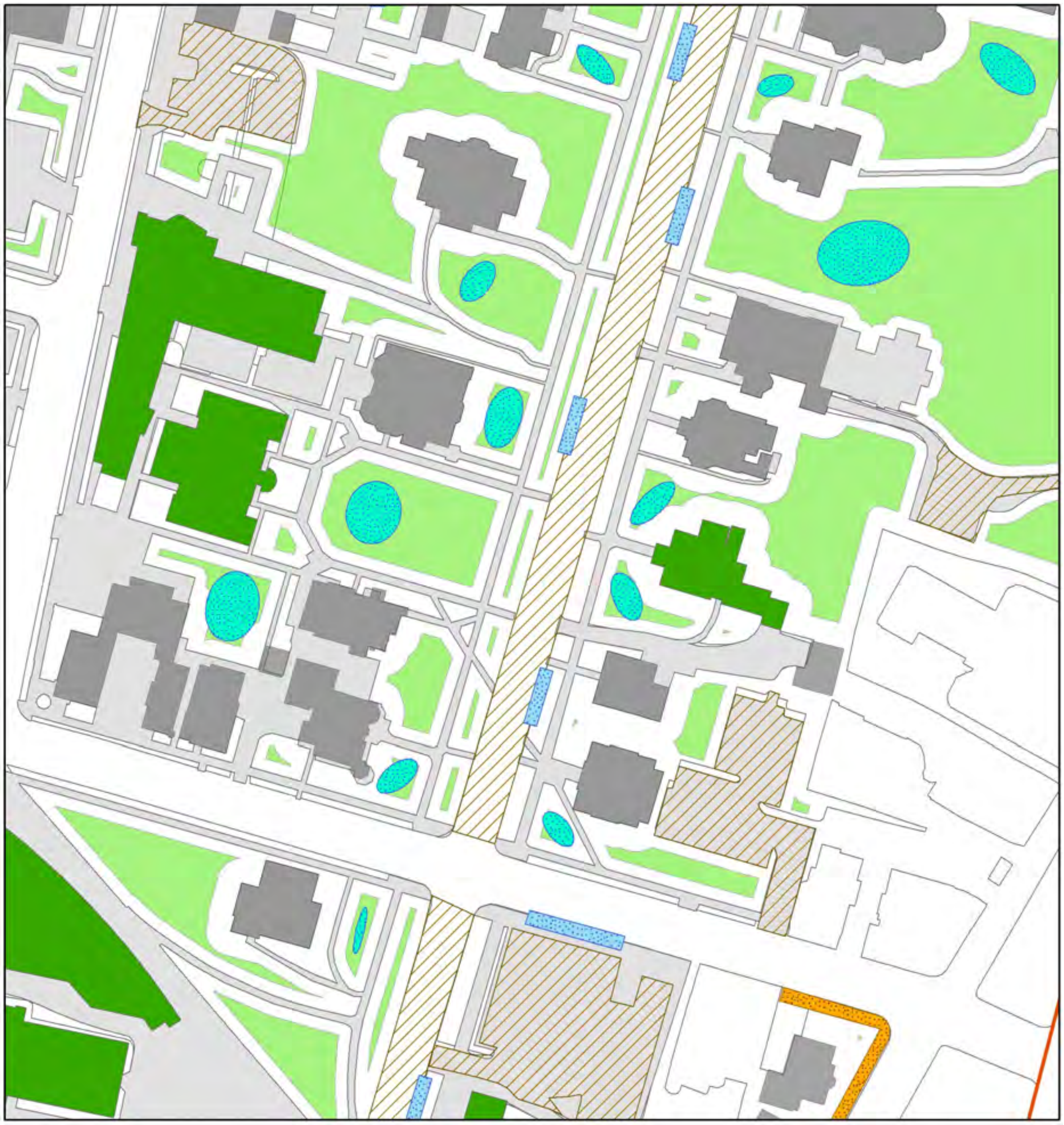
0 62.5 125 250 375 500 Meters



Yale Campus: Hillhouse Precinct GI Opportunities – Close Up I

Hillhouse Precinct
Academic Buildings
Potential Green Roof
Potential Rain Garden
Potential Raised Planter Boxes
Potential Bioswale
Potential Pervious Pavement
Potential Permeable Sidewalk
Pervious Surfaces
Impervious Surfaces

0 25 50 100 150 200 Meters



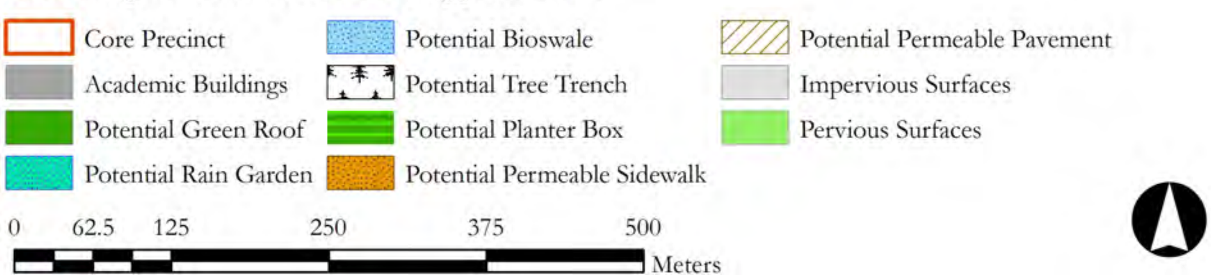
Yale Campus: Hillhouse Precinct GI Opportunities – Close Up II

Yale Campus: Core Precinct Priority Areas

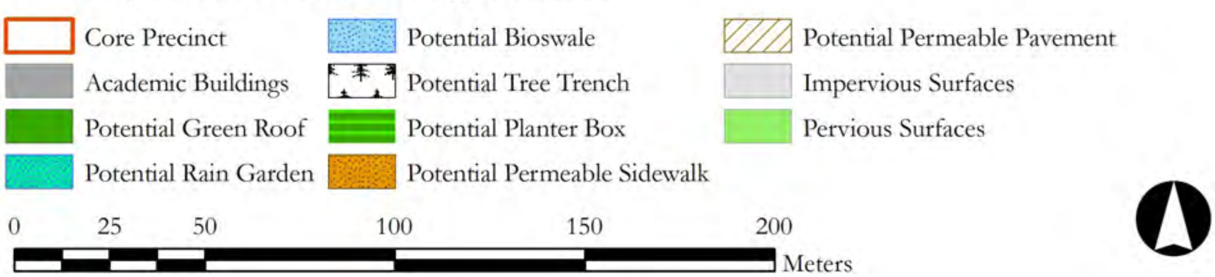
Core Precinct
Areas of High Water Accumulation
Academic Buildings
Flooded Building: August 2012 Storm
Impervious Surfaces
Pervious Surfaces

0 62.5 125 250 375 500
Meters

Yale Campus: Core Precinct GI Opportunities



Yale Campus: Core Precinct GI Opportunities – Close Up I



Yale Campus: Core Precinct GI Opportunities – Close Up II

Core Precinct
Academic Buildings
Potential Green Roof
Potential Rain Garden
Potential Bioswale
Potential Tree Trench
Potential Planter Box
Potential Permeable Sidewalk
Potential Permeable Pavement
Impervious Surfaces
Pervious Surfaces

0 25 50 100 150 200 Meters

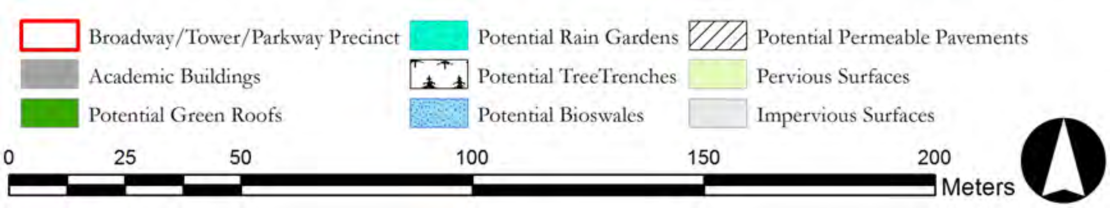
Yale Campus: Broadway/ Tower/ Parkway Priority Areas

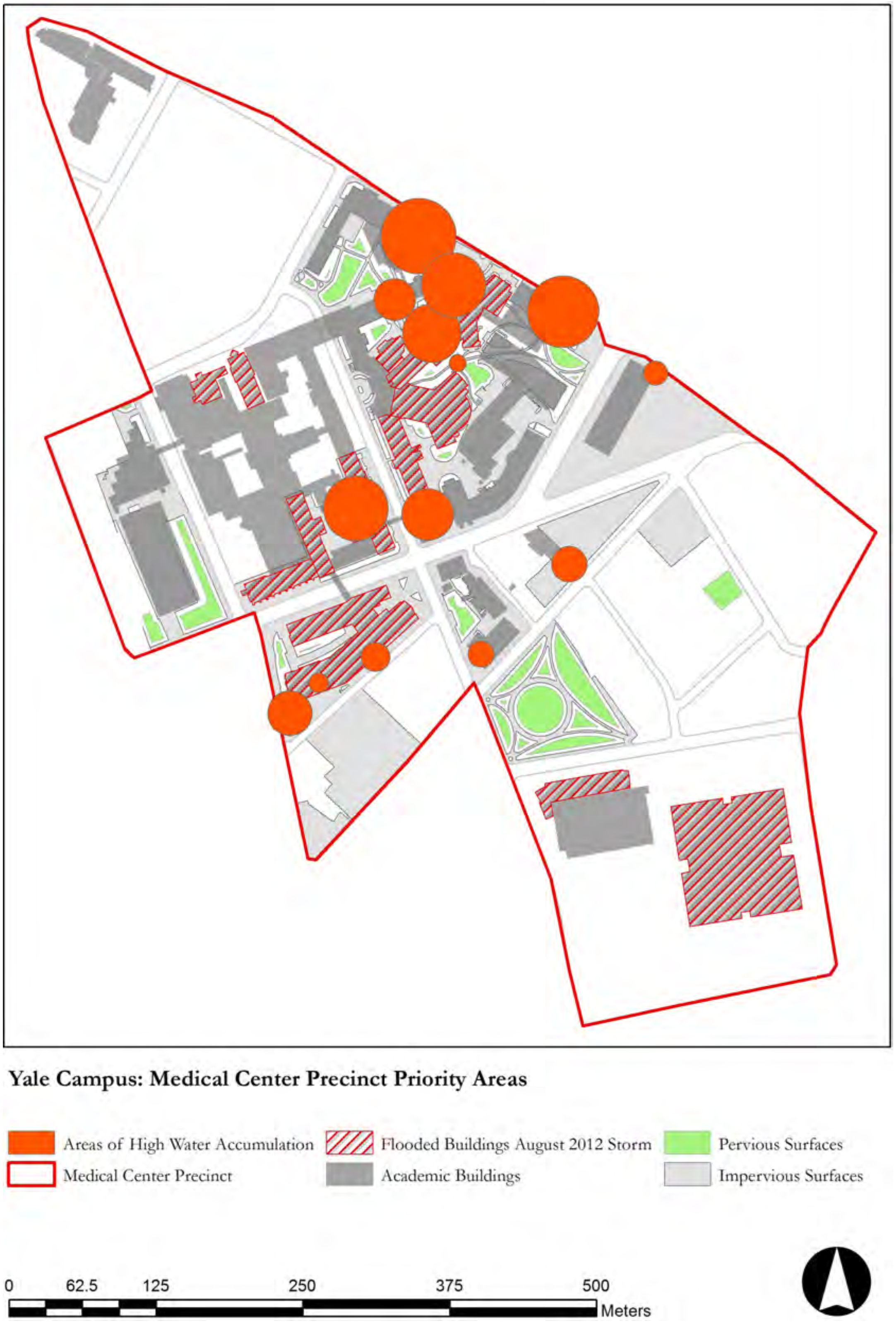
Yale Campus: Broadway/ Tower/ Parkway Precinct GI Opportunities

Broadway/Tower/Parkway Precinct
Academic Buildings
Potential Green Roofs
Potential Rain Gardens
Potential TreeTrenches
Potential Bioswales
Potential Permeable Pavements
Pervious Surfaces
Impervious Surfaces

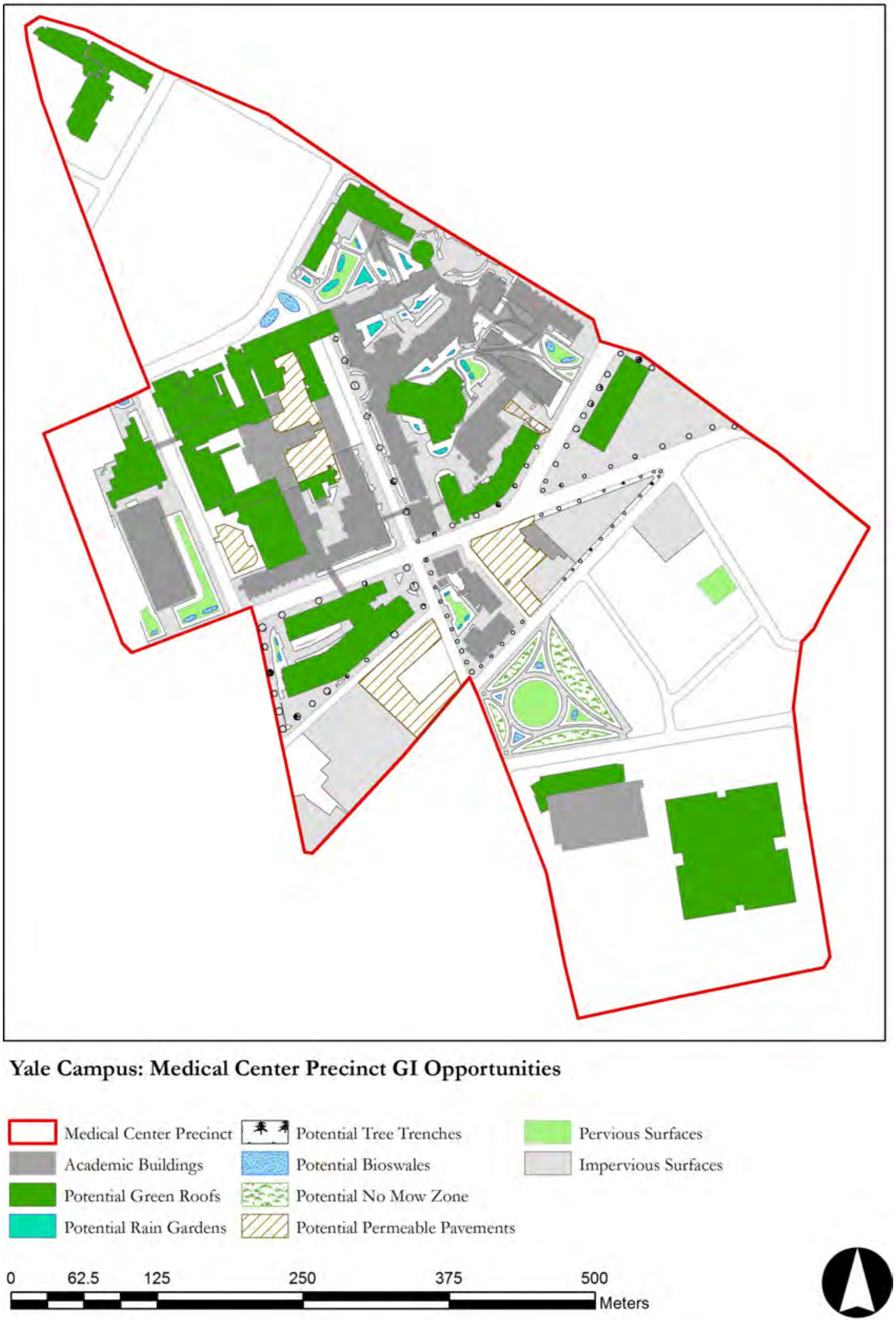
0 25 50 100 150 200
Meters

Yale Campus: Broadway/Tower/Parkway Precinct GI Opportunities – Close Up I

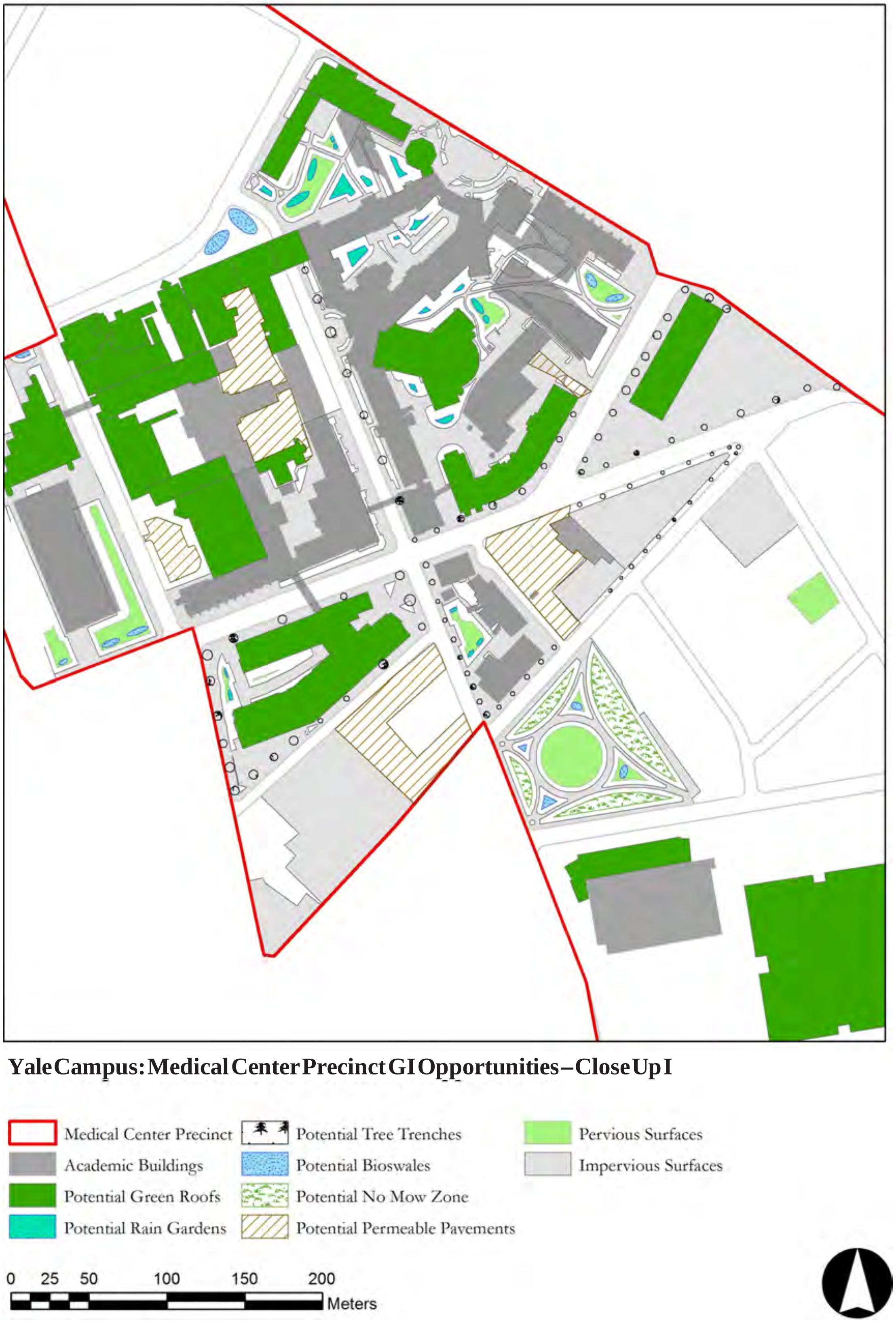




Yale Campus: Medical Center Precinct Priority Areas



Yale Campus: Medical Center Precinct GI Opportunities



Yale Campus: Medical Center Precinct GI Opportunities – Close Up I

Appendix F

Recommendations for Yale University's Downspout DisconnectionProgram

Contents

Figure 1: Steps to Disconnecting a Downspout

Measure

Cut

Cap

Attach

Screw

Place

Source: DDOE.

Introduction

Of the many surfaces that create stormwater runoff, the stormwater that comes in contact with rooftops offers perhaps the greatest opportunity for rainwater harvesting and management because it tends to be significantly less contaminated than the runoff from other surfaces like roadways. If directly connected to the sewer system, this stormwater can enter the sewer system, where it combines with more heavily contaminated stormwater or combined sewage. This relatively clean stormwater adds excess volume to the sewer system that can cause the system to reach its capacity. For areas that are serviced by combined sewer systems, the additional stormwater that flows from rooftops can contribute to combined sewer overflow events, leading to the discharge of untreated wastewater directly into waterways. For areas that are serviced by separate storm sewer systems, the rooftop stormwater flows untreated directly into waterways along with the contaminated water from other surfaces.

With over five million square feet of impervious area created by buildings on Yale University's campus, disconnecting downspouts and managing roof runoff offers one method to help Yale manage stormwater more sustainably. This appendix covers recommendations for how Yale University could approach and implement a downspout disconnection program.

Considerations for Establishing a Downspout Disconnection Program

Downspout disconnection requires very few tools or advanced skills. A disconnection project typically requires little more than a hacksaw, a drill, a pipe cap, a downspout extension and elbow, and a mechanism to protect the adjacent surface from erosion due to the newly directed runoff (District Department of the Environment [DDOE], n.d.). Figure 1 illustrates the steps for disconnecting a downspout.

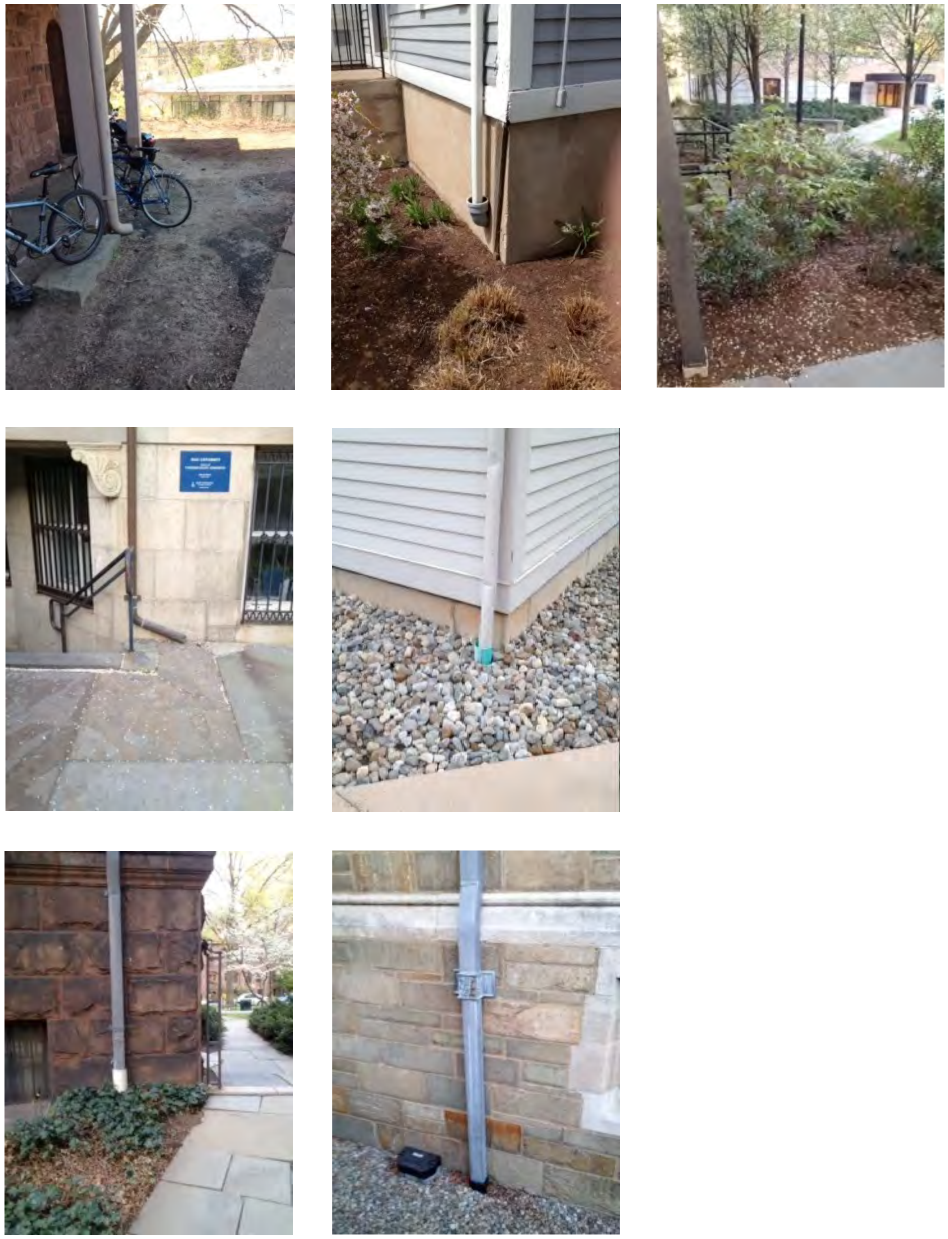
Though the steps to disconnection are relatively simple, the complexity of disconnection projects stems from the need to provide the downspout drainage with a pervious area or retention asset to avoid creating a new issue from directing the additional runoff adjacent to a building. Specifically, for a downspout disconnection project, the following property/structural aspects should be considered (DDOE, n.d.):

Slope The adjacent pervious area should drain away from the building, and the slope should measure less than 10%.

Drainage The adjacent pervious area should be large enough to encourage infiltration.

Extensions Downspouts should be extended to discharge water at least 5 feet from the building.

Figure 2: Examples of Downspout Connections from Yale's Science Hill and Central Campus Areas



Campus photos, May 2013

Property lines The end of the downspout extension must discharge at least 5 feet from a non-Yale-owned property line.

Other hazards

- Do not disconnect within 10 feet of a retaining wall.
- Downspouts should be at least 6 feet away from the nearest impervious area to favor infiltration over drainage to a nearby catch basin.

Downspouts at Yale

Since the founding of Yale University in the early 1700s, the campus has grown and developed to support the expansion of the university. As Yale developed and expanded, buildings were constructed to serve a variety of functions. The campus buildings encompass a wide range of sizes, scales, and architectural styles and are surrounded by an assortment of landscapes. Included in this mix are buildings that are converted residences as well as large-scale institutional buildings. Because of this range and variety, the roof drainage systems found on Yale's buildings are all different, including drainage systems that drain the roofs by internal roof leader systems as well as the more typical system of externally draining gutters. Figure 2 shows some examples of the downspout connections for the externally draining roof systems found on parts of Science Hill and Central Campus.

These differences make it di∞cult to define a disconnection program until more is known about the various connections. It is important to capture these system and connection differences to realistically disconnect the wide variety of downspouts on campus.

Recommended Approach to Program Development

At this point, the number and connection status of downspouts on campus are unknown. Until these data are collected, a comprehensive program for disconnecting the downspouts to effectively redirect or slow the flow of rooftop runoff cannot be determined. To be able to prioritize and effectively invest in the disconnection of downspouts, the following approach to collecting and analyzing data to build a successful program for Yale's campus is recommended:

1. Conduct a survey of the downspouts on campus, including data collection on the areas adjacent to downspouts;
2. Develop a database of survey information using a geographic information system (GIS);
3. Create a program for disconnecting downspouts based on an established prioritization strategy; and
4. Using additional information collected during the survey, identify opportunities for coupling green infrastructure projects with downspout disconnections.

The following sections describe each of these steps. As part of the analysis to create these recommendations, we used Marsh Hall, located at 360 Prospect, as a case study to test the process. An additional property, a Yale-owned and student-occupied residence, 101 Mansfield Street, was used to validate the process.

Conducting a Downspout Disconnection Survey

A survey will document the number, location, connection status, and potential drainage area for the rooftop downspouts on campus to understand the opportunities associated with managing the rooftop runoff on Yale's campus. The following sections detail recommendations for the particular skillset of the student or students to conduct the survey as well as the survey process. This survey process has been developed to document external roof drainage systems. Because it is difficult to visually observe downspout connection status associated with internal roof leaders, part of this survey will require the student to analyze the drainage systems on building plans to understand the opportunities for internally draining systems.

Student Help Description

The survey work will require on-location analysis of the conditions found at each downspout. Because of the need for a more comprehensive understanding of the purpose of disconnected downspouts, it is recommended that the student have familiarity with reading building plans, how stormwater runoff is managed on campus and at the municipal level, and the purpose of downspout disconnection and green infrastructure as tools in this management. The ideal candidate for the survey work would be a graduate student or students with proficiency in ArcGIS. Familiarity with the buildings on campus would also be an asset.

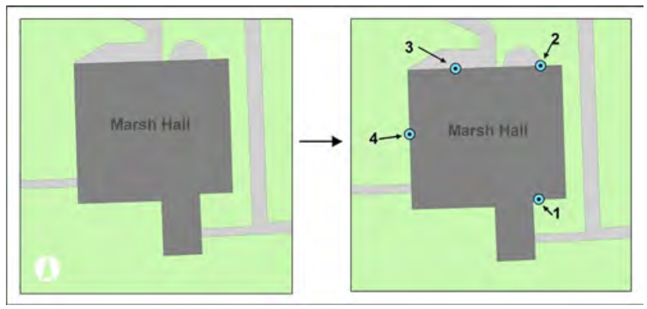
To prepare for the survey work, the student should read the Sustainable Stormwater Management Plan, including all the appendixes, and the reports on Yale's campus from the 2011 Payments for Ecosystem Services class. The student should understand the process for disconnection and the needs associated with developing green infrastructure.

Recommended Preparation, Materials, and Process

To conduct a survey of a building, we created a form based on the conditions necessary for disconnecting a downspout, as explained in the "Considerations" section above. This form is intended to assist in capturing the necessary conditions for disconnecting downspouts during the survey. This form is included as Attachment 1 to this appendix and was completed using Marsh Hall at 360 Prospect Street as an example.

Prior to beginning the survey, the student should print a form for the building and bring a printout of an image showing the building's footprint and the adjacent impervious areas. An example of the printout for Marsh Hall is provided as the image on the left in Figure 3. The student should also bring a measuring tape to measure the adjacent pervious area and an instrument to measure the approximate slope of the pervious area.

Figure 3: An Example of the Recommended Building Footprint Printout and Identified Downspout Locations and Numbering.



During the survey, the student should number each downspout, as shown in the image on the right in Figure 2, and document the information obtained, as shown in Attachment 1. A description of the adjacent pervious areas should be captured on the form and as notes on the printed map of the building footprint. Pictures of each downspout and the potential drainage area should also be taken and logged for later reference. Figure 4 shows examples of the pictures taken at Marsh Hall and some of the observations made about the downspouts and associated drainage areas.

Based on conversations with Yale Facilities and Planning staff, with recent building renovations, it is likely that a renovated building's downspouts have been redirected to an underground basin that overflows into the sewer system. If this is the case, the downspout will appear to still be connected. If possible as part of the preparation work, the student should identify whether a building has been recently renovated, as this may help identify cases where the downspouts have been disconnected, even when they do not appear so.

This process may be simplified by use of a GPS unit with the form input into it. We used this process for the tree survey conducted on campus in fall of 2012. We recommend further investigation to determine whether the same procedure could be used for the downspout survey.

Downspout Database Development in GIS

The greatest benefit of conducting the survey will be development of a summary of the downspout assets on campus that can be used for planning downspout disconnections over the next several years. The data collected on each downspout should be input into a digital format for analysis and use in prioritizing projects. We recommend inputting the data into a GIS shapefile. Attachment 2 of this appendix shows an example shapefile and the associated data fields to input based on the information collected on the form.

Figure 4: Example Pictures and Observations of Marsh Hall Downspouts

Downspout 1
Connected.
Drains to too small of an area or easy rain garden.

Downspout 2
Connected.
Drains to a small pervious area.
Potential for a rain garden of approx. 14 ft. x 8 ft.

Downspout 3
Disconnected.
Drains to a pervious area.
Erosion could be reduced with rocks.
Potential for rain garden.

Downspout 4
Connected.
Drains to a pervious area.
Potential for a rain garden.

Marsh Hall, April 2013

Figure 5: Example of an Alternative for Priority 2 Disconnections

Prioritization Strategy for Disconnection

Probable funding limitations mean that downspouts will probably need to be disconnected over several years. Additionally, the drainage areas adjacent to many downspouts may require adjustments before the downspouts can be disconnected—some downspouts may not be feasible for disconnection. Based on discussions with the Office of Facilities and the considerations outlined above for disconnecting downspouts, we recommend prioritizing downspouts in the following manner, with Priority 1 being the highest priority and Priority 3 being the lowest priority disconnections.

Priority 1: Easy Disconnections

Using the information collected in the GIS database, downspouts can be prioritized as easy disconnections and therefore Priority 1 connections if the adjacent pervious area meets all of the following conditions:

- Large enough to allow for drainage based on predicted runoff volume;
- At least 5 feet from the building's basement;
- Slope of less than 10%;
- At least 6 feet from the nearest sidewalk, driveway, or impervious area;
- At least 5 feet from the adjacent property, if adjacent property is not Yale owned; and
- At least 10 feet from a retaining wall.

Priority 2: Disconnections with Complexities

Downspouts that drain to areas that do not meet one or more of the above requirements should be categorized as Priority 2 disconnections. Many of these issues may be able to be resolved in a simple way, such as through the replacement of adjacent sidewalks with permeable pavement or through a stormwater planter, similar to the example shown in Figure 5, but these solutions will require more planning than the Priority 1 disconnections.

Priority 3: Disconnections That Are Not Recommended at This Time

Downspouts that do not meet the characteristics of Priority 1 downspouts and have conditions that make these downspouts too difficult to recommend disconnection at the time of the survey should be characterized as Priority 3. These downspouts might be addressed through renovation projects, or, with knowledge gained from the Priority 1 and 2 disconnections, the issues associated with these downspouts may later become simpler to address.

Priority R: All Major Renovations or Adjacent to City of New Haven Construction

Based on discussions with Yale Facilities staff, to comply with the Greater New Haven Water Pollution Control Authority's stormwater regulations during the renovation process, a building's downspouts are disconnected and redirected to an underground storage tank that overflows to the sewer system. For these systems, it is believed that over time, these underground storage tanks fill with sediment and lose their function as stormwater storage. When a building is scheduled for renovations, the building's downspouts should be re-prioritized to "R" to indicate that these downspouts should be disconnected. Prior to the renovation process, additional options that are less maintenance-intensive than an underground storage tank but have the same performance ability should be investigated. Specifically, the construction of other green infrastructure options with aboveground maintenance like rain gardens may be more feasible during the renovation process and should be investigated.

Priority PR: Buildings Previously Renovated

Buildings renovated in recent years have likely had their downspouts disconnected from the sewer system and instead are connected to an underground storage tank that overflows to the sewer system. To re-investigate the effectiveness of the underground storage systems, the downspouts on these buildings should be indicated as "PR." Because there has not yet been an established maintenance program, these downspouts should be identified either to help create the needed maintenance plan to clean these basins out or to consider options for alternative, less maintenance-intense drainage designs to replace the underground storage.

Managing the Roof Runoff with Green Infrastructure: Example Project

Green infrastructure offers the ability to manage downspout drainage by more actively encouraging infiltration. The design for green infrastructure, however, is highly dependent on soil characteristics and drainage area. Following the survey, larger adjacent pervious areas should be further investigated for potential green infrastructure investigation. Based on the information collected during the survey, additional analysis is needed to determine whether an area should be recommended for a green infrastructure project.

Marsh Hall was used to investigate the potential for green infrastructure accompanying its downspout disconnections. For the purposes of this analysis, only rain gardens were explored for their potential use on campus. Other green infrastructure approaches could be investigated and used, such as bioswales, subsurface infiltration, or enhanced tree pits. We used the following method to determine the potential size of rain garden required for Marsh Hall's rooftop drainage. It is based on a method to size a rain garden from the University of Connecticut's rain garden design guide.

Calculate drainage area. Drainage Area = % of roof draining to rain garden

Determine rain garden depth. The slope of the adjacent pervious area should be measured approximately, and this information should be collected in the survey. The measured slope of the Marsh Hall pervious area was estimated at 5%. Based on the rain garden design guide, the rain garden requires a depth of 6–7 inches.

Determine soil factor. To properly design a rain garden, the adjacent pervious area's soil type and percolation rate should be determined. A soil assessment was not conducted for this effort. The backyard is assumed to be a silty soil. Using a depth of 6–7 inches and a silty soil characterization, the soil factor is 0.25.

Calculate rain garden size. Required Area for Rain Garden = Drainage Area × Soil Factor.

With a rain garden size calculated, it is possible to determine if the adjacent pervious area that was documented in the survey is large enough to handle the drainage from that downspout. The calculation was completed for two scenarios at Marsh Hall. The first scenario is for a rain garden sized to intercept the drainage from one downspout, and the second scenario is for a rain garden or multiple rain gardens to intercept the drainage from one downspout as well as the parking lot at Marsh Hall.

Scenario 1 Size of a rain garden required for drainage from one downspout
Drainage Area (3090 sq. ft.)/4 = 772 sq. ft.

Rain Garden Area 772 sq. ft. × 0.25 = 193 sq. ft.

Result: This drainage area produces a need for 1 rain garden of approximately 12 feet by 16 feet, which would cost $600–$800.

Scenario 2 Size of a rain garden required for drainage from one downspout and the parking lot

- Drainage Area (3090 sq. ft.)/4 + 3090 sq. ft. = 3862 sq. ft.
- Rain Garden Area 3862 sq. ft. × 0.25 = 966 sq. ft.
- Result: This drainage area produces a need for 2 rain gardens of approximately 20 feet by 24 feet, which would cost $2,900–$3,900.

Additional Assumptions for Rain Garden Calculation:

¼ of Marsh Hall's roof drains to each downspout

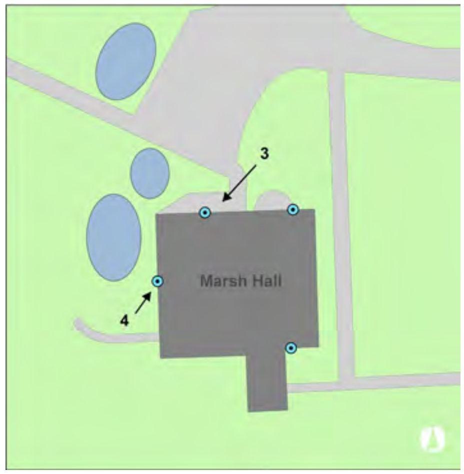
The parking lot at Marsh Hall is assumed to be approximately the same area as Marsh Hall's building footprint. Marsh Hall's building footprint is 3090 sq. ft.

A cost of $3–$4 per sq. ft. of residential rain garden was used to estimate the price.

Based on the above calculations, either scenario is possible for implementation behind Marsh Hall. Our suggested placement of the rain gardens is shown in Figure 6.

This calculation shows how variable the size of the rain garden will be based on differences in drainage area. Additionally, different soils and slopes will result in varied soil factors and therefore different rain garden sizes.

Figure 6: Potential Rain Garden Locations at Marsh Hall



Conclusion

With the more than five million square feet of impervious area created by rooftops across campus, Yale is in the unique position to begin to slow the flow or reduce the total volume of runoff from roofs through a disconnection program. The recommendations in this report are intended to help Yale move closer toward successfully disconnecting the downspouts through a comprehensive program. If executed fully, this program may serve as an example for other universities and municipalities, including New Haven, to successfully implement a similar program.

References

Dietz, Michael. n.d. "Rain gardens: A design guide for homeowners in Connecticut." University of Connecticut Cooperative Extension System, College of Agriculture and Natural Resources. http://www.sustainability.uconn.edu/pdf/raingardenbroch.pdf.

District Department of the Environment (DDOE). n.d. Downspout disconnect. River Smart Homes. http://greenup.dc.gov/Library/Downspout%20Disconnection.pdf.

Attachments

Attachment 1: Example Form for Marsh Hall

building name	Marsh Hall
building address	360 Prospect
building type	Academic
managed by	Marsh Botanic Gardens
building area	3090 sq. ft.
renovations?	

Instructions On a printout of the building's footprint, indicate and number downspouts on the building, indicate pervious areas adjacent to downspouts, and indicate roofline, if possible.

Downspout 1

location?	South middle
disconnected?	No
properly?	–
splash guard or rocks?	–
adjacent to pervious area?	Yes
if yes, approximate size?	4 ft x 6 ft
if yes, approximate slope?	Flat
if yes, greater than 5 ft from building?	No
if yes, is less than 6 ft from sidewalk, driveway, or other impervious area?	No
describe pervious area:	Landscaped
recommend disconnection?	Not yet
additional comments:	–

Downspout 2

location?	NE corner
disconnected?	No
properly?	–
splash guard or rocks?	–
adjacent to pervious area?	Yes
if yes, approximate size?	14 ft x 8 ft
if yes, approximate slope?	Flat
if yes, greater than 5 ft from building?	Yes
if yes, is less than 6 ft from sidewalk, driveway, or other impervious area?	Yes
describe pervious area:	Small pervious area adjacent to steep slope
recommend disconnection?	Yes
additional comments:	–

Downspout 3

location?	North middle
disconnected?	Yes
properly?	Yes
splash guard or rocks?	No
adjacent to pervious area?	Yes
if yes, approximate size?	18 ft x 30 ft
if yes, approximate slope?	4%
if yes, greater than 5 ft from building?	Yes
if yes, is less than 6 ft from sidewalk, driveway, or other impervious area?	Yes, in one direction
describe pervious area:	Currently dirt, partly used as a storage area for a boat.
recommend disconnection?	NA
additional comments:	Pervious area likely receives drainage from adjacent parking lot

Downspout 4

location?	West middle
disconnected?	No
properly?	–
splash guard or rocks?	–
adjacent to pervious area?	Yes
if yes, approximate size?	15 ft x 20 ft
if yes, approximate slope?	4%
if yes, greater than 5 ft from building?	Yes
if yes, is less than 6 ft from sidewalk, driveway, or other impervious area?	Yes
describe pervious area:	
recommend disconnection?	Yes
additional comments:	Two impervious slabs of concrete/asphalt in the vicinity of pervious area

Attachment 2: Downspout GIS and Database Directions

Using Marsh Hall as an example, a GIS shapefile was created as an example of the input process and database development for the downspout disconnection survey. With the completion of a survey of a building's downspouts, the downspout location and information should be input into GIS. Where the downspouts are represented, create points to represent the downspouts on the building. With the locations logged, input the information associated with each downspout into the point file. Along with the creation of this shapefile, the associated fields to input information were also created for the example. The fields are shown below, with definitions and instructions for each field are shown below.

Definitions

Down_Num *(Downspout Number)* Input downspout number.

Build_Nam *(Building Name)* Input building name.

Build_Addr *(Building Address)* Input building address.

Build_Typ *(Building Type)* Input building type — Academic, Residential, etc.

Managed *(Entity that Manages Property and Building)* Input name of entity that manages property — Yale Grounds, Marsh Botanic Gardens, etc.

Build_Area *(Building Area)* Input the building's area in square feet.

Reno_Year *(Renovation Year)* Input the year that the building had or will have renovations.

Connected *(Downspout Connected)* Input whether the downspout has been disconnected or not — Yes or No

Con_Proper *(Downspout Disconnected Properly)* If the downspout was disconnected, input if the downspout has been disconnected properly, i.e. should additional work be done? Yes, No, or NA

Con_Protec *(Downspout Disconnected with Erosion Protection)* If the downspout was disconnected, is there erosion protection, i.e. spashblock or rocks? Yes, No, or NA

AdjPervAr *(Adjacent Pervious Area)* Is there pervious area directly adjacent to the downspout? Yes or No.

Perv_Area *(Area of the Adjacent Pervious Area)* If there is adjacent pervious area, input the area of the adjacent pervious area.

Perv_Slope *(Slope of the Adjacent Pervious)* If there is adjacent pervious area, input the slope of the adjacent pervious area.

6ft_build *(Adjacent Pervious Area Is 6 ft. from the Building)* If there is adjacent pervious area, is it 6 ft. from the Building? Yes, No, or NA

6ft_ImpA *(Adjacent Pervious Area Is 6 ft. from Impervious Areas)* If there is adjacent pervious area, is it 6 ft. from the impervious areas? Yes, No, or NA

Perv_Desc *(Adjacent Pervious Area's Description)* Input description of adjacent pervious area.

Disc_Rec *(Recommend Disconnection?)* Is disconnection recommended? Yes, No, or NA

GI_Rec *(Recommend Green Infrastructure?)* Is green infrastructure recommended?

Priority *(Priority Number)* What is the priority number of the disconnection? (Based on Appendix descriptions.)

Comments Input additional comments.

Appendix G

Developing a Green Infrastructure Monitoring Program

Contents

Introduction

The design philosophy of green infrastructure (GI) is based on the implementation of distributed small-scale stormwater control practices throughout a site or drainage basin. Because of their non-centralized distribution and the range of practices that can be installed at one site, monitoring their performance is a unique challenge. In many cases, it is not realistic to monitor the performance of each individual practice, as it can turn out to be relatively expensive. Monitoring approaches must be carefully considered to obtain meaningful data.

Unlike conventional stormwater management practices, some green infrastructure practices (e.g., rain gardens, bioswales, pervious pavement) are designed to store water through infiltration or do not have a localized influent, requiring a different approach for performance monitoring. Additionally, monitoring might require additional infrastructure (e.g., weirs or flumes to measure flow) that should be considered during site design. Monitoring should be considered during the planning and design process to ensure a well-structured and successful integrated monitoring approach.

An Integrated Monitoring Approach

An integrated approach incorporates performance monitoring into the process of developing stormwater management practices or retrofits rather than considering it as an isolated activity to be completed after project design and construction. Integration of monitoring includes strategic placement of monitoring stations, design that incorporates mo nitoring structures and equipment, and continued monitoring and maintenance once the practice has been installed. Figure 1 illustrates the recommended approach for green infrastructure monitoring. This approach is applicable to green infrastructure in new developments as well as to stormwater retrofits.

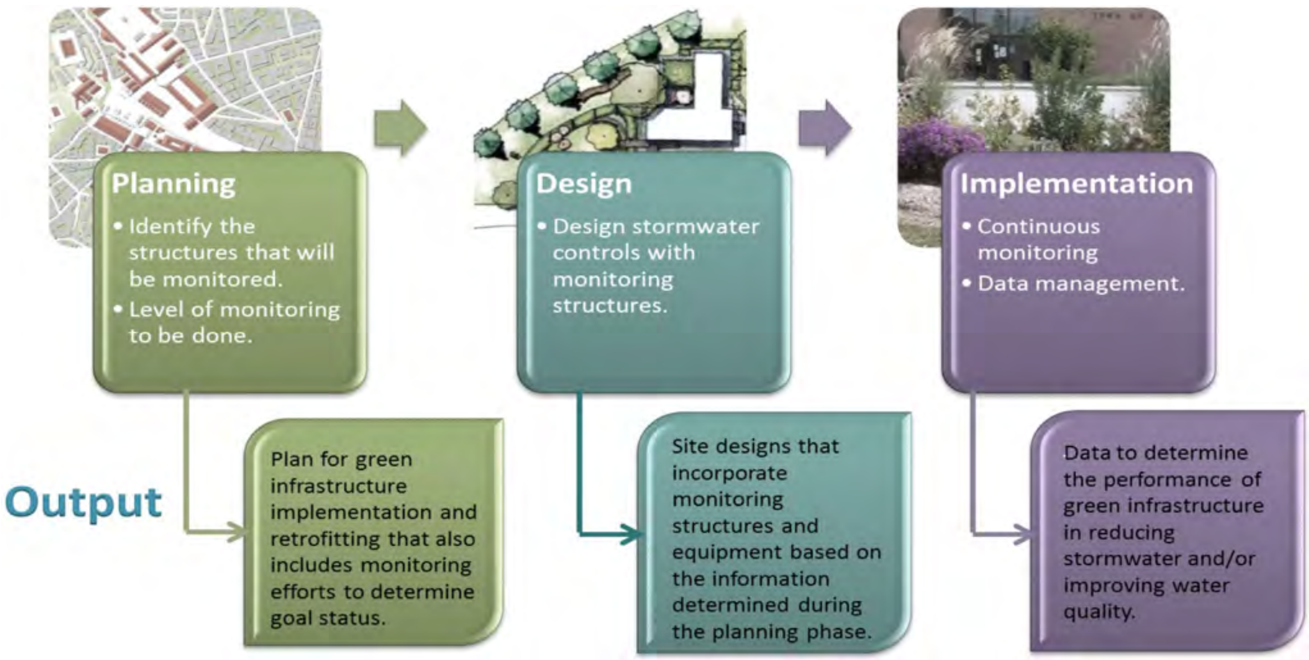
Planning

The monitoring of each green infrastructure practice is not a feasible and realistic activity due to its cost and resources needed for it to take place. For this reason, during the planning stage for green infrastructure implementation, the structures that will be monitored should be identified using a strategic approach. Aspects to be considered when selecting the sites to be monitored are:

- Location within the watershed
- Type of GI practice
- Monitoring objectives and priorities
- Goals of the Sustainable Stormwater Management Plan

During this stage, the type of monitoring that will be done (see Monitoring Methods) should also be determined for each structure.

Figure 1: Recommended Approach for Green Infrastructure Monitoring



Output Plan for green infrastructure implementation and retrofitting that also includes monitoring to determine performance and goal status and achievement.

Site Design

The information obtained during the previous stage can be used to determine site design specifications required by the type of monitoring that will be conducted at each site. For example, certain monitoring activities will require the installation of weirs, flumes, and other devices to measure flow as well as structures to house and secure the equipment. Considering and incorporating these features during the design stage of the GI practice is critical, as it will reduce the risk of:

- Being unable to monitor the site, as some physical features may not allow proper data collection or equipment installation.
- Increasing the cost of installation if site needs to be modified to facilitate monitoring.

Output GI site designs that incorporate monitoring structures and equipment based on the information determined during the planning phase.

Implementation

During the installation of the green infrastructure projects to be monitored, most of the monitoring structures and equipment should also be placed. Once the sites become active, continuous and rigorous monitoring can take place. In most cases, personnel training is necessary to ensure proper collection of data and management of samples.

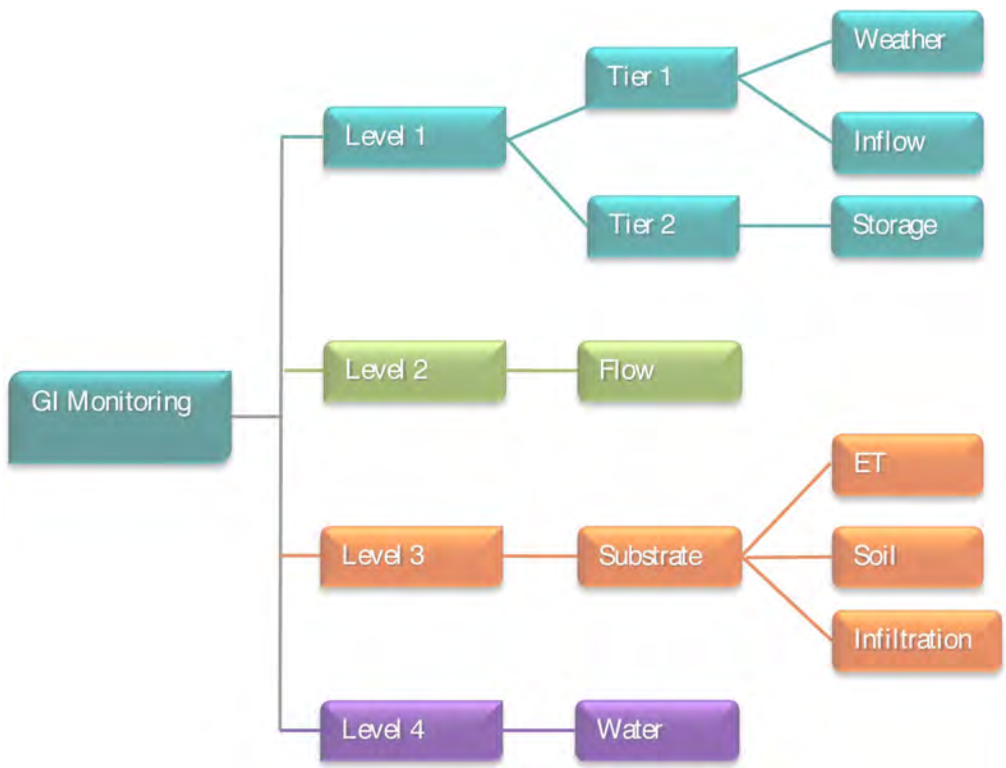
Output Data to determine the performance of green infrastructure in reducing stormwater and/or improving water quality. The level of detail of the collected data will depend on the type of monitoring implemented.

To make this approach successful, a shift in thinking is necessary since monitoring needs to be considered at all stages of the process and resources need to be allocated for this activity. However, due to the potential of stricter stormwater retention requirements in New Haven, a shift toward the direction of an integrated approach that allows monitoring performance will become increasingly valuable.

Determining Monitoring Objectives

One common reason to conduct monitoring in a managed system is to evaluate the success of the management actions employed to achieve a goal. However, in order to design a monitoring program that can effectively provide information on goal performance, its objectives need to be clearly defined. These objectives, which will correspond with the goals of the Sustainable Stormwater Management Plan, will serve as a guide to determine the information to be collected when monitoring takes place. Some example objectives for a stormwater monitoring program are:

Figure 2: Levels for Green Infrastructure Monitoring



- Evaluate the effectiveness of green infrastructure to reduce stormwater quantity and improve quality.
- Compare performance between practices to determine which are most effective.
- Determine the impact of design variables in performance.

Monitoring Plan Development Considerations

In order to appropriately address the monitoring objectives, it is necessary to identify the information inputs necessary. Once the information inputs are known, a number of aspects that will impact monitoring efforts should be considered. This assessment should:

- Identify data already being collected in the area (e.g., weather stations) or other studies that have been done on campus to measure stormwater. This can reduce the amount of new information that needs to be collected as well as the cost associated with obtaining new equipment. One example is the availability of nearby weather stations in Hamden, Kline Geology Laboratory, and Tweed–New Haven Airport that can provide precipitation and additional weather data for evapotranspiration calculations.
- Determine the number of storms to be monitored in order to obtain a valid statistic data assessment, which can be done through a power analysis (Geosyntec Consultants and Wright Water Engineers 2009, ch. 2; Hill and Lewicki 2005).
- Determine the characteristics of the storms that need to be monitored (depth, intensity, duration). Identifying the precipitation patterns in the region before implementing a monitoring program is a useful effort to determine the characteristics of commonly occurring storms. These are the types of storms that a monitoring program should focus on because they will be the ones treated by the green management practice on a regular basis. Monitoring large, uncommon storms is also valuable, because they can provide information on the limitations of the structures.

Monitoring Methods

To address a range of monitoring objectives, a variety of complexity levels and approaches can be developed in response to available funding, personnel, and data requirements. In general, two major approaches to stormwater monitoring are usually considered: individual GI site monitoring and catchment-scale monitoring. Although they differ in their complexity and data collection approach, some principles and information requirements are similar. Figure 2 illustrates monitoring approaches according to these different levels of complexity. The subsequent text describes their application to individual and site-level monitoring.

Level 1, Tier 1: Meteorological Data and Inflow Estimation

Meteorological Data Collection No stormwater monitoring program can exist without the collection of precipitation data. This information is essential to characterize storm characteristics like duration, intensity, and depth. It can also be useful to determine the starting and ending time of a storm and when to start sampling, as rain gauges are sometimes used to trigger sample collection. Collecting detailed precipitation data is relatively inexpensive, and Yale's Office of Facilities can take advantage of previously installed weather stations or rain gauges in the area. Although it is sometimes recommended to place a rain gauge at each site, due to the scale of the Yale campus, precipitation might not vary significantly spatially and rain gauges can be placed strategically. In the case that new precipitation gauges are needed, a range of precipitation gauge types should be considered (see Geosyntec Consultants 2009, pp. 2–7; HydroViz, n.d.):

- Standard rain gauge
- Tipping bucket
- Weighing gauge
- Optical rain gauge

Other Meteorological Data Meteorological data such as temperature, wind speed, humidity, and pressure might be needed in some cases where water balance or evapotranspiration calculations are needed. Because regional variations in these parameters are small within the study area, data from the weather station at Tweed–New Haven Airport or at weather stations installed at Yale University can be used.

Inflow Estimation Measurement of the amount of stormwater being transported into the system is necessary to determine the performance of a stormwater control. This provides the information needed to determine the quantity of water being treated by these practices.

When the site characteristics or budget constraints do not allow collection of inflow measurements, inflow can be estimated. However, the level of detail of this estimate will vary depending on the method used, which can range from a simple equation to complex hydraulic models (see Ahiablame, Engel, and Chaubey 2012; Boone County, Missouri; Elliot and Trowsdale 2005; Geosyntec Consultants 2009, p. 35). Inflow estimation is considered to be the minimum level of monitoring, since, depending on the method used, it might not require extensive data inputs and field measurements.

Estimating flow can prove to be more useful at the catchment-level monitoring approach, where models to estimate stormwater flow can be used. Nevertheless, at the site level, this can also be done if there is only one structure receiving the water of the drainage area. Note that inflow estimation does not directly provide information about the performance of the stormwater controls unless it is compared with baseline information collected before implementation or analyzed with additional data such as outflow or water storage or infiltration. Additionally, depending on the method used, varying degrees of error can be associated with the estimation. It is recommended that, whenever possible, direct flow measurements are made in selected stormwater controls to compare and validate the accuracy of estimated values. If accurate water flow data are needed, Level 2 monitoring should be conducted.

Tier 2: Storage Volume

Storage volume and water-level data provide information about the response of the system to rain events and their contribution to peak flow attenuation. In individual infiltration practices, such as tree trenches, rain gardens, and bioswales, water storage can be measured using water-level sensors in observation wells. Pressure transducers are often used to record water levels continuously. In some cases, water-level data from the monitoring well can be su∞cient to analyze the response of the stormwater control to rain events. However, if volume measurement is necessary, a simple equation can be used:

Storage volume = water level × infiltration area × soil porosity

Soil porosity is relatively easy to measure by gravimetric techniques and should be determined in representative samples of soil from the stormwater control. In case that soil is not saturated, or if the soil is rarely saturated, soil moisture should be determined (see Level 3). For practices that store water above the soil surface, a water-level sensor can also be placed and storage estimated by multiplying by its area.

Level 2

Flow Measurements In order to accurately quantify the performance of green infrastructure in reducing stormwater runoff, flow data at each practice or site are essential. Flow is typically measured using a rating curve, a quantitative relationship between water depth and discharge. This requires the installation of a device that can measure water depth and a weir or flume with a known geometry and a previously determined stage-discharge relationship. In general, these are low maintenance and can be used to measure a broad range of flows. However, the range of flows that can be measured depends on the type of weir or flume installed.

Weirs and Flumes There are different types of weirs that vary in shape. Some of the most common are the v-notch weir, the rectangular weir, and the Cipolletti weir (trapezoidal). Each of these has a specific equation to determine discharge based on water level. Compared with flumes, weirs are easy to install, accurate, and have a low cost. Some disadvantages of weirs are that they can cause backwater and hold sediment and debris that need to be removed frequently, increasing maintenance costs.

A flume is a prefabricated channel with a known stage-discharge relationship. Some common type of flumes are Parshall, H, and HL flumes. Compared with weirs, a flume can be more expensive and more di∞cult to install. However, backwater and sediment issues are usually not encountered, as they are with weirs.

Water Depth To measure water depth, instruments are available that vary in their accuracy, cost, and requirements. For example, some require the installation of additional structure such as stilling wells or can be inaccurate at certain flow ranges. In general, for stormwater monitoring, bubbler tubes, pressure transducers, and ultrasonic sensors are the most common (see Geosyntec Consultants 2009, pp. 7–38).

Flow can be measured with methods other than the recommended stage-based method discussed above (Maheepala, Takyi, and Perera 2001). Velocity-based measurements use ultrasonic or acoustic sensors to determine velocity, which can be related to the area of the channel using simultaneous depth measurements. Other methods include tracer dilution, which is not suitable for infiltration practices, and the use of empirical flow equations. When selecting the method for flow measurement, it is important to consider advantages, limitations, and site suitability.

To determine the performance of GI in reducing stormwater runoff, there needs to be a baseline measurement of flow. In individual practices, inflow is considered to be a baseline. However, when it cannot be measured, inflow estimates can be used. When monitoring at the watershed level, baseline data are more di∞cult to obtain. One way to obtain stormwater runoff baseline data is to monitor for some time before implementing green infrastructure. However, this is usually costly and time consuming. The second approach is to find a catchment with similar characteristics that can be used as a control to compare with another with installed green infrastructure (reference catchment). Although this approach is the most common, it is not realistic to find two watersheds that are exactly the same, which introduces uncertainty that should be considered when reaching conclusions about the performance of the installations.

Level 3: Substrate and Processes

Infiltration Infiltration is part of the design of many green infrastructure projects, as it contributes to water quality improvements and the reduction of runoff volume. This process is the downward movement of water through the soil substrate and is measured as a rate of unit depth per time. Monitoring infiltration rates is useful for quantifying runoff reduction and for hydraulic and hydrologic modeling. Infiltration can be estimated or measured in various ways (Geosyntec Consultants 2009, 844:8-49), including:

- Field measurement of infiltration: Vertical filtration of water at the ground surface can be measured on site using ring infiltrometers. Water is added to the instrument, and the infiltration rate can be calculated by measuring the rate at which the water level falls. A disadvantage of this method is that ring infiltrometers might overestimate infiltration rates. Nevertheless, they still produce useful data that can be used for hydraulic and hydrological modeling.
- Soil moisture: Tensiometers or soil moisture sensors can be installed at different depths within a soil profile to measure moisture content in the soil. For the purposes of stormwater monitoring, these should collect data continuously in order to

determine changes in soil water content through time as the wetting front progresses downward. Because tensiometers measure matrix potential as a pressure instead of moisture content directly, converting the raw data to soil moisture might require additional work. A soil moisture characteristic curve, which relates matrix potential to soil moisture, must be experimentally created for each site in order to accurately determine soil moisture content. A benefit of monitoring soil moisture is that it allows an estimation of infiltration rates and a quantitative measure of water storage for unsaturated soils.

Evapotranspiration

In green infrastructure, evapotranspiration (ET) is a pathway in which stormwater can leave the system. The quantification of evapotranspiration for these structures is challenging, but several methods that provide different levels of confidence can be used to estimate this value (Geosyntec Consultants 2009, 8-44:8-49). Measuring ET in individual stormwater controls is simpler than in an urban watershed with multiple controls. However, this parameter is more useful for watershed scale monitoring, as it provides information for the water balance calculation. Because most of the equations used to measure ET were developed for crops growing in fields, it necessary to translate reference ET values to ET rates of the landscaping applicable to these practices. Some methods to measure ET are shown below.

- Weighing lysimeters measure the actual amount of evapotranspiration released by plants. They are vegetated enclosures of a representative sample of soil through which the flow of water can be determined by mass. ET is calculated by completing the water balance within the boundaries of the lysimeter. This method is the most appropriate for monitoring individual practices.
- The Penman-Montieth equation is used to determine ET rates of vegetated surfaces (Howell and Evett, n.d.; Montieth 1965). It requires extensive data inputs such as net radiation flux of ground, humidity, saturated vapor pressure of air, specific heat of air, among others. This method is commonly used and recommended when the accuracy of ET measurements is not essential.

Level 4: Water Quality

Water quality monitoring is a complex and detailed activity that requires substantial planning. This includes determining the parameters to be measured, sample collection and analytical methods, quality control, and other activities. This section provides an overview of water quality monitoring for green infrastructure practices and specific recommendations for Yale University. Consult Davis (2007) and Geosyntec Consultants (2009) for more detailed information.

Water Quality Parameters Stormwater contains a variety of pollutants that can unfavorably affect the health of the receiving waters. Because stormwater characteristics vary by land use and location, selection of the parameters to be analyzed in a monitoring program should take into consideration the following aspects:

- Characteristics of the watershed: Since Yale University is located in an urban area, pollutants associated to this type of land use should be considered. Common pollutants in urban areas are sediments, nutrients, some heavy metals, and oil and grease.
- Expected removal from stormwater controls: Given the design and characteristics of the structures and based on available literature on performance, it is possible to have a general idea of the potential pollutants that could be removed by the practice.
- Inexpensive basic water quality characterization parameters such as temperature, conductivity, and pH, among others, should be included.
- Availability of funds for chemical analysis.

Sample Collection Methods The development of a water quality monitoring plan involves the selection of sampling methods or techniques. The methods selected will vary depending on the objectives and structure of the stormwater monitoring plan and on the resources available for this activity (e.g., funds, time, and personnel).

Grab vs. Composite Samples Grab samples are individual samples collected at a specific time or over a short period of time. They provide information about the stormwater quality at the point in time when the sample was collected. For stormwater monitoring, single grab samples are not reliable estimates of stormwater quality, because concentrations of pollutants tend to vary significantly with time. However, grab samples collected throughout the duration of a storm are useful to characterize patterns of pollutant concentration and to calculate an estimate of the event mean concentration (EMC). Analyzing each grab sample for every storm monitored can add significant costs to the monitoring program. For this reason, composite samples are recommended unless detailed information is needed to understand pollutant concentrations over the course of storms.

A composite sample is the combination of aliquots from multiple samples of one storm to create a representative single sample. When analyzed, a composite sample can provide an estimate of the EMC and pollutant load for a single storm event. There are two approaches to creating a composite sample: time-proportional, which consists of aliquots collected at equal increments of time, and flow-proportional, which accounts for variation in flow during the course of a storm. Because stormwater flow is not constant, time-proportional samples do not provide a reliable estimate of pollutant loads. For this reason, flow-proportional methods are recommended for stormwater monitoring (Geosyntec Consultants 2009, ch. 4).

Manual vs. Automated Sampling Manual sampling involves sampling by personnel on site using a bottle. For a monitoring program that will monitor water quality for only a few storms, this approach might be preferable because it does not require a high capital investment. However, this approach is less practical for programs that involve a large number of sites or sampling events. Additionally, it requires personnel to be working outside of normal work hours, which is not always possible (Geosyntec Consultants 2009, ch. 4).

An alternative to collecting manual samples during storm events is to use automated sampling. This involves the collection of samples using a device that does not require personnel to be on-site during sample collection. Automated sampling is more accurate than manual sampling, as sample collection can be triggered with a sensor or when a specific flow rate is detected. Additionally, it removes the uncertainty of relying on the weather forecast to send personnel to collect the samples, which can also result in often missing first flush samples or waiting for too long until runoff is produced by the rain event (Geosyntec Consultants 2009, ch. 4). This is the method recommended for composite sample collection and for programs where long-term monitoring is expected. If more than a few storms are going to be assessed, automated sampling is suggested because, in the long run, it will be less costly than manual sampling.

Quality Assurance/Quality Control To ensure meaningful water quality data, it is essential to use proper sampling and analysis methods that maintain the integrity of the sample collected:

- During sample collection: The correct container specific for the parameter to be analyzed must be used. Recommended preservatives for the analyte should be added to the sample.
- Because contamination can be introduced into a sample at different times when the sample is being handled, determination of the level of contamination can be done using blanks. Blanks are used at different stages (e.g., in the field, during sample analysis, and before traveling to the field).
- Duplicate samples, collected at the same location, at the same time should be collected to determine laboratory analysis precision.
- The maximum holding time for a sample, which varies between analytes, should also be taken into consideration.

Performance Assessment It is common to see performance of stormwater controls expressed as a percent removal of a particular pollutant. However, percent removal has been known to vary with influent concentrations and may not provide a useful assessment of performance. The EPA recommended method to assess stormwater control performance, presented by Geosyntec Consultants and Wright Water Engineers (2009, ch. 7), is the e±uent probability method. This method consists of determining if there is a significant difference between inflow and outflow concentration and creating probability plots with the event mean concentration data for each pollutant.

Site-Level Monitoring

Although monitoring individual practices is useful to determine their performance and compare their effectiveness, monitoring at the watershed level provides information about the collective effects of the installed practices. This type of monitoring should be considered for use on the Yale campus, as it is more useful to determine the overall effect of green infrastructure.

This approach presents more challenges than individual practice monitoring and requires a higher level of understanding of the characteristics of the catchment as well as a significant amount of planning. For example, the watershed studied must be characterized and delineated previous to conducting monitoring. Additionally, it requires the collection of baseline data before GI implementation or a comparison with a similar watershed in the area, requiring detailed spatial analysis and an extensive knowledge of the physical characteristics of the study area. Furthermore, a water balance needs to be calculated and flow measurements must be collected at a single outflow.

An advantage of this monitoring approach is that, in some instances, monitoring an individual practice is not possible because certain locations might have many downspout planters or rain gardens that cannot be monitored individually. Although the understanding of this monitoring approach is currently in its early stages, as green infrastructure continues to be implemented, its usefulness will become more evident and a shift will be necessary to capture the benefits of GI implementation for stormwater management.

Conclusion

Monitoring performance is essential for determining the contribution of green infrastructure to achieving stormwater management goals and will become increasingly valuable as municipalities turn to the decentralized approach to stormwater management. In order to obtain meaningful data for goal assessment, effective monitoring requires careful and extensive planning and a shift to investing resources for this activity. Additionally, monitoring should be developed in alignment with the strategies and future specific goals of the Sustainable Stormwater Management Plan in order to select the correct approach that will produce the information needed to determine performance. Because the performance of green infrastructure is not entirely understood, Yale University, as an educational institution, has the opportunity to provide information to the scientific community and facilities managers to close gaps regarding the effectiveness and limitations of these stormwater mitigation practices.

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Appendix H

Recommendations for Including Green Infrastructure in Yale's Landscaping and Planning Approach

Contents

Introduction

When implemented, green infrastructure has the potential to significantly reduce stormwater while offering additional environmental and social benefits. Despite all the potential benefits of green infrastructure, though, one of the main challenges to implementing a successful program is developing a maintenance protocol. Maintenance of these systems is not just a capital investment; it is also a critical step in developing and adapting green infrastructure design standards. Similar to gray infrastructure, if green infrastructure is not maintained, it will fail. The maintenance of these sites is a purposeful management practice to preserve the functionality and extend the lifetime of the green infrastructure (Detwiler, n.d.).

When green infrastructure sites are established, they become an asset, and therefore it is critical to ensure that the landscapes remain high performing in order to get the maximum return on investment. Maintenance is integral to guarantee this high level of performance. Consistent maintenance not only ensures that the landscape is operating as designed, it also improves public perception. For example, a no-mow zone may look like an un-kept and forgotten parcel of land, but when an intentional mow zone is maintained at the edge, the public understanding that these practices were intentional is increased.[1] This appendix will outline the maintenance manual development process in other cities, describe how other campuses are embracing the living laboratory concept for sustainable stormwater management practices, and provide recommendations for the development of Yale's green infrastructure maintenance plan.

Maintenance Plan Development

Developing a maintenance plan is a complex process that needs to reflect the types of green infrastructure installed, budgetary limitations, landscape dynamics, and other operational details. The plan should be developed for use by a variety of individuals, including university staff, students, and any parties responsible for performing maintenance activities, such as contractors. A successful first edition of the maintenance plan will outline the tasks related to different types of green infrastructure and suggested maintenance protocols based on an inventory of maintenance practices and procedures from around the country. Currently, two large cities in the eastern United States are developing maintenance manuals for their green infrastructure programs. Yale can use these two cities as a model for how and what the maintenance manual development process entails.

New York City

New York City's Green Infrastructure Plan, a component of Mayor Bloomberg's PlaNYC, was developed to "meet the twin goals of better water quality in New York Harbor and a livable and sustainable New York City" (PlaNYC 2010). In 2011, the New York City Department of Parks and Recreation (NYC Parks) and the New

York City Department of Environmental Protection (DEP) signed an agreement establishing the roles and responsibilities concerning green infrastructure in the right-of-way. This agreement stipulated that DEP would fund the NYC Parks crews who will maintain the Greenstreets and bioswales. According to New York City's expense summary, the NYC Parks Green Infrastructure Maintenance Program will cost $462,385 for fiscal year 2013 (NYC Environmental Protection 2012). The crews will be specialized green infrastructure maintenance crews, with at least one member having expertise in horticulture and vegetation management.[2]

In addition, the Green Infrastructure Plan calls for the development of a maintenance manual, and NYC Parks is currently operating under an interim version. The final version of the manual is in draft form and expected to be online by the end of 2013.[3] NYC Parks formulated their plan by adapting what other municipalities have implemented and information from their field crews, who currently maintain nearly 50 green infrastructure sites. Their manual will explicitly state what the maintenance tasks are and how often they will be performed, in addition to other relevant logistics, such as safety considerations and standard operating procedures.

Finally, an important aspect of New York City's maintenance plan is the constant revisions based on feedback from their field operations. By continually monitoring their initial infrastructure sites, New York City has already adapted their design standards to reflect field reports and monitoring data. A salient example of this is the Greenstreet curb bump out. Three years ago a first-generation curb bump out was installed, which allowed water to flow directly into the planting area, but the maintenance crews continually encountered a problem with sediment accumulation. In order to mitigate the sediment, a pre-treatment bio-filter was installed. The small ponding area allowed the sediment to settle out before entering the planting bed.[4] Now, these pre-treatment areas are incorporated into the design standards. Furthermore, New York City plans to scale up their green infrastructure program rapidly. Currently they have 50 bioswales in the ground, and they plan on having more than 6,000 by 2015. This underscores the importance of a flexible approach to green infrastructure design that is continually informed by field maintenance operations.

Important maintenance considerations to take away from New York City:

- Design with maintenance in mind.
- Remember that the biggest maintenance problems are floatables (litter) and sediment accumulation.
- Use specialized green infrastructure maintenance crews.
- Log all maintenance activities in the field (New York City uses handheld devices).
- Continually monitor and input field data to inform the design standards.

Philadelphia Similar to New York City, Philadelphia is currently involved in the green infrastructure maintenance manual development process. Philadelphia Water Department (PWD) is operating under an interim maintenance manual, and the first edition is expected by June 2014, as required by the consent order and agreement (COA) with the Environmental Protection Agency. As described by the COA, "The manual will address the operation and maintenance of the full range of types of green stormwater infrastructure projects that have been, and that are proposed to be, implemented by the City as part of the CSO Program" (PWD 2012).

The key objectives of PWD's maintenance program are to:

- Ensure su∞cient maintenance of green stormwater infrastructure to keep assets performing as designed,
- Develop and standardize long-term, cost-effective maintenance protocols,
- Assess existing organizational capacity of the PWD and partnering organizations for supporting maintenance, and
- Provide feedback to improve future designs to the green stormwater infrastructure design group based on maintenance, inspection, and monitoring experiences (PWD 2012).

The PWD is currently developing standard maintenance processes for 14 green infrastructure types. The PWD is actively maintaining more than 20 sites and working to adapt the processes to a more standardized procedure. Unlike New York City, which is only conducting surface maintenance, Philadelphia is actively maintaining both the surface and subsurface features, such as underdrain pipes. In addition to developing standard operating procedures, the PWD compiled a nationwide review of green stormwater infrastructure maintenance programs and manuals to inform their decision-making. Their interim manual estimates that operations and maintenance will be 15% to 20% of total program cost, or 1.5% to 2% of capital expenditures annually over the 25-year lifespan of the project (PWD 2012).

Finally, an important part of the maintenance planning process is ensuring that the green infrastructure sites were constructed as designed. PWD found that sometimes the contractor did not follow design specs and therefore maintenance protocols were unattainable. For example, PWD utilizes closed-circuit television (CCTV) to inspect underdrain pipes. In some instances, upon their initial inspection, the maintenance crews found that the distribution of pipes was incorrect, making it impossible to use CCTV. An example of incorrect construction is when a distribution pipe makes a right angle (90 degrees), a turn that is impossible for the camera to navigate. Therefore, without CCTV to inspect the pipes, subsurface maintenance is unable to be performed.[5]

Important maintenance considerations to take away from Philadelphia:

- Review the national inventory of more than 150 maintenance practices and manuals.
- Delineate the surface and sub-surface maintenance requirements.
- Inspect sites to ensure they are constructed as designed.
- Develop a field reporting data sheet to support and track maintenance operations.
- In addition to monitoring maintenance activities, also evaluate public acceptance, aesthetics, and stewardship.

Creating a Living Laboratory on Campus

The Yale Office of Sustainability promotes the idea of using the campus and city of New Haven as a living laboratory, with the goal of "helping to educate Yale's students and engaging in the development and analysis of innovative approaches to diminishing the University's environmental impact."[6] Implementing green infrastructure pilot projects on campus is an excellent opportunity to further promote this initiative. Several universities across the nation have implemented living laboratories featuring various green infrastructure practices on campus, providing a model Yale could adapt and implement on its own campus.

Villanova Urban Stormwater Partnership

The Pennsylvania Department of Environmental Protection and Villanova University's Department of Civil and Environmental Engineering founded the Villanova Urban Stormwater Partnership (VUSP) in 2002. The mission is "to advance the evolving field of sustainable stormwater management and to foster the development of public and private partnerships through research on innovative stormwater Best Management Practices, directed studies, technology transfer and education" (VUSP, n.d.). Noteworthy is the number of private and public partners and members involved in this partnership, which includes the Philadelphia Water Department. The VUSP field sites are spread across the campus, including a stormwater wetland, infiltration trench, bio-infiltration systems, porous paving (concrete and asphalt) comparisons, a green roof, and several infiltration test sites. All of the field sites are used extensively in the undergraduate and graduate water resource classes. Furthermore, some of the sites have been continuously monitored for over a decade, providing a data set that has contributed extensively to the body of scientific literature on sustainable stormwater management practices.[7]

University of New Hampshire Stormwater Center

The University of New Hampshire Stormwater Center (UNHSC) is a research, testing, and educational facility to provide resources for students, water managers, planners, and engineers focusing on stormwater management practices (UNHSC 2010). Their mission is to protect water resources through effective stormwater management, and "The primary functions of the center are twofold: (i) Research and development of stormwater treatment systems, (ii) To provide resources to the stormwater management community currently challenged by the effective design and implementation of required stormwater management" (UNHSC 2010). The UNHSC's field-testing facility is offsite and designed for direct, side-by-side comparison of the various stormwater technologies. The UNHSC prides itself on the fact that the facility "has collected performance data for over 80 storms and has evaluated over 30 different types of stormwater treatment systems" (UNHSC 2010). Moreover, the UNHSC holds workshops on various stormwater management topics such as porous pavement and bioretention system design to enhance professional development.[8]

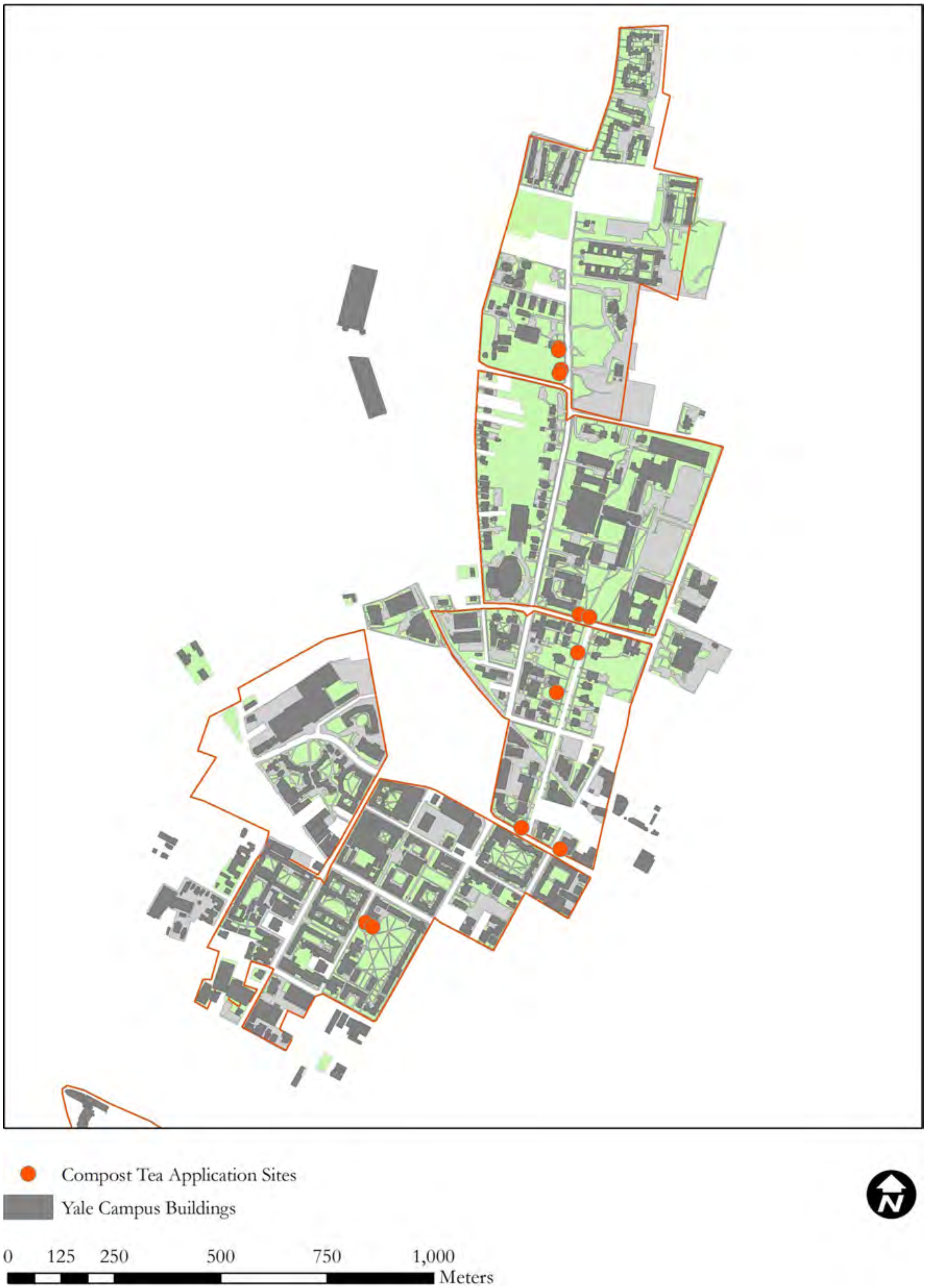
North Carolina State University and University of Minnesota Training Programs

Similar to the UNHSC's workshops to enhance professional development, North Carolina State University (NCSU) and the University of Minnesota Extension have developed training and certification programs for inspection and maintenance activities. The North Carolina State University Best Management Practice Inspection and Maintenance Certification is a workshop that provides a certification from the NCSU Cooperative Extension to participants who pass the examination at the end of the training. The certification is largely targeted at engineers and surveyors. The course covers stormwater and how it affects water quality, regulations, management devices used and how they function, and most important, inspection and maintenance requirements for each practice (NCSU, n.d.). The University of Minnesota Extension has a similar program, the Stormwater Education Program, targeted at Municipal Separate Storm Sewer System (MS4) operators, contractors, developers, engineers, and field staff. The locally tailored workshops are entitled "Stormwater U" and are designed to help MS4s meet their stormwater permit control measures (University of Minnesota Extension 2011). In the past they have done workshops specifically on maintenance of stormwater control measures, such as bioretention systems. Yale can join the ranks of these university-based training and certification programs if they provide professional development workshops on operation and maintenance activities using the knowledge gained from the green infrastructure sites on campus.

Compost Tea Project

Green infrastructure pilot projects provide an excellent opportunity for a living laboratory on campus, and there is already a framework for collaborative research that has been highly effective on Yale's campus. The Compost Tea Study is a collaborative initiative between students and faculty from the School of Forestry and Environmental Studies, Yale Grounds and Maintenance, and the Oﬃce of Sustainability. The joint

Figure 1: Compost Tea Project Plots



pilot project involves monitoring four different treatment protocols at eight test sites across campus, as shown in Figure 1 (Yale O∞ce of Sustainability 2010–13). In order for green infrastructure pilot projects to become successful research efforts, the same protocol should be followed.

Recommendations for Yale University

It is clear that maintaining green infrastructure is integral to the performance and effectiveness of each green infrastructure system. Moreover, when developing a maintenance plan for green infrastructure on Yale University's campus, several principles should be applied.

Pilot Projects

Pilot projects have proven to be a successful mechanism for integrating green infrastructure into traditional stormwater management planning. A successful green infrastructure plan for Yale University would establish pilot projects across the campus landscape, following a protocol analogous to that of the Compost Tea Project (see Figure 1).

When developing and designing these pilot projects, consider siting and landscape:

- The desired location should be in areas that do not conflict with Yale's overall aesthetic vision.
- The aesthetics on Yale's campus range from well manicured (Central Campus) to non-uniform (Science Hill) (Branerjee et al. 2011). Therefore, on Science Hill, landscapes can be more experimental in terms of their aesthetic appeal, versus Central Campus, where the aesthetic component of landscapes is weighted heavily.
- Several areas of campus should be prioritized for implementing pilot projects, including Science Hill, West Campus, and the athletic fields.
- The landscape will need to be maintained for function and aesthetics.

Designing with Maintenance in Mind

Routine maintenance of green infrastructure is needed to maximize the full range of benefits the landscape provides (PWD 2012). Therefore, green infrastructure sites should be designed with maintenance as a core consideration.

The maintenance considerations that should be reflected in the design iterations include:

Maintenance frequency How often does the site need to be visited? Weekly, monthly, quarterly, biannually, upon failure, as needed, etc.

Inspection requirements What should be inspected when the site is visited? What are the surface maintenance requirements? What are the sub-surface maintenance requirements?

Maintenance activities and field practices What should be done when the site is visited? Consider required crew members, safety, equipment, etc. Collection of monitoring data, if applicable.

Reporting of field activities What data should be collected? Time spent at the site, duties performed, problems encountered, monitoring data collected, etc.

Adapting designs How should the design iterations be adapted to reflect reports from the field and data analysis?

Collaboration

To ensure that the green infrastructure and related landscapes are high performing, the maintenance effort should be a collaborative project between the students, faculty, the O∞ce of Sustainability, and the O∞ce of Facilities.

A collaborative effort on green infrastructure implementation and maintenance will ensure the success of the pilot program. A successful collaboration will have the following components:

A written protocol with standardized procedures A clear delineation of the scope of the project and who is responsible for each component is essential to fostering an open dialogue and transparent process. A written protocol will also guarantee that the logistical aspect of scheduling and coordinating maintenance is carried out. Standardizing procedures will ensure that the project is consistently held to the highest standards possible. Uniform procedures will not only streamline the process, but also eliminate any uncertainties. A written protocol will also serve as a model for other collaborative research efforts and can be replicated at other institutions.

Long-term commitments from a faculty member This will lead to the development of a long-term data set that can contribute to the body of scientific literature on sustainable stormwater management practices. Students will continually rotate through the program, and to reduce the variation, a faculty member with oversight will provide consistency. A long-term commitment is also essential for securing innovative funding mechanisms for the pilot projects, such as National Science Foundation grants or other research-based grants.

Finally, the most noteworthy aspect of this type of collaboration is the opportunity for enhanced professional development for the students, faculty, staff, and interested parties at Yale University through specialized trainings, like those offered at North Carolina State University and the University of Minnesota Extension. The Yale School of Forestry and Environmental Studies could host the specialized trainings, in conjunction with the Hixon Center for Urban Ecology and the Yale O∞ce of Sustainability. It would be an opportunity for all involved parties, such as the Yale Facilities Grounds Maintenance crews and student collaborators, to continue advancing their knowledge of green infrastructure operations and sustainable stormwater management planning. All trainings that are held should be available to any interested parties, including members outside the Yale community.

Adaptive Management

In order to develop a successful maintenance plan, it is critical that adaptive management underpin the formulation process. As mentioned above, the maintenance plan will need to be revised, as the design iterations are adapted to reflect the reports from the field and the monitoring data that have been analyzed. This will allow for continual updates to the existing plan as new information becomes available from the pilot project sites. This will ensure that each step is scrutinized for its relative effectiveness before the next step is taken. This will also limit the liability of the decision maker should an initial pilot project prove inadequate (Burroughs 2011).

Conclusion

It is clear that maintenance is an essential activity when designing and implementing green infrastructure. Before pilot projects come online it will be critical to evaluate the maintenance requirements and additional considerations mentioned above. In order to become a leading institution in sustainable stormwater management, Yale needs to embrace the campus as a living laboratory and provide opportunities for professional development.

Though not detailed above, to ensure that Yale moves forward as a leader in sustainable stormwater management practices, educational signage should be included as part of the maintenance plan development. This will enhance community engagement, promote awareness about the impacts of stormwater runoff, and brand its green infrastructure efforts; however, this can be included in the next phase of green infrastructure planning.

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Appendix I

Recommendations for Design Guidelines That Include Green Infrastructure

Contents

Introduction

To move toward a campus that will comprehensively implement green infrastructure, all future designs of new buildings, retrofits, and landscapes must include reference to how green infrastructure is incorporated. One of the purposes of this appendix is to provide recommendations for influencing specifications and design guidelines based on the updated LEED NC v4, due to be released in late 2013. The appendix also discusses the challenges of transitioning from a design-based specification to a performance-specification approach. Finally, the University of Pennsylvania's Stormwater Master Plan is used as a case study example.

Performance-Based Metrics for Green Infrastructure

One of the challenges that Yale Facilities faces today with respect to its building and construction design guidelines is how to successfully transition from a design-based specification to a performance-based specification. As such, the long-term vision for stormwater management on campus focuses on selecting green infrastructure (GI) technologies based on their relative performance characteristics rather than on their design. One of the main challenges to this approach is that performance of GI depends greatly on the location and climatic, soil, and hydrologic conditions where it is to be installed. Moreover, information on the actual performance of already installed green infrastructure technologies in the Northeast and across the country is very limited, and the information that is available is specific to that location. A non-comprehensive review of existing stormwater management plans for other universities shows that performance-based metrics are sparsely or not at all discussed. In the few cases where the topic has been mentioned, regional or site-specific performance results have been cited.

To illustrate the di∞culty of finding performance-based metrics for green infrastructure, available performance data from the University of New Hampshire (UNH) were compiled and compared. The UNH Stormwater Center Biannual Report from 2009 offers data on the relative performance of a set of conventional, manufactured, and low-impact devices compared with their previous performance on UNH's campus and data from the U.S. Environmental Protection Agency (EPA). Results are summarized in Table 1.

Each treatment device is being measured to calculate its pollutant removal and hydraulic performance. The observation period is from 2004 to 2008, and the site and design specification source is UNH's Stormwater Center (UNH 2009). Where available, results have been compared with performance data from the EPA. Performance was reported on a seasonal base—summer and winter—and then average annual performance (reported in Table 1) was calculated.

Table 1: Performance of Three Categories of Stormwater Management Practices

	metric	total suspended solids (% Removal)		annual average peak flow reduction (% removal)
	reference	unh	epa	unh
	treatment unit description			
conventional treatment devices	Retention Period	68	50–90	86
	Stone Swale	50		8
	Vegetated Swale	58	81	52
	Berm Swale	50		24
	Deep Sump Catch Basin	9		–
treatment devices	Infiltration Unit	99		87
	Stormtech	80		76
	Aquafilter	62		–
	Hydrodynamic Separator	27	52–84	–
low-impact devices (lids)	Surface sand Filter	51	70	69
	Bioretention		90	
	Bio I 48" Depth	97		75
	Bio II 30" Depth	87		79
	Gravel Wetland	99	80–93	87
	Porous Asphalt	99	82–95	82
	Pervious Concrete	97		93
	Tree Filter	93		–

It is evident from the results in Table 1 that in the case of pollutant removal e∞ciency some treatment practices overperform and some underperform when compared with the EPA data. Having a reference point for comparison is helpful, but it gives us no reason to believe that the practices implemented by the University of New Hampshire are better or worse on average. As referenced previously, performance depends on a variety of factors—location, climate, soils, and measurement, among others.

Transitioning to a performance-based design specification is a process that will require long-term monitoring of the installed technologies and availability of comparative results based on similar characteristics (e.g., location, climate, etc.). While challenging, the development of such a design guideline would position Yale as a leader and innovator in effective stormwater management design, would likely be more cost effective than a more traditional "prescriptive" design specification, and would likely yield better long-term performance. Finally, the importance of installing monitoring equipment to test the performance of different technologies over time on Yale's campus is an absolutely essential component to generate the performance data that will ultimately be most useful to Yale Facilities.

Design Specification Recommendations Based on LEED NC v4

Given that it is unrealistic to adopt a performance-based approach to stormwater management in the immediate term, it is recommended to move toward prescriptive recommendations that are adapted to LEED NC v4 (U.S. Green Building Council 2013), due to be phased in starting in late 2013. While all new construction must already obtain at least a LEED Gold certification, the most effective and e∞cient way to incorporate GI into the Yale campus is to use the Yale University Design Standards, Section 01352, Sustainable Design Requirements, to mandate that certain stormwater-related credits be achieved. These are listed in Tables 3 and 4.

First, however, it is important to note the following local zoning, Greater New Haven Water Pollution Control Authority (GNHWPCA), and Environmental Protection Agency (EPA) MS4 requirements, since these would supersede any Yale-mandated requirement:

Table 2: Local and State Stormwater Management Requirements

agency	requirement	areas affected
GNHWPCA	Contain first 2.05" of rain (two-year storm) on-site (GNHWPCA 2008)	CSO areas
Local Zoning	Collect, retain, treat first 1" of rain on-site Post-development runoff must be ≤ pre-development runoff Development of a stormwater management plan (as applicable)	All areas
EPA/DEEP (anticipated)	Collect, retain, treat first 1" of rain on-site Post-development runoff must be ≤ pre-development runoff	MS4 (separated areas)

Table 3: Recommendations for LEED NC 4 Credits to Be Included in Yale 01352 Design Supplement

SSc 1 Site Assessment

Max Points Available: 1

Credit Requirement Complete and document a site survey or assessment that includes: topography, hydrology, climate, vegetation, soils, human use, human health effects.

Reasoning Local zoning requirements for most types of development already require that most of this information be collected. Most of this information about the site is necessary in order to properly select, design and construct most GI technologies.

SSc4 Rainwater Management

Max Points Available: 3

Credit Requirement Option 1 (2 points): Manage runoff from developed site for 95th percentile of regional or local rainfall events using low-impact development and GI (equates to approximately first 1.7” of rain) (U.S. EPA 2009, p. 14). Option 2, Path 1 (1 point): Achieve Option 1 and manage on-site the annual increase in run-off volume from the natural land cover condition to the post-developed condition. Option 2, Path 2 (1 point): Achieve Option 1 but for the 98th percentile of regional or local rainfall events.

Reasoning GNHWPCA mandates that projects in combined sewer overflow (CSO) areas (which compose the majority of the Yale campus) manage the first 2.05" of rain on-site, which already exceeds the Option 1 requirement. It is therefore recommended that Yale Facilities mandate SSc4 Option 1 and Option 2. Neither Path 1 nor Path 2 is likely to exceed the WPCA's first 2.05" requirement, if it does at all. Additional calculations must be completed to convert the 98th percentile into inches of rain for the New Haven area. This is the only credit that deals explicitly with stormwater management. While this credit is ambitious in its stormwater management requirements, it still provides significant flexibility for different GI design options. This credit should help with Yale's transition to a more performance-based design approach given that it requires that a certain level of performance be achieved.

LTc2 Sensitive Land Protection

Max Points Available: 1

Credit Requirement Option 1: Locate development footprint on land that has been previously developed. Option 2: Locate development footprint on land that does not meet criteria for sensitive land (see LEED NC v4 for specific definitions).

Reasoning Undeveloped greenscapes are already limited within New Haven. Developing on them creates additional impervious surface in an already highly impervious area. Developing on previously developed and likely impervious land creates new opportunities to improve the site's capacity to reduce stormwater runoff.

SSc2 Protect or Restore Habitat

Max Points Available: 2

Credit Requirement Preserve and protect 40% of the greenfield area on the site (if such area exists), and using native or adapted vegetation, restore 30% of all portions of the site identified as previously developed.

Reasoning Undeveloped greenscapes are already limited within New Haven. Developing on them creates additional impervious surface in an already highly impervious area. Green spaces are already an essential part of Yale's aesthetic. Meeting this requirement will both ensure that they continue to be prioritized and offer opportunities to add them where they previously didn't exist, creating aesthetic, air quality, heat island, and stormwater management benefits. This requirement requires vegetation-based GI design vs. underground infiltration/storage.

SSc3 Open Space

Max Points Available: 1

Credit Requirement Provide outdoor space ≥30% of total site area (including the building footprint). A minimum of 25% of that area must be non-turf grass vegetation or have overhead vegetated canopy.

Reasoning This credit is mostly fulfilled already if the project achieves credit SSc2. Green spaces are already an essential part of Yale's aesthetic. Meeting this requirement will ensure that they continue to be prioritized and will create aesthetic, air quality, heat island, and stormwater management benefits. This requirement requires vegetation-based GI design vs. underground infiltration/storage.

SSc5 Heat Island Reduction

Max Points Available: 2

Credit Requirement Option 1 (2 points): Use combination of vegetated roof and/or high solar reflective index (SRI) roofing material to fulfill the equation requirement associated with this credit. Option 2 (1 point): Place a minimum of 75% of parking spaces under cover. Roof used to cover parking must meet specific SRI value, be vegetated, or be covered by energy generation systems.

Reasoning Water use monitoring and gathering current data will be the most effective way to understand Yale's water footprint. This credit is particularly important for projects that intend to use reclaimed water. Without such monitoring it would be di∞cult for Yale Facilities to understand whether the size of the water retention system was appropriate or not. This could help inform subsequent reclaimed water system designs.

WEc4 Water Use Measurement

Max Points Available: 1

Credit Requirement Install permanent water meters for two or more water subsystems, including: irrigation, indoor plumbing fixtures and fittings, domestic hot water, boiler, reclaimed water, and other process water.

Reasoning Water use monitoring and gathering current data will be the most effective way to understand Yale's water footprint. This credit is particularly important for projects that intend to use reclaimed water. Without such monitoring it would be di∞cult for Yale Facilities to understand whether the size of the water retention system was appropriate or not. This could help inform subsequent reclaimed water system designs.

Table 4: Recommendations for 01352 Design Supplement for Small and Limited Scope Projects Using LEED NC v4 Credits

Downspout Disconnection

Credit Requirement Assess downspout disconnection options for all relevant projects; wherever possible, make disconnection.

Reasoning Downspout disconnection is a very easy and inexpensive means of reducing stormwater flow into the sewer system. Downspout disconnection has already been deemed a high priority for Yale Facilities and the Office of Sustainability. Ties well into the Downspout Disconnection Pilot, described in Appendix F.

SSc1 Site Assessment (Modified)

Credit Requirement Complete and document a site survey or assessment that considers how GI can be incorporated into existing site to reduce stormwater runoff (as applicable).

Reasoning This requirement will ensure that no retrofit projects for which stormwater is relevant (roofs, sidewalks, lawns, parking lots, etc.) will be implemented without first considering how GI could potentially be incorporated. This will ensure that potential GI opportunities are not missed due to rushed planning/design schedules or other reasons.

SSc4 Rainwater Management (Modified)

Credit Requirement Manage runoff from developed site for the 98th percentile of regional or local rainfall events (as applicable).

Reasoning GNHWPCA mandates that projects in CSO areas (which constitute the majority of the Yale campus) manage the first 2.05” of rain on-site. Depending on the rainfall equivalent to the 98th percentile for New Haven, the GNHWPCA requirement may already achieve this standard. While this credit is ambitious in its stormwater management requirements, it still provides significant flexibility for different GI design options. This credit will encourage Yale Facilities to use applicable retrofits as an opportunity to incorporate GI on campus.

SSc2 Protect or Restore Habitat (Modified)

Credit Requirement Using native or adapted vegetation, restore 30% of all portions of the site identified as previously developed (as applicable).

Reasoning Green spaces are already an essential part of Yale's aesthetic. Meeting this requirement will both ensure that they continue to be prioritized and offer opportunities to add them where they previously didn't exist, creating aesthetic, air quality, heat island, and stormwater management benefits. This provides an opportunity for Yale to convert existing impervious surface to a permeable and more aesthetically pleasing surface.

SSc5 Heat Island Reduction (For roofs/parking lots as applicable)

Credit Requirement Option 1 (2 points): Use combination of vegetated roof and/or high SRI roofing material to fulfill the equation requirement associated with this credit. Option 2 (1 point): Place a minimum of 75% of parking spaces under cover. Roof used to cover parking must meet specific SRI value, be vegetated, or be covered by energy-generation systems.

Reasoning A similar LEED 2009 credit is already mandated under the 01352 standards for Limited Scope Projects. Using a vegetated roof to achieving this credit provides stormwater management, heat island reduction, building insulation, and aesthetic benefits.

Case Study: University of Pennsylvania Management Plan

In March 2013, the University of Pennsylvania became one of the few higher-education institutions in the country to develop its own stormwater management master plan. The main purpose of the plan is to "aid campus planning by identifying opportunities to incorporate sustainable stormwater management practices into future projects" (University of Pennsylvania 2013). By doing so the university hopes to reduce its negative stormwater runoff impact and, consequently, utility costs associated with the runoff, and increase environmental sustainability and green spaces on campus.

The plan delineates ambitious goals focused on: better understanding of the challenges the university is facing in complying with the Philadelphia Water Department's (PWD) stormwater management requirements; a complete analysis of the existing stormwater management infrastructure on campus; a comprehensive overview of potential new practices for new construction and retrofitting on-campus projects, including a list of "representative details for green stormwater management practices"; development of an operations and maintenance manual for existing practices; crafting of a model to track the construction and removal of impervious surfaces; and a review of current stormwater legislation and grant/funding opportunities. These goals demonstrate University of Pennsylvania's strong commitment to find "opportunities to reduce the campus impact on its surrounding environment through the creation of additional green space and construction of sustainable stormwater management practices."

A special section of the plan discusses innovative practices that could be used in solving stormwater runoff problems on campus. Some of these green infrastructure techniques, such as green roofs, bioretention areas, and pervious pavements, have already been implemented around campus. Other contemporary practices that concentrate on treating runoff as a groundwater recharge resource rather than a waste discharge include stormwater capture and reuse systems, green hardscape treatments, green streetscapes, bioinfiltration systems, and evapotranspiration systems. While the plan suggests that these practices be considered when designing stormwater management systems, it does not require their exclusive use for that purpose.

The plan provides a detailed list of market-available products in each category. The product description, however, does not deliver specific performance-based characteristics and thus serves more as a guide for further research and not a useful, ready-to-use drop-down menu of available solutions for a specific project.

University of Pennsylvania's Stormwater Master Plan is a helpful document that offers guidelines for university o∞cers and outside consultants working on reducing the negative impacts of rainwater runoff from campus property.

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Appendix J

Collaborative Partnerships

Contents

Introduction

The purpose of this appendix is to describe possible partnership opportunities for Yale to undertake as it moves forward with its Sustainable Stormwater Management Plan. This is not meant to represent an exhaustive list of potential collaborators, but rather an overview of the public and private organizations already interested in green infrastructure (GI) in New Haven and Connecticut. A brief exploration of the possible nature of those collaborative relationships follows.

The Case for Collaboration

Yale is a fundamentally open campus; the borders between the university and New Haven are blurred by Yale's diverse landholdings throughout the city and the critical city infrastructure that supports the university. With 26,000 faculty, staff, and student visitors per day, in addition to countless tourists annually, green infrastructure projects on Yale's campus will undoubtedly affect the wider Yale community, the city of New Haven, and the larger region (Yale University Sustainability Task Force 2010).

The O∞ce of Sustainability has demonstrated a commitment to collaboration, both with o∞ces and departments across Yale's campus, as well as with the city of New Haven and its residents. The O∞ce of Sustainability's Campus as a Living Laboratory program facilitates student and faculty research projects on Yale grounds. The Yale Community Carbon Fund supports energy e∞ciency projects in low-income households in New Haven, while simultaneously reducing the carbon footprint of events on campus. The O∞ce of Sustainability is also a member of numerous international alliances to improve on-campus sustainability initiatives.

The concept of universities taking a central role as drivers of urban sustainability has garnered significant attention in recent years. Academic institutions such as Yale are a unique force in the move to a more widespread application of GI principles. They are sources of technological and social innovation; they are firmly rooted in place but also convene regional, national, and even international interests, and they can bridge expansive areas of expertise (Trench, Yarime, and Kharrazi 2013). Examples of universities taking proactive steps to collaborate with public and private entities can be found across the globe.

Collaboration that happens from the outset of a project can inspire community participation and engagement. The practice of civic ecology, where community members take responsibility for the enhancement of the green infrastructure and community health, particularly in urban areas, can foster psychological and physical well-being, encourage a sense of place, and expand naturally from small-scale work to much larger partnerships (Krasny and Tidball 2012).

More specifically, collaboration will help Yale ensure the success of future green infrastructure installations. Coordination with the appropriate deans, college masters, staff, faculty, and students (both current students and alumni) will go far in ensur-

Table 1: Five-Level Framework for Partnerships

summary of five-level framework				
Scope (What?)	Target (Where?)	Key Actors (Who?)	Motivation (Why?)	Role (How?)
1. Comprehensive 2. Focused	1. Local 2. Regional 3. National 4. International	1. Faculty/researchers 2. Administration 3. Students 4. Bridging organizations	1. Missional 2. Funding 3. Scientific/scholarly 4. Social contribution/ community relations 5. Developmental/ strategic 6. Entrepreneurial	1. Inventor/innovator 2. Revitalizer/ retrofitter 3. Builder/developer 4. Director/linker 5. Scientific advisor/ communiicator 6. Facilatator/ empowerer

Source: Krasny and Tidball (2012)

ing aesthetic acceptance of projects. Collaboration with city agencies will allow the university to undertake projects in an opportunistic way, when road and sidewalk work are already under way, for example. Yale's ability to convene researchers from around the nation will allow for scientific collaborations that inform the university's first steps. Rather than entering the process of GI design and installation uninformed, Yale can benefit from the experience of other universities.

Goals of Collaboration

The nature and number of Yale's collaborators in implementing a sustainable stormwater management plan will vary based on its ultimate goals. Is collaboration primarily meant to encourage research? Or to leverage funding? One analysis of academic cross-sector collaborations to achieve sustainability results found that there are five levels of questioning that can inform the type of collaboration necessary, as shown in Table 1.

First, is the work going to be comprehensive or focused in scope? A comprehensive project might include advancing the goals of sustainability very broadly, while a focused one might only target sustainable stormwater management. Next, we must ask about the target region. Is Yale hoping to impact only areas on campus, or does it hope to inform the thinking on green infrastructure nationally and internationally? Who are the key actors, and what is the motivation? Finally, what role will Yale University play? Some universities may push the innovation agenda by focusing collaboration on design advances. Others may be conveners, or "linkers" of key players, with a stress on the collective power and knowledge of many actors, rather than one.

None of this is to say that Yale must choose one path from each of the five columns and stick with it. Rather, each project may include a slightly different mixture of key actors, motivations, and target areas.

Case Study: Temple–Villanova Sustainable Stormwater Initiative

This initiative is an example of the potential for collaboration across academic institutions. The initiative reflects the partnership between Temple University's Center for Sustainable Communities and the Villanova Urban Stormwater Partnership. It is meant to facilitate collaboration on research (with particular attention to creating a standard monitoring plan), support a broad green infrastructure outreach program (utilizing symposia, workshops, tours, and an advisory committee), and facilitate the installation of stormwater Best Management Practices (BMPs) demonstration projects. The partnership between these two research centers is supported by grants from the William Penn Foundation, as well as the Pennsylvania Department of Environmental Protection's Growing Greener program. The ultimate goals of this partnership are to leverage additional research funding dollars, to generate publishable work on the effectiveness of green infrastructure technology, and to improve the design, construction, and monitoring standards related to BMPs.

Source: Villanova Urban Stormwater Partnership website, http://environment.yale.edu/hixon. Accessed May 4, 2013.

Partner Profiles

In this section potential partners are highlighted from offices within Yale, within the city of New Haven, within the state, and beyond. Each agency or organization is listed with a brief explanation of its role in green stormwater infrastructure. Key contact names are also listed, when available.

Opportunities for Partners within Yale

Office of Sustainability The Office of Sustainability at Yale is coordinating efforts in the drafting of this Sustainable Stormwater Management Plan, and will continue to be a convener of resources and staff when it comes to sustainability on campus. Sustainability may be positioned such that it can take on the role of coordinating efforts between the academic and strategic sides of Yale.

Facilities Office The Facilities Office houses multiple staff persons that will be integral to the application of GI on Yale's campus. From design inception to installation and long-term maintenance, the success of GI projects will depend heavily on the coordination of Facilities staff. Specifically, efforts should be made to bring together the planning office, landscaping and design, engineering, and the sustainability initiative.

Environmental Health and Safety This office is responsible for ensuring the workplace safety of Yale's students, faculty, and staff. In addition, they have committed to a high level of environmental monitoring, which could come into play when Yale is faced with creating the infrastructure and operations plan for an intense monitoring system for its green infrastructure. Brenda Armstrong is the Environmental Affairs Manager and may be interested in coordinating with the Office of Sustainability.

College Masters, Department Deans, Key Faculty, and Staff Critical to the acceptance of any project on central grounds will be the involvement of the appropriate college masters, department chairs, and deans. Specific projects will likely be sited throughout campus, and coordinating efforts with those members of the Yale community who will be most directly affected by the installation will facilitate a smooth process. It may be that some sites are more suitable to the installation of demonstration projects, including the property around the Yale Sustainable Food Project Farm and Marsh Botanic Garden on Science Hill. The directors of these programs — Eric Larson and Mark Bomford, respectively — would be good partners to involve early in the process.

The Hixon Center for Urban Ecology The Hixon Center could serve as a critical convener of faculty and student research interest around green infrastructure. The Hixon Center is a research center with a focus on advancing knowledge of urban ecosystems and advancing the practice of environmental design in urban areas.[1] Led by Colleen Murphy-Dunning, the center also features numerous Forestry & Environmental Sciences faculty with an interest in urban water quality issues. The

Hixon Center could facilitate grant applications and collaborations between departments. The Hixon Center has also taken on a strong outreach component within F&ES, convening regular speaker series and symposia. If sustainable stormwater management could be included in the center's outreach goals, it could provide an opportunity for influencing the national dialogue.

Other Yale Research Labs and Centers The Urban Ecology Design Laboratory is run by Professor Alex Felson, who has worked directly on GI projects related to stormwater in Connecticut and who is interested in the study of urban engineered systems. In addition, the Center for Green Chemistry & Green Engineering at Yale represents an interdisciplinary approach to green design efforts, with faculty and students that may be interested in collaborating on green infrastructure work.[2] Within F&ES, Professor Julie Zimmerman and Professor Thomas Graedel sit on the executive committee of the center.

Case Study: University of New Hampshire Stormwater Center

The University of New Hampshire (UNH) Stormwater Center is a center for research and education surrounding the protection of water quality through green stormwater management. The center features faculty and students interested in studying the differences between low-impact development and traditional gray infrastructure. Funding comes from the National Oceanic and Atmospheric Administration, the Environmental Protection Agency, and the New Hampshire Department of Environmental Services. Public education is a core tenet of the center's mission, and the staff host workshops on topics ranging from gravel wetland design to the installation of permeable paving. In addition, the center focuses on the potential for GI to provide economic returns to low-income communities. Their focus has been primarily on coastal communities, and partnership building is a core focus of the program.

Source: UNH Stormwater Center, www.unh.edu/unhsc. Accessed May 9, 2013.

Opportunities for Partners within New Haven

Mayor's Office The November 2013 election is slated to bring about the first change in the mayor's office that New Haven has seen in two decades. With this change, there will be not only a change in leadership, but also a significant turnover of politically appointed agency heads within the city.

The Department of Engineering New Haven's Department of Engineering has taken an active interest in green infrastructure, and is beginning the process of creating an organized design manual for GI throughout the city. Their interest is in identifying cost-effective infrastructure projects that can be replicated and are somewhat easy to maintain. As Yale approaches the design portion of its stormwater sustainability challenge, a partnership should be formed with Giovanni Zinn (Yale College '05), who is in the Department of Engineering.

New Haven Office of Sustainability The city's Office of Sustainability was funded by a one-time grant whose resources have run out. While Giovanni Zinn is still technically the city staff person responsible for the office, he has been relocated to the Department of Engineering.[3] Should additional funds be identified for this office in the next administration, it could be a good partner for Yale to coordinate its efforts with the city.

Other New Haven Agencies There are multiple city agencies that would have an interest and contribution to Yale's efforts. In order to ensure the opportunistic installation of green infrastructure, communications with the City Planning Department as well as the Department of Transportation, Parking, and Traffic would be helpful. Those agencies have an understanding of when projects will be happening on New Haven streets. Adding green infrastructure to an already existing construction project is much easier than adding it independently. The New Haven Department of Parks and Recreation as well as the Department of Public Works (DPW) may be good partners for understanding the complex maintenance associated with green infrastructure. Parks is responsible for the care of the city's street trees and open spaces, while DPW handles the maintenance of roads and sidewalks.

City Resource Allocation Committee This committee was formed in 2012 in order to prioritize road paving and sidewalk construction work in the city. The four-person committee is composed of two members from the administration and two from the board of aldermen, and is tasked with the fair distribution of roadwork funds to each neighborhood in the city. If Yale is interested in attaching a green infrastructure project onto ongoing construction priorities, working with the members of this committee would be beneficial. Dick Miller, City Engineer, is one of the administration's representatives on the committee.

Urban Resources Initiative The New Haven Urban Resources Initiative (URI) is a nonprofit organization affiliated with the Yale School of Forestry & Environmental Studies. URI is responsible for planting all of the public street trees in New Haven, and runs a Community Greenspace program that supports the work of residents in greening their local communities. URI is run by Colleen Murphy-Dunning, who has extensive knowledge and experience in partnering with New Haven for GI—specifically tree planting. Associate Director Chris Ozyck has a wealth of landscape design and community organizing experience, and would be a valuable partner.

New Haven Environmental Justice Network The New Haven Environmental Justice Network has been advocating for an increased role for GI in the management of stormwater in the city. Lynne Bonnett leads the group's GI advocacy work. Through public meetings, awareness campaigns, and social media, the network has rallied support around several environmental justice campaigns in New Haven. This is a grassroots organization that would support any work that Yale does that could be applied elsewhere in the city.

Case Study: The Urban Ecology Collaborative (UEC)

The UEC is an informal partnership organization between the organizations involved in urban tree planting and care in cities on the East Coast of the United States. The member organizations are from Boston to the north, to Washington, DC, in the south, and include the New Haven Urban Resources Initiative. The purpose of the group is to share information, research, and technical expertise across the spectrum of public and private agencies that work to advance urban tree canopies. The group has no dedicated funding, and meets remotely once per month for a webinar. Each webinar has a different theme, ranging from the effects of major storms and hurricanes on urban trees to new funding opportunities and federal partnerships. Each month a different member organization organizes the webinar so that the work is shared evenly. The partnership has furthered the knowledge of the state of tree planting initiatives in the East and has fostered deeper relationships in the field.

Opportunities for Partners within the Region and State

Greater New Haven Water Pollution Control Authority (GNHWPCA) The GNHWPCA handles all of the stormwater that flows through the combined sewer system in New Haven. They are also responsible for projects that work to keep New Haven in compliance with the Clean Water Act and the city's MS4 permit. GNHWPCA established strict requirements for on-site detention of stormwater in new buildings, which has led to the installation of holding tanks and stormwater infiltration at several sites on campus.[4] GNHWPCA is responsible for sewer separation projects, and is interested in understanding how GI might be incorporated into compliance projects. In particular, Tom Sgroi (Director of Engineering) has been working with the Connecticut Department of Energy and Environmental Protection on understanding how Clean Water Fund moneys might be made available for the installation of GI.

Regional Water Authority Responsible for providing clean drinking water for more than 500,000 consumers in New Haven and its surrounding towns, the South Central Connecticut Regional Water Authority has extensive experience in protecting water quality by using GI—namely, watershed protection.[5] The Water Authority established the Watershed Fund to provide grants that protect the larger drinking watershed and educate landowners about steps that they can take to ensure environmental vitality.

Connecticut Department of Energy & Environmental Protection (DEEP) DEEP is responsible for ensuring city compliance with the requirements of Phase II of the Clean Water Act, and runs the Clean Water Fund, which provides funding for infrastructure projects meant to protect water quality. DEEP has engaged in earnest discussions regarding the role that GI might play in urban stormwater management, and formed a Committee on Green Infrastructure to further those conversations. Ivonne Hall has been an active partner in the formation of this Management Plan.

Save the Sound/CT Fund for the Environment (CFE) CFE has been a strong nonprofit environmental advocate for the increased application of green infrastructure tools as a way to achieve compliance with Clean Water Act phase II regulations in Connecticut. CFE's mission is to "protect and improve the land, air and water of Connecticut and the Long Island Sound" and to "bring people to achieve results that benefit our environment."[6] CFE staff, including Senior Attorney Curt Johnson, have extensive knowledge of the regulatory drivers of stormwater management, and could speak to the important role of education, outreach, and advocacy in spreading sustainable stormwater infrastructure.

National Fish and Wildlife Foundation (NFWF) Long Island Sound Futures Fund NFWF has invested more than $10 million over the past eight years in projects designed to protect the health of the Long Island Sound. One project funded within the past year included an analysis to determine the potential for green infrastructure along the Long Island Expressway.[7] The Long Island Sound Futures Fund could be a potential source of funding to support demonstration projects, or an important informant on additional green infrastructure work that is happening in the Long Island Sound area.

Opportunities for National Partnerships

Other Academic Institutions There are numerous other academic institutions with which Yale is in a prime position to partner. The Villanova Urban Stormwater Partnership is conducting extensive research on GI technology and has a close working relationship with the Philadelphia Water Department. Arizona State University has created a Sustainable Cities network to address sustainability in urban areas broadly. New Hampshire University has created its Stormwater Center, with dual core missions of research and educational outreach. Yale is already a part of the Campus Consortium for Environmental Excellence, which brings together like minds to discuss the challenge of sustainability in an academic environment.

Partnership for Sustainable Communities A partnership between the U.S. Department of Housing and Urban Development, the U.S. Department of Transportation, and the U.S. Environmental Protection Agency, the Partnership for Sustainable Communities works to coordinate funding for housing, transportation, and other infrastructure such that they work together toward sustainability. While these funding mechanisms typically go to public agencies, the program offers a wealth of information regarding green infrastructure, and could be an interesting partner should Yale and New Haven choose to work together on GI projects in the future.

American Rivers This national nonprofit is doing advocacy and outreach work to promote the health of our nation's rivers, and the importance of GI as a way to protect that health. They have compiled a series of resources about the value of specific GI technologies, and could be an effective educational outreach partner for Yale.

Recommended Next Steps for Collaboration at Yale

In this section concrete partnership goals are laid out, with possible actions that Yale can take to achieve those goals. Some actions may be easier to adopt than others. Understanding that partnership building is a gradual process, the Office of Facilities and the Office of Sustainability should more formally establish short-, medium-, and long-term collaboration goals.

Partnership Goals

- Improve communication between the Office of Facilities and the Office of Sustainability across Yale and across the private/public divide for better awareness of the state of GI in the region.
- Increase educational outreach on the challenge of stormwater in urban areas and the steps being taken by Yale and New Haven to manage stormwater more sustainably.
- Implement successful design and construction of green infrastructure projects with monitoring instrumentation for research purposes.
- Leverage partnerships toward synergistic research goals and shared funding opportunities.
- Establish a thorough maintenance plan that incorporates job training and understanding of the function of green infrastructure.
- Generate enthusiasm and support for widespread application of green infrastructure on campus.

Partnership Actions

Increase communication with partners Create a green infrastructure email listserv. A listserv would allow for mass communication with partners and interested parties within Yale and New Haven. This email listserv would be an inexpensive way to expand current efforts at identifying and communicating with all of the appropriate stakeholders in the area. Communications could be confined to weekly or monthly updates, and could be used to share important developments between the university and the city.

Establish a green infrastructure working group A working group with annual or biannual meetings on the progress of green infrastructure on campus and in New Haven would be a way to invite stormwater stakeholders to literally sit around the same table. The Office of Facilities or the Office of Sustainability could facilitate these meetings on campus. Face-to-face interaction is the best way to form true partnerships, and even an informal working group would facilitate better communication between the city, the university, and the public and private entities engaged at both levels.

Engage campus leaders in GI installation Critical to the success of green infrastructure on campus will be the support of college masters, deans, and other important faculty and staff on campus. Creating an outreach system that engages those stakeholders early in the process will facilitate smoother installation process.

Increase education to partners Work with education and advocacy groups to design a signage and outreach campaign. Yale has already done good work in installing green infrastructure projects on campus, from green roofs to infiltration basins and bioswales. What is missing is a coordinated effort at establishing educational signage around these projects so that the wider public understands their value. Nonprofit organizations with expertise in public outreach might be interested in partnering with Yale to achieve their goals for broader public support for GI. Public outreach can also come in the form of materials on the Yale Sustainability website that inform visitors of the role and nature of green infrastructure projects.

Work with faculty to establish rigorous research and monitoring standards for GI To more fully engage the academic community at Yale, including both faculty and students, a partnership with a research center such as the Hixon Center for Urban Ecology could facilitate greater communication between the stages of green infrastructure design and long-term monitoring. The Yale O∞ce of Environmental Health and Safety has also demonstrated a commitment to monitoring and research.

Implement installation and obtain funding Work with public agencies to establish common GI goals. The City of New Haven, the GNHWPCA, and CT DEEP all have an interest in establishing green infrastructure as one way of achieving compliance with clean water regulations. Opportunities could exist to install green infrastructure in an opportunistic way in the public right-of-way, and to leverage funding from the state level to advance green infrastructure monitoring.

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Notes

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Glossary

Adaptive Management A structured, iterative process of robust decision making in the face of uncertainty, with an aim to reduce uncertainty over time via system monitoring.

Bioretention Landscaped features that are adapted to provide on-site treatment of stormwater runoff.

Bioswale/Vegetated Filter Strip A linear, gently sloping, vegetated, open channel that slows, infiltrates, and filters stormwater as it moves along the slope.

Blue Roof A non-vegetated rooftop that incorporates a series of weirs and flow-restriction devices to reduce the rate of stormwater runoff to the sewer system during peak rainfall events.

Combined Sewer Overflows (CSOs) During extreme storm events, the combined sewer system overloads its capacity and excess combined sanitary and stormwater sewage discharges untreated into nearby waterways.

Combined Sewer System Stormwater runoff and sanitary sewage flow into the same pipe for conveyance to the water treatment plant.

Constructed Wetlands Manmade systems built to mimic the functions of natural wetlands. Useful for flood storage and nutrient removal, these basins can filter runoff through a combination of plant, soil, and microbial processes.

Downspout Disconnection The process of redirecting roof drains that are directly connected to the sewer system to an adjacent pervious surface where the stormwater can infiltrate or flow over surfaces until it enters the storm system through a catch basin.

Enhanced Tree Pit Tree pits collect stormwater runoff from small areas such as portions of parking areas or stretches of roads. Stormwater filters through the tree roots and surrounding soil mix, trapping sediment and pollutants before infiltrating into the soil or flowing to a piped stormwater system.

GIS A geographic information system (GIS) is a spatial mapping tool used to analyze and visualize data. This software can be especially helpful in assessing the effects of stormwater runoff.

Gray Infrastructure Traditional systems designed with the sole purpose of protecting the built environment from flooding and conveying wastewater to a water treatment plant. Interventions for management include separating the wastewater and stormwater sewers in a combined system or constructing large tanks and tunnels to temporarily store excess combined sewage during rain events to be treated when the treatment plant has capacity.

Green Infrastructure All potential practices, landscapes, and storage devices that can be used to slow the flow of stormwater, reduce stormwater volume, and improve stormwater quality before it enters the sewer system.

Green Roof A rooftop covered with soil and vegetation to retain and mitigate the flow of stormwater through absorption and evapotranspiration. Green roofs also help to filter and cool water as it passes through the soil and plant roots.

Impervious Area Non-vegetated surfaces, such as rooftops, walkways, and roads that expedite the movement of water and do not allow for infiltration.

Infiltration Trench/Drywells Designed to capture runoff, these small trenches are useful for routing runoff away from properties, particularly in the case of downspout disconnections. Water infiltrates the systems and is stored between the void spaces of rocks.

Permeable Pavement Asphalt or concrete that is mixed with fewer fine particles to create more air space allowing for percolation of stormwater runoff. An underlying layer of fine sediment filters the water, and a sub-base of uniform-grade stones stores the water as it infiltrates into the ground.

Rain Barrels/Cisterns Storage tanks designed to capture stormwater runoff, usually from a roof downspout, allowing for future reuse of water for non-potable uses.

Rain Garden A vegetated basin designed to collect stormwater runoff and utilize the natural properties of plants and soils to remove pollutants and encourage infiltration in situ. Rain gardens are designed to mimic natural hydrology, and thereby slow water velocity and improve groundwater recharge.

Rainwater Harvesting The method of connecting a roof drain to a rain barrel or cistern, allowing for storage and use of stored stormwater for non-potable uses.

Separate Storm Sewer System Stormwater runoff and sanitary sewage flow into separate pipes. Sanitary sewage is sent to a water treatment plant, and stormwater runoff is discharged untreated into local waterways.

Stormwater Runoff Water produced from precipitation and snowmelt that does not infiltrate the ground and instead flows over it.

Subcatchment The area that drains to a common sewer system.

Underground Storage Tank Large vessels used to store stormwater underground that can later be reused or added to the drainage network.

Watershed The area of land that drains to a common point on a waterway.

Acknowledgments

Project Team

Team Leaders

Caitlin Feehan, P.E., LEED A.P. MEM, 2014
Ryan Withall, MEM/MBA, 2015

Contributors

School of Forestry and Environmental Science course: Payments for Ecosystem Services: Are Investments in Green Infrastructure a Viable Ecosystem Services Approach for Stormwater Management at Yale?

Taught by Professors Mark Ashton and Bradford Gentry, and Teaching Assistant Jennifer Hoyle

Appendix A: Chris Magalhaes, Kristin Merony, and Teodora Stoyanova
Appendix B : Kendall Barbery, Caitlin Feehan, Ambika Khadka, Justin Lindenmayer, and Katherine Romans
Appendix C: Mio Kitayama, Mary Ellen Lemay, Zulimar Lucena, Benjamin Rothfuss, and Ryan Withall
Appendix D: Caitlin Feehan and Ryan Withall
Appendix E: Kendall Barbery and Ambika Khadka
Appendix F: Caitlin Feehan and Chris Magalhaes
Appendix G: Zulimar Lucena
Appendix H: Kristin Merony
Appendix I: Justin Lindenmayer and Teodora Stoyanova
Appendix J: Katherine Romans

Joan Suris Miret, ETH Zurich, 2012 International Alliance of Research Universities Fellow
Keri Enright-Kato, Project Manager, Office of Sustainability

Clients

John Bollier, RA, Associate Vice President for Facilities
Virginia Chapman, AIA, LEED AP BD+C, Director, Facilities Sustainable Initiatives
Anthony Kosior, PE, CEM, Director, Utilities and Engineering
Julie Newman, Ph.D., Director, Office of Sustainability
Sam Olmstead, PE, Associate Director, Utilities and Engineering
Julie Paquette, PE, LEED AP BD+C, Director, Energy Management

Editorial Consultant

Joyce Ippolito, Editor

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Lynne M. Reichentahl, Yale Printing and Publishing Services
Rachel Needle, Office of the Yale University Printer

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