Guide for using green infrastructure in urban environments for stormwater management

Journal:	*Environmental Science: Water Research & Technology*
Manuscript ID	EW-TRV-07-2018-000498.R1
Article Type:	Tutorial Review
Date Submitted by the Author:	09-Jan-2019
Complete List of Authors:	McFarland, Andrea; University of Michigan, Civil and Environmental Engineering Larsen, Larissa; University of Michigan, Urban and Regional Planning Yeshitela, Kumelachew; Addis Ababa University, Urban and Regional Planning Nigussie Engida, Agizew; Addis Ababa University, Civil Engineering Love, Nancy; University of Michigan, Civil & Environmental Engineering

Guide for using green infrastructure in urban environments for stormwater management

Andrea R. McFarland
Master of Science in Engineering
amcf@umich.edu
University of Michigan, Department of Civil and Environmental Engineering

Larissa Larsen*
Associate Professor
larissal@umich.edu
University of Michigan, Urban and Regional Planning Program, Taubman College of Architecture and Urban Planning

Kumelachew Yeshitela
Professor
kumeyesh@googlemail.com
Addis Ababa University, Ethiopian Institute of Architecture, Building Construction, and City Development

Agizew Nigussie Engida
Professor
agiz70@yahoo.com
Addis Ababa University, Addis Ababa Institute of Technology, Department of Civil Engineering

Nancy G. Love
Professor
nglove@umich.edu
University of Michigan, Department of Civil and Environmental Engineering

**corresponding author*

Abstract

Green infrastructure, sometimes referred to as nature-based solutions, promotes urban livability. It reduces stormwater quantity and improves surface water quality while simultaneously providing a multitude of other environmental, economic, and social benefits. However, it can be challenging for designers and decision-makers to select a specific type of green infrastructure system for a particular location in a complex urban water network. This paper is a guide for urban planners, landscape architects, engineers, and local decision-makers in selecting and locating different types of green infrastructure in a city for stormwater management purposes. Maximizing the effectiveness of green infrastructure requires considering the site's biophysical characteristics and location in the watershed, the connectivity of the existing urban water system, and the probable pollutants from the site and adjacent areas. Our recommendations are based on previously published studies and we synthesize these in tabular format to highlight differences. Then, we illustrate the sequence of decisions and evaluate our eventual site level recommendations with pre and post- SWMM runoff simulations in Detroit, Michigan and Addis Ababa, Ethiopia. Our two cases address different stormwater challenges. In Detroit, the most pressing stormwater goal is to reduce combined sewer overflow events that degrade water quality. In Addis Ababa, stormwater management must address seasonal flooding and poor river quality caused by discharging large volumes of untreated stormwater. Through this stormwater guide, we highlight key decisions at the watershed, urban water system, and site-specific scale.

Water Impact

Green infrastructure can address water quantity and quality problems associated with stormwater runoff in urban environments. We provide a framework for urban designers and decision-makers to select and implement green infrastructure for stormwater management purposes by considering its overall effectiveness at three scales: the watershed, the urban water system, and the site.

1. Introduction

In early cities, the original purpose of stormwater infrastructure was to quickly transport runoff through pipes away from the city to prevent damage to the built environment and avoid insects, disease, and odor caused by stagnate water. Recently, bioengineered green infrastructure systems (GI) that use vegetation, soil, and/or infiltration to retain stormwater and naturally filter out contamination[1] are gaining popularity as an alternative to 'grey infrastructure'. While we concentrate on its stormwater management potential, GI offers a multitude of other benefits. Some of these benefits are the reduction of the urban heat island, the provision of additional ecosystem services, the increase in urban biodiversity and wildlife habitat, the enhancement of climate change resilience, and the addition of attractive green spaces that have salutary effects on human physical and mental health.[1–6] However, different GI systems vary in their ability to address water quantity, water quality, pollutant removal issues and their effectiveness is significantly impacted by their location.[7] In this paper, we synthesize prior research about the impact of GI systems to provide local designers and decision-makers with guidance. After defining our terminology, we begin by outlining concepts underlying siting recommendations at the watershed, urban water system, and site scale. To demonstrate how these concepts influence decision-making, we have selected sites in Detroit, Michigan and Addis Ababa, Ethiopia. These sites have distinct watershed, urban water system and local characteristics. In both locations, GI is a preferred approach to the challenge of stormwater management due to lower start-up costs and additional environmental and social benefits compared to piped systems. We are actively collaborating with decision-makers and local residents in the design of their local GI systems. Based on the preferred designs, we analyze the effectiveness of the GI systems with pre and post-SWMM (Stormwater Management Models) to estimate the impacts on peak and total stormwater volumes. See Appendix 1 for modeling details.

2. Background

Urban settlements alter natural water cycles and can present significant challenges for sustainability and human health.[8,9] As urban settlements replace a portion of a watershed's natural land cover with impervious cover, they decrease onsite infiltration and increase stormwater runoff that conveys pollutants into nearby surface waters.[10] An urban water system may be comprised of drinking water, wastewater, and stormwater management systems. In developed countries, the majority of urban water services are provided through constructed and piped centralized drinking water, wastewater, and stormwater systems.[11,12] In developing countries, construction of buildings and roads often precedes the development of urban water systems and subsequent improvements often favor smaller-scale, decentralized systems.[13–17] In both developed and developing settings, augmenting constructed water management infrastructure with GI is an ongoing discussion.[11]

GI nomenclature can vary between and within countries. To reduce confusion, we state our definitions in the following text. *Retention ponds* retain runoff, reduce peak flow rates, and are always filled with water. However, the water volume within retention ponds fluctuates with storm events.[18] *Constructed wetlands* are engineered systems that channel runoff through a vegetated path and remove pollutants through the soil, vegetation, or the inherent bacterial community. *Detention ponds* hold runoff during storm events and slowly release their volume to the environment until dry. *Rain gardens* are shallow vegetated basins often installed next to impermeable surfaces such as roads, sidewalks, and parking lots to pool that eventually permit the infiltration of runoff.[19] *Bioswales* are located along the edge of a large impervious areas such as roads or parking lots. Unlike rain gardens, bioswales are elongated in shape, have a deeper depression so they can slow and filter more peak run-off volume, and are more likely to use engineered soils.[20] *Green roofs* are roofs with vegetation and/or stormwater collection basins that allow for infiltration and evapotranspiration of runoff to reduce runoff due to impervious surfaces.[21] The effectiveness of infiltration and pollutant removal by GI systems increases when they are well-maintained (weeded, watered, debris removed), and when water has with longer residence times within the systems.[22] In this paper, we also consider non-vegetated GI, because these decentralized systems also reduce the peak flow of runoff and divert stormwater from entering the sewer/wastewater network. Examples include *permeable pavements,* which are porous surfaces installed in parking lots or sidewalks that infiltrate and store rainwater on-site.[23] Finally, *rainwater harvesting* is when rainwater is collected and stored for later use to reduce runoff and decrease centrally treated water use.[18]

As mentioned above, GI requires careful placement within the urban water network to avoid failure. We define GI failure when there is a loss of function because 1) the system cannot accommodate runoff volume, 2) plants are washed out due to high flowrates, or 3) plants cannot withstand high contaminant loads.[7] When selecting an effective type of green infrastructure for a specific location, decisions can be organized from the broad watershed, to the intermediate urban water system scale, and then fine scale site factors that consider adjacent land uses. This hierarchical thinking ensures that the effectiveness of the GI system extends beyond the site, to the existing urban water system, where it can reduce the flux of runoff in the stressed pipe network, and to the overall watershed, where it can improve overall environmental water quality and reduce runoff flowrates.

3. Scale-Specific Design Guidelines

3.1 Watershed Guidelines

Watersheds, also referred to as catchments or drainage basins, are defined as the land areas that drain water to a particular stream, river, or lake. The extent of the watershed is found by tracing a line along the highest elevations between two areas on a map, often a ridge.[24] Watersheds are complex systems that combine physical properties with dynamic processes. Some of the important physical properties include topography, geology, climate, and land cover. Some of the dynamic processes include rainfall, stream flow, evapotranspiration, groundwater interactions, and soil moisture regimes. Due to this complexity, there is no one categorization system used across disciplines.[25–30] Since the 1990s, there has been a rise in watershed planning initiatives that recognize that the majority of these systems are also social-ecological systems impacted by environmental planning, policy, and management practices. For GI installation placement for stormwater management purposes, our location decisions begin at the broad watershed level with considerations of climate, terrain, location within the watershed, and imperviousness.

Climate is important because it influences the volume, duration, and intensity of rainfall within the watershed. Green infrastructure installations must have capacity and flow characteristics to handle the runoff from regional precipitation events. Temperature can also influence green infrastructure decisions as is linked to species selection and vegetation growth. If a watershed has extreme temperatures, the plants of green infrastructure installations must be able to accommodate rapid growth or adapt to intense sunlight. If designed properly, the green infrastructure system can perform consistently in terms of water quality improvement and quantity reduction despite seasonal variations.

Terrain, also referred to as topography or slope of the land surface, is an important first consideration. Where the terrain is steeply sloping in hilly or mountainous areas the run-off will move more rapidly reducing infiltration and these steep slopes will generally have shallower layers of soil. These shallow soils also reduce water storage potential. Conversely, less sloping watersheds generally more infiltration due to slower run-off speeds and also have deeper layers of soil that also increase the absorption and storage potential. Installing GI systems in watersheds or sub-watersheds with significant terrain will be generally less successful than in less sloping watersheds or sub-basins. Most vegetation-based GI systems are designed to intercept sheet flow runoff. If there is a steep slope, the runoff volume and flow rate can overwhelm the system to the point of soil washout. In general, the slope for vegetation-based green infrastructure should not exceed 12% .[31] If it does, site grading is required to reduce the slope. With vegetative GI, flatter slopes allow for a longer retention time which then improves the effectiveness of different pollution control strategies

The site's location within the watershed or sub-watershed relative to the receiving waters is the third consideration. Marsh[30] notes that a small watershed or sub-watershed can be divided into three zones. These three main hydrological zones are the contributing zone, the collection zone, and the conveyance zone. The contributing zone is located farthest from the point of collection in the upper watershed. Land in the contributing zone (which is generally but not always the largest hydrologic zone) receives the most water and generates three types of run-off; overland flow, interflow (water that moves laterally in the soil and into the stream channels), and groundwater. In general, it is desirable to capture and retain stormwater in the contributing zone to prevent flooding lower in the watershed.[19–21] The collection zone is located between the contributing zone and the conveyance zone. In the collection zone, flooding problems are generally greater as groundwater saturation may occur and rainfall begins to pool as stormwater is collected and infiltrated. This middle collection area is generally a good location for small-scale stormwater management installations for both water quality and water quantity purposes.[20] Finally, the conveyance zone is the lowest section of the watershed. In this zone, stormwater is at its highest volume and poorest quality. Volume reduction using GI is difficult in the conveyance zone due to the rapid runoff flowrate and likelihood that the water table is close to the surface. Table 1 provides a guide for relating the best type of GI installation relative to the general characteristics of Marsh's hydrological zones.

Table 1. Guidelines for GI system selection based on location within the watershed or sub-watershed.
.●=very appropriate,.◍=moderately appropriate,.○=mildly or not appropriate.

	Location in Watershed[30,32]		
	Contributing Zone (Upper Watershed)	*Collecting Zone (Middle Watershed)*	*Conveyance Zone (Lower Watershed*
Retention basins	●	●	○
Rainwater Harvesting	●	●	○
Constructed Wetlands	◍	◍	●
Detention basins	●	●	○
Bioswales	○	●	◍
Rain Gardens	○	●	●
Green Roofs	●	●	◍
Permeable Pavement	●	●	●

Urbanization increases the area of impervious surface in a watershed, which significantly impacts stormwater runoff. Klein[33] found that when total area of impervious surfaces of a watersheds exceeded 12%, it negatively impacted the quality of the receiving waters. At 30% imperviousness, these environmental degradation effects were considered severe.[33] Equally as important as the percent of imperviousness in a watershed is the connectivity of the GI systems used to combat it. It is suggested that uncoordinated placement of GI systems in terms of stormwater retention time can cause the hydrographs to compile, actually contributing to larger downstream flows.[34] By considering these GI systems as just that – a connected system – rather than individual implementations, impacts in reduced runoff flow throughout the watershed can be seen.

3.2 Constructed Urban Water System Guidelines

The constructed urban water system, which for our purposes includes drinking water, wastewater, and stormwater systems, is the backbone of water access and management within cities in developed and emerging nations. When thinking about GI type and placement, we believe that it is important to know whether the urban system combines wastewater and stormwater collection or whether wastewater and stormwater systems are separated. Combined stormwater systems (CSS) are still in use today in America's older cities in the Northeast and Midwest. In CSS, both sewage and stormwater is transported to a wastewater treatment plant rather than being directly discharged. A major issue with CSS occurs during heavy precipitation events, where the flow can exceed capacity within the pipe network, resulting in combined sewer overflows (CSOs). When CSOs occur, untreated or partially treated human and industrial waste, toxic materials, debris, and stormwater directly discharges into the receiving waters. These CSOs cause pollution and can lead to public exposure and subsequent health hazards.[35] CSS pipe networks are also very expensive to maintain considering their age and size.

In more modern urban water infrastructure systems, separate sewer systems (SSS) transport raw sewage to treatment plants while the stormwater runoff is collected in separate pipes that are discharged untreated (or in some cases, minimally treated with an end-of-pipe bar screen) into the receiving waters. With SSS management, stormwater collection pipes discharge directly into receiving water bodies, and constituents within the stormwater can be toxic to aquatic life and degrade the environment. In comparing CSS and SSS, studies show that effluent water quality is slightly superior in CSS.[36–38] However, a SSS is typically more cost-effective compared to a CSS, considering the conveyance pipe maintenance and the sheer volume of wastewater being treated in a CSS versus an SSS.[36,39] Additionally, with increasing impervious surfaces and more intense storm events due to climate change, CSS are significant sources of water pollution due to system overloading and subsequent CSOs. Therefore, some cities with older CSS infrastructure have begun the expensive process of decoupling stormwater and sewer lines.

While expansive centralized urban water collection, treatment, and distribution systems are standard in the American constructed urban water system, smaller, decentralized water treatment systems and large grey storage tunnels or reservoirs are two possible alternatives. Decentralized systems manage drinking and wastewater treatment at the local level to service adjacent residents or businesses immediately. Particularly in developing countries without an old and established water conveyance system, decentralized water treatment and distribution allows the flexibility to address water access and sanitation as needed in a modular treatment network that can flex with the expanse or sparsity of a dynamic population.[13,40] However, the flexibility of small-scale systems is often associated with significantly stronger sensitivity to variable flows throughout the water system and subsequently less reliability.[41] GI can be a beneficial addition to decentralized water systems, acting as a pre-filtration step for drinking water treatment, polishing step for wastewater treatment, or comprehensive runoff treatment zone before reentering the watershed.

Different types of constructed urban water systems in place can stress the benefits of GI systems. For example, in drinking water systems, if the water originates from a surface source, GI can improve water quality by filtering runoff through a vegetative treatment barrier before it enters the surface water body. Improved surface water quality is an advantage for the receiving environment as well as the downstream communities that then use that surface water as a source of drinking water. In a groundwater-sourced drinking water, GI can offset the effects of overdrafting by recharging groundwater aquifers through infiltration. Wastewater systems, whether centralized or decentralized, can also benefit from GI. In centralized wastewater treatment that has a CSS network, GI can reduce the volume of stormwater entering the system that must then be treated at a wastewater treatment plant, thus reducing operation costs and, in some cases, improving environmental and public health by reducing CSO events.[35] In centralized wastewater treatment with separate sewer and storm systems, stormwater is in most cases directly discharged into the receiving water body without treatment. With GI, some of this runoff can be intercepted and treated before entering the environment, thus removing harmful contaminants that would have otherwise degraded water quality.[42–44] Finally, in a decentralized wastewater treatment system, GI installations can be used as a tertiary polishing step and vegetative buffer before treated wastewater effluent reenters the watershed.[13,45,46]

3.3 Site Level Guidelines

The final considerations for guiding GI using our stormwater framework occur at the site scale. At the site scale, we recommend considering on-site soil type and the adjacent land uses that contribute contaminants (slope must be considered to anticipate which adjacent areas are of concern) through the GI system. At the site level, soil composition influences drainage capabilities. Soils are composed of a blend of sand, silt, and clay. The particle size distribution of the soil determines soil characteristics such as packability and drainage capability.[47] Typically, for GI systems, it is important to have well-drained soils that are a loamy mix of sand and silt with less clay. This allows for stormwater infiltration and groundwater recharge rather than overland flows that contribute to urban flooding.[48,49] Accurate information on urban soil types can be difficult to obtain because of the amount of disturbance. Herrmann et al.[50] noted that urban soils may be functionally different due to their local management (mixing, removal, and replacement) and lack specific soil horizons. Therefore, we recommend taking soil samples and have them locally tested.

Stormwater runoff picks up contaminants from the land it flows over before eventually discharging in to the receiving water body. These contaminants are harmful to the environment and human health depending on the type and concentration.[51] We divide common contaminants found in runoff into seven categories: 1) pathogens, 2) natural organics, 3) synthetic organics, 4) nutrients, 5) heavy metals, 6) sediments, and 7) pharmaceutical and personal care products. Table 2 shows a brief description of each contaminant category as well as their sources.

Table 2. Detailing the source and description of the most common contaminants in stormwater runoff.

Contaminant	Description	Sources
Pathogens	Disease-causing microorganisms that cause public health concerns	Animal fecal matter, animal agriculture, wastewater effluent and sludge
Natural Organic Matter (NOM)	Organisms (plant and animal) and their associated waste cause decreased dissolved oxygen in receiving waters	Food waste, decaying plant and animal matter, animal fecal matter
Synthetic Organic Chemicals (SOCs)[52]	Fabricated chemicals for anthropogenic use that are usually toxic and are persistent in soil and water environments	Car byproducts (oil, fuel, exhaust), road wear, detergents, pesticides, fertilizers
Nutrients	Nitrogen and phosphorus. Used heavily in agriculture. Can cause eutrophication and stimulate harmful algal blooms	Fertilizer, manure, pet waste, soil erosion, wastewater effluent, leaf and lawn litter
Heavy Metals	Common due to widespread residential, industrial, and commercial use. Toxic to aquatic life.	Tire wear, metallic road structures, traffic signs, industrial byproducts
Sediments	Small solids disrupt aquatic life by reducing light penetration, filling in critical small-life habitat, and providing a mobile sorption surface for contaminants	Every type of land use, but major sources include soil erosion from construction sites and road debris
Pharmaceuticals and Personal Care Products (PPCPs)[53]	Products used to prevent/treat disease or improve quality of life; persistent in environment and potential threats to environmental and public health	Pharmaceuticals, antibiotic resistant genes, disinfectants, sunscreen

Understanding the adjacent upstream land uses and anticipating probable pollutants downstream helps planners, engineers, or decision-makers select the appropriate green infrastructure installation type.[54] Based on a review of existing literature, we identify the frequent contaminants associated with seven common urban land use types: residential, public institution, transportation, industrial, urban agriculture, open space, and commercial. Contaminants for open space land uses may be a source for nutrient contamination through lawn maintenance as well as animal waste (pathogens) and plant debris that can clog both green and grey infrastructure installments.[55,56] For commercial land uses like offices, shops, and restaurants, the main source of pollution is from vehicles used to transport consumers and workers to these areas as well as landscaping on site and the people frequenting these locations.[57,58] The waste from commercial dry cleaners and other similar establishments are disposed of as industrial waste, but residual surfactants may end up in the environment. Automotive commercial facilities do not have separate waste disposal, so outdoor car washing does introduce heavy metals and complex organics to the environment.

Residential, public institution, transportation, industrial, and agricultural land uses are of greatest concern for runoff pollutants. In residential areas, while contaminants are diverse, the primary contaminants of concern are synthetic organics from oils and machinery (vehicles, lawn mowers, etc.), household cleaners like bleach or non-biodegradable surfactants, lawn fertilizers (nutrients), and natural organics and pathogens from yard, animal, and human waste.[55,57–59] The primary contaminants of concern for public institutions such as government properties, religious institutions, schools, hospitals, and wastewater treatment plants (WWTPs) are nutrients from lawn maintenance and wastewater treatment as well as any pathogens from the dense concentration of people and the wastewater they produce.[55,60–63] Transportation land uses include highways, roads, and sidewalks. The most detrimental contaminants related to transportation land uses are hazardous synthetic organics like polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) derived from car byproducts (oil, fuel, exhaust, road wear, tire wear), heavy metals, and sedimentation from litter, and other debris.[58,64,65] For industrial land uses, pollutants can be extreme and varied based on the specific industry. The types of pollutants from industrial land uses range from natural organics from food production, to synthetic organics and heavy metals from car manufacturing, or other diverse but damaging industrial pollutants. Agricultural land uses include the land to grow and produce crops and raise animals. These crops may be supplemented with fertilizer and manure, thus making nutrient runoff a concern due to the likelihood of stimulating eutrophication in receiving water bodies.[66–68]

Tables 3, 4, and 5 summarize the type of GI most effective for different contaminants, the likely type of contaminant by land use, and the relative desirability of different green infrastructure types for different adjacent land use types. These tables do not offer an invariable solution; rather, they are a compilation of literature that offer an informed hypothesis and subsequent rated guideline to follow when considering GI and its placement in an urban network for stormwater purposes. In the next section, we illustrate our sequence of decisions at different scales in two locations and then quantify the impact of our GI framework on stormwater peak flow reduction and volume reduction quantity by comparing pre and post- flow hydrographs generated by U.S. EPA's SWMM software.

Table 3. Identifying the contaminants that each green infrastructure implementation can best target based on the effective removal mechanisms of each contaminant and the major active removal mechanisms within each green infrastructure system.. ●=very effective in terms of stormwater runoff water quality improvement, ◍=moderately effective, ○=mildly or not effective.

	Quality						
	Pathogens	Natural Organics	Synthetic Organics	Nutrients	Heavy Metals	Sediment	PPCPs
Main Removal Mechanisms	*Filtration, sedimentation, storage (removal, not inactivation)* (69,70)	*Filtration, sorption, bioaccumulation* (69)	*Sorption, redox* (69,71)	*Sorption, redox, bioaccumulation* (69)	*Filtration, sorption, redox, bioaccumulation* (69)	*Sedimentation* (69)	*Filtration, bioaccumulation* (69,72)
Retention Basin (73)	◍ Retention, infiltration	● Vegetation, retention, infiltration	● Vegetation, retention	◍ Sparse vegetation	◍ Sparse vegetation, retention	◍ Settling	◍ Sparse vegetation, infiltration
Rainwater Harvesting (74)	○ Retention	○ Retention	○ -	○ -	○ Retention	◍ Settling	○ -
Constructed Wetland (75)	◍ Retention, infiltration	● Vegetation, retention, infiltration	● Vegetation, retention	● Heavy vegetation	● Heavy vegetation, retention, infiltration	● Settling and catchment	◍ Heavy vegetation, infiltration
Detention Basin (73)	◍ Retention, infiltration	● Vegetation, retention, infiltration	● Vegetation, retention	◍ Sparse vegetation	◍ Sparse vegetation, retention, infiltration	◍ Settling	◍ Sparse vegetation, infiltration
Bioswale (76,77)	○ Infiltration	◍ Vegetation, infiltration	◍ Vegetation	◍ Sparse vegetation	○ Sparse vegetation, infiltration	◍ Settling	◍ Sparse vegetation, infiltration
Rain Garden (78)	○ Infiltration	◍ Vegetation, infiltration	◍ Vegetation	● Heavy vegetation	◍ Heavy vegetation, infiltration	● Settling and catchment	◍ Heavy vegetation, infiltration
Green Roof (79)	○ Infiltration	◍ Vegetation, infiltration	◍ Vegetation	● Heavy vegetation	◍ Heavy vegetation, infiltration	● Settling and catchment	◍ Heavy vegetation, infiltration
Permeable Pavement (80)	○ Retention	◍ Retention, infiltration	○ -	○ -	○ Retention, infiltration	● Settling and catchment	○ Infiltration

Table 4. Identifying the major sources of each individual contaminant class from each land use and raking the comparing severity of each contribution, where ●=high contribution of an individual contaminant class from an individual land use type, ◍=moderate contribution, ○=mild contribution.

	Residential Land Use	**Transportation Land Use**	**Public Land Use**	**Industrial Land Use**	**Urban Agriculture Land Use**	**Open Space Land Use**	**Commercial Land Use**
Pathogens	● Domestic animal and human fecal matter, septic systems (81–84)	○ Road-killed animals (85)	● Fecal matter, WWTPs, hospitals (56,59,61,81,84,86)	-	● Animal fecal matter, land-applied biosolids (81,87)	◍ Animal fecal matter (81,87)	◍ Dense population of people (56,81,87)
Natural Organics	● Food waste from composting, municipal solid waste, yard waste, animal fecal matter (55,82,83,88–90)	○ Road-killed animals, greenery maintenance (55,91)	◍ Decaying greenery, food waste, municipal solid waste (55,88,92)	○ Food production, greenery maintenance (93)	● Decaying greenery and animal matter, animal fecal matter (90,94)	◍ Decaying greenery and Animal matter, animal fecal matter (55)	◍ Decaying greenery, food waste, municipal solid waste (89)
Synthetic Organics	◍ Detergents, lawn fertilizer, car byproducts (95–97)	● Car byproducts, fertilizer, de-icers and salts (91,96,97)	◍ Car byproducts, fertilizer (96,97)	● High synthetic material usage and production (96,97)	◍ Farm equipment maintenance and byproducts, fertilizer/pesticides (96,97)	○ Pesticides/fertilizers (98)	◍ Car byproducts, fertilizer (96,97)
Nutrients	● Fertilizer, domestic animal fecal matter, yard waste, soil erosion, septic systems (55,82,88,90,99–102)	○ Fertilizer (91,101,103)	● Fertilizer, soil erosion, WWTPS (92,99,101,102)	○ Fertilizer (101,102)	● Fertilizer, manure, animal fecal matter, soil erosion (90,94,99,101,102)	◍ Animal fecal matter, fertilizer (55,90,99,101,102)	○ Fertilizer (101,102)
Heavy Metals	◍ Municipal solid waste, car byproducts, roof corrosion (64,82,96,100,104)	● Car byproducts, metallic road structures, traffic signs (64,91,96,104)	◍ Car byproducts, WWTPS (64,100,104,105)	● Metal processing, metal production, metal working fluids (106)	◍ Farm equipment maintenance and byproducts, land-applied biosolids, fertilizer (105,107)	-	◍ Municipal solid waste, car byproducts (64,104)
Sediment	◍ Soil erosion, yard work, construction (102)	● Road debris, soil erosion, car byproducts, construction (91,108)	◍ Soil erosion and debris, WWTPS, construction (92,102)	◍ Soil erosion, industrial process byproducts, construction (106)	◍ Soil erosion, construction (68,102)	◍ Soil erosion (102)	● Soil erosion and debris, construction (102)
PPCPs	● Pharmaceuticals in municipal solid waste, disinfectants, sunscreen (109)	-	● WWTPS, hospitals (59,86,109)	◍ PPCP production companies (109)	● Pharmaceuticals, ARGs, antibiotics for animals (66,109)	○ Sunscreen (109)	◍ Pharmaceuticals in municipal solid waste, disinfectants (109)

*Table 5. Combining Table 3 and Table 4 results to pair common land uses with suitable green infrastructure installations based on contaminant load, where ** is an excellent match and * is a good match (See Appendix 2)*

	Residential Land Use	Transportation Land Use	Public Institution Land Use	Industrial Land Use	Urban Agriculture Land Use	Open Space Land Use	Commercial Land Use
Retention Basins	**	*	*	*	**	*	**
Rainwater Harvesting		*	*	*		**	*
Constructed Wetlands	*	*	*	*	*	*	*
Detention Basins	**	*	*	*	**	*	**
Bioswales	*	*	*	*	*	**	**
Rain Gardens	*	*	**	*	*	*	**
Green Roofs	*	*	**	*	*	*	**
Permeable Pavement		*	*	*		**	**

4. Case Study Applications

4.1 Case Study: Detroit, Michigan

Detroit, Michigan is considered a Rust-Belt legacy city in the American Midwest. In 2010, 711,299 people lived in the city – a notable decline from its peak population of 1.8 million in the 1950s. Today approximately 40 square miles (103 square kilometers) of the city's 139 square miles (360 km^2) is vacant due to population decline and industrial exodus. This vacant land gives Detroit a unique opportunity for large-scale GI installations.[5] Relative to other major cities in the U.S., Detroit is a low-resource city given its low tax base and lack of employment opportunities. While the Detroit Metropolitan Area's mean household income in 2013 was $50,000, the mean household income in Detroit was considerably less at $25,000 in 2011.

Within Detroit there are three major watersheds: Rouge River Watershed, Clinton River Watershed, and Lake St. Clair Watershed. For this study, we selected a site within the Lake St. Clair Watershed (Figure 1). Detroit sits in the lower watershed, where stormwater runoff collects before discharging into the Detroit River. Lake St. Clair is at the head of the Detroit river and Lake Erie is at the mouth. Therefore, Detroit's stormwater runoff eventually flows into Lake Erie – the most polluted of the Great Lakes. Lake Erie has experienced issues with harmful algal blooms as well as extreme eutrophication. The topography in this watershed, consistent with Detroit as a whole, is relatively flat with a slope ranging from 0 to 2%. The lack of slope makes GI design easier, because the runoff flowrate will not increase due to land patterns, making GI failure less likely.

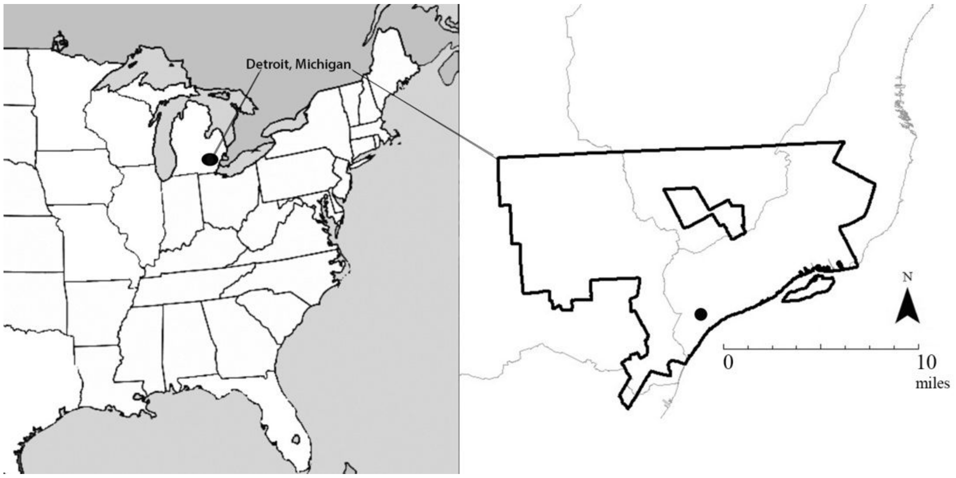


Figure 1. Three watersheds are within the boundaries of Detroit, Michigan. The Holy Redeemer site is indicated with a black square and is within the Lake St. Clair Watershed.

Located in a temperate climate zone, the average annual rainfall in Detroit is 33 inches with 113 days per year of precipitation. Precipitation is dispersed relatively evenly throughout the year as rainfall and snowfall, with heavier precipitation seasons in spring and winter. Because this land is in the river floodplain, the majority of the soil is relatively poorly drained clay and silt, which is a consideration for plant-based green infrastructure. Climate in this watershed follows a four-season pattern, with warm temperatures up to 83°F (28°C) on average and cold temperatures down to 31°F (-0.55°C) on average. This means that vegetated GI installations must be robust enough to withstand extreme temperatures.

The city of Detroit's water and sewerage services are provided by Great Lakes Water Authority (GLWA)/Detroit Water and Sewerage Department (DWSD). GLWA manages regional water and wastewater services, while DWSD retains control of water and sewer services within the city limits. In terms of drinking water, the network contains five drinking water treatment plants servicing eight different counties, totaling approximately four million people serviced with 600 million gallons of water per day (2,300,000 cubic meters per day).[110] Drinking water treatment begins with surface source water from either the Detroit River or Lake Huron.[111] The current issues with the drinking water system within Detroit are related to deteriorating infrastructure; the drinking water distribution network is leaking, or in some cases, valves are left open when buildings are deconstructed but not disconnected from the network (leaks can sometimes go unreported for months).[112]

The Detroit Wastewater Treatment Plant is the second largest wastewater treatment plant in the world.[113] With the combined sewer network feeding to this system, the designed primary treatment capacity of the plant is 1.7 billion gallons per day and the designed secondary treatment is 930 million gallons per day. The average daily treatment of the plant on a non-rainy day is 650 million gallons per day (2,500,000 m^3/day). This plant services 35% of the total population in the state of Michigan, with a service area spanning approximately 950 square miles (2,460 square kilometers). The stormwater management in Detroit is a CSS. On a day without precipitation or snow melt, all waste and runoff is directed to the wastewater treatment plant where it undergoes secondary treatment and disinfection before being discharged into the Detroit River. When precipitation or snow melt events occur, the volume sometimes exceeds the wastewater plant's treatment capacity, leading to approximately 50 combined sewer overflow (CSO) events annually where raw sewage and stormwater runoff are directly discharged into the Detroit River.[114] In extreme precipitation situations, wastewater and stormwater can contaminate residential basements in low lying areas.[114] This is not only inconvenient for the home owners, but poses a severe public health concern.

Our specific site is the Holy Redeemer Church and School property located in Southwest Detroit. This site is primarily (88%) impervious, which increases the runoff volume as well as the pollutant load on site. The site contains a church and school as well as associated buildings to support daily public services. The on-site land cover is approximately as follows: 39% buildings, 38% parking, 4% green space, and 19% roads or sidewalks. Commercial land use dominates adjacent land use to the northwest of the site, while residential land use dominates the southeast side. The residential land use will contribute nutrients from lawn fertilization, pathogens from household pets, as well as organics and sediments to a lesser degree. Homeowners sometimes dispose of car byproducts in their yard inappropriately, such as when changing car oil, which contributes damaging contaminants to the watershed as well. With commercial land use, the contaminants of concern are mainly heavy metals from the heavily trafficked parking lots as well as sediments from general debris. Synthetic organics from car byproducts and nutrients from landscaping may also contribute to runoff contaminant load from commercial land use. The surrounding transportation land use will also contribute heavy metals and synthetic organics from car byproducts.

The primary concern in this location is the overwhelming percentage of impervious surface area and the need to accommodate significant areas of parking. To address this, we propose a large permeable pavement installment covering the secondary parking lot of the site to reduce peak flow. This area gets less traffic than the main parking lot, which should extend the lifetime of the permeable pavement and make its maintenance easier. We also propose a rain garden to provide an attractive green space that will address contaminant loads through biotreatment and infiltration. In SWMM we modeled the implementation of a 4,530 square foot (ft^2) (420 square meter, m^2) rain garden and a 33,000 ft^2 (3065 m^2) area of permeable pavement. The site as well as suggested GI installations are shown in Figure 2.

Figure 2. Holy Redeemer Church Site, Detroit, Michigan. This site includes a rain garden and a large area of permeable pavement for secondary parking.

Using the U.S. EPA's SWMM model[115], we estimated how adding the rain garden and pervious pavement would decrease stormwater runoff (Figure 3). The simulated storm event was modeled after the heaviest six-hour precipitation period in Detroit in 2016, which occurred on March 24th. The precipitation data in 5-minute increments was provided by a weather station in Recovery Park, Detroit through the United States Geological Survey.[116] The total stormwater runoff volume for the simulated storm event was reduced from 0.49 cubic feet (ft^3) to 0.14 ft^3 (0.014 m^3 to 0.004 m^3), a 70% reduction, by implementing both the designed rain garden and the permeable pavement. What this SWMM model does not consider, however, is that the runoff will be partially treated through the rain garden as well, thus reducing pollutant load at the end of the watershed. The church is considering this design for green infrastructure as newly proposed stormwater utility fees would significantly burden the institution's financial well-being.

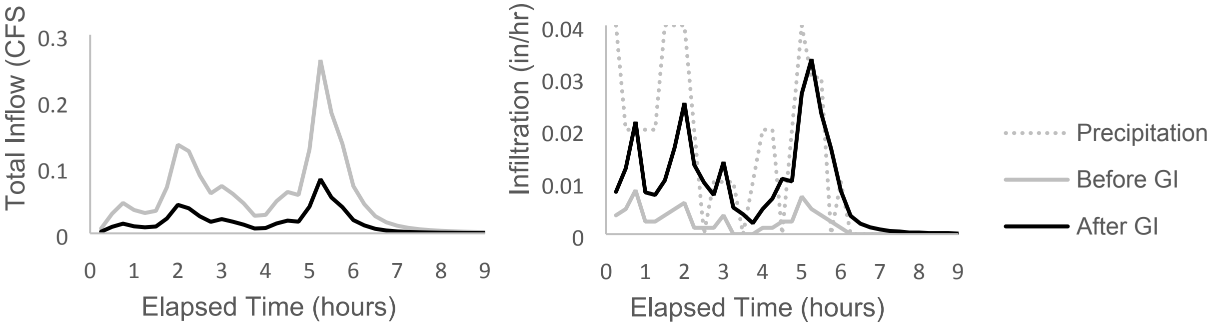


Figure 3. Hydrograph (left) and infiltration (right) of the Most Holy Redeemer Church site before and after implementing a rain garden and permeable pavement. Achieved volume reduction of 0.49 ft^3 to 0.14ft^3. Simulation in SWMM used Detroit's heaviest 6-hour precipitation period of 2016.

Residents of Detroit are charged a drainage fee to help support the cost of sewage infrastructure such as pipe networks and combined sewer overflow facilities. In 2017, the Detroit Water and Sewerage Department implemented an updated stormwater drainage fee for its residents. Previously, most properties were charged a flat drainage fee of $20.63. Now, the stormwater drainage fee is based on the amount of impervious surface area on the property. This caused an extreme increase in stormwater fees for some residents and business owners with previously established impervious infrastructure such as roofs, driveways, and parking lots. However, there is opportunity to reduce this fee. Residents receive an automatic 25% Green Credit on their bill if they redirect their downspouts to run onto their lawn instead of directly into the sewer, allowing for natural infiltration. Residents can also earn Green Credit through incorporating GI on their property to reduce the impervious surface area. There is therefore strong motivation to implement GI on Detroit properties. Installing GI is often more economical than paying a stormwater drainage fee, especially for larger properties like the Most Holy Redeemer Church site.

4.2 Case Study: Addis Ababa, Ethiopia

Addis Ababa, Ethiopia, a city in East Africa, is experiencing rapid growth. According to the Federal Democratic Republic of Ethiopia Central Statistical Agency (2014), the population of Addis Ababa in 2013 was 3.2 million people and growing. The total area of the city is 209 mi^2 (540 km^2) with mixed land uses including informal/unplanned settlements. On a global scale, this country is considered a "less-developing country" because the average income per person is less than $2 per day (GDP is $505) [117].

Addis Ababa contains two watersheds: Little Akaki and the Big Akaki (Figure 4). Our site is in the Little Akaki Watershed, an area that covers approximately one third of Addis Ababa's total land area. Industrial, commercial, and residential land uses contribute pollutants such as heavy metals, carcinogenic tanning effluents, agricultural waste and byproducts like antibiotics and pathogens, and other wastes to the Little Akaki [118]. The river and its contributing runoff proves to be a health risk to the residents of Addis Ababa who depend on it for agricultural irrigation, washing, and other vital activities. Therefore, it is important to infiltrate and treat as much stormwater runoff as possible before it enters the watershed's hydraulic network.

Figure 4. There are two main watersheds in Addis Ababa, Ethiopia. The Little Akaki is highlighted in grey and the Biruh Tesfa Condominium site is indicated with a black square.

The climate of Addis Ababa is relatively temperate due to its high elevation, with a mean annual rainfall of about 42.7 in (1200 mm).[119] Fifty percent of the annual rainfall occurs during two months of the year (July and August). This rainy season leads to flashy and flood-prone areas in a city with rapidly increasing areas of impervious surface. The city's topography amplifies flooding within the city network, as Addis Ababa contains very steep slopes due to its location on a mountain. There is a change in elevation from 9800 ft (3000 m) in the north to 6900 ft (2100 m) in the southern extent of the city. This leads to faster flows at higher volumes, which regularly disrupts vehicular travel along the city streets during the rainy season.[120] The soils are a product of this seasonality, falling into two major types: vertisols and nitisols. While both soils are used for low-density vegetation and crop growth, vertisols have a high clay content and are not well drained while nitisols are well-drained.[121]

With regards to water access and sanitation, the system is stressed due to the population surge, socio-economic transformations, climate change, and low system management and maintenance. Drinking water comes from both groundwater and surface water. The groundwater is pumped from different wells located within and outside the city limits. The groundwater is directly stored, treated with chlorine, and pumped in to the city. The surface water comes from three dams in the east and northwest of the city that feed into two drinking water distribution plants. While the majority of residents have access to treated drinking water, approximately 19% of the population does not. Of the distributed drinking water, an estimated 37% is lost to system leaks or illicit access.[122]

In terms of sanitation, the majority of the population has access to either the piped sewer collection system (7%) or vacuum trucks for pit latrines (80%).[122] In addition to several scattered decentralized treatment sites, two larger centralized wastewater treatment facilities service the city: Kality and Kotebe. The Kality Wastewater Treatment Plant (design capacity 7,600 m^3 per day) is over capacity, treating 10,000 m^3 per day of sewer line waste and vacuum truck waste using screening and stabilization ponds as treatment before discharging in to the river. Kotebe Wastewater Stabilization Pond (design capacity 2,000 m^3 per day) is also operating beyond design capacity to treat vacuum truck waste. There are also several decentralized wastewater treatment plants that primarily serve condominiums and usually consist of a series of stabilization ponds, or in some cases, more advanced treatment processes.

Because the city is rapidly growing, it is difficult to track industries and the effluents they discharge. Lack of stricter water quality regulations and the associated enforcement of those regulations allows for undertreated wastewater effluents to enter the environment and effect public health and quality of life throughout the city.[123] This includes runoff from industries such as dyeing and tanneries with synthetic organics, heavy metals, and carcinogens, as well as urban agriculture with increased nutrient loading in the runoff. Urban farming is also practiced, which can introduce nutrients as well as pathogens to the stormwater runoff.

Stormwater management is limited and generally confined to underground concrete pipes buried along both primary arterial streets and local streets as well as roadside ditches [120]. Most stormwater is directly discharged into local streams and rivers along with untreated wastewater and solid waste. When it rains in Addis Ababa, due to the increasing impervious surface area, runoff floods the streets and eventually turns them to rivers of contaminated stormwater runoff. To ensure the viability of the city and the safety of the population, it is important to reduce runoff quantity and improve runoff quality whenever possible.

Our site is called “Biruh Tesfa Condominium Residents Association” and is located in the Jemo Condominium area. The site lies in the middle of the watershed (Figure 4). This location is convenient for implementing GI solutions. The site itself is approximately 53% impervious. To characterize the site, the land cover breaks down approximately as follows: 25% buildings, 8% parking, 37% green space, and 30% partially permeable roads. This series of 11 condominium blocks contains 316 household units mostly occupied by low income working families, totaling an average population of approximately 1580 residents. These units are equipped with running water and flush toilets, but the water supply is sporadic, especially in the dry season. As such, many inhabitants are turning to grey water as a supplemental water supply used to clean and flush toilets [124]. Adjacent land uses include urban agriculture to the north, commercial to the south, and residential to the northeast. The runoff from this site is discharged into the closely located Jemo River, as shown in Figure 5. Due to the diverse adjacent land uses, contaminants contributing to this site runoff are varied. Urban agriculture can contribute pesticides, nutrients, and pathogens depending on fertilizer use or if farms include animals. The residential land uses contribute surfactants from outdoor laundry as well as sediment and debris. The commercial land use and transportation land use, although dependent on the commerce, contribute priority contaminants such as heavy metals and synthetic organics that can pose a risk to human health.

The primary stormwater concern in this location is the site's proximity to the Jemo River and reducing the quantity of pollution that enters the river. After conversations with local residents and government officials, we propose a detention basin on the southern portion of the area to reduce peak stormwater flow and encourage slow infiltration-based runoff treatment. When there is no precipitation, the basin will not hold standing water (which would otherwise be a safety concern for the children playing around the lot and could serve as an insect hub). In the parking lots, we propose permeable pavement to reduce the runoff volume and reduce potential for standing water on site. Finally, a rain garden is proposed for the large green space on the northwest side of the site. The rain garden can treat runoff before it enters the river, thus reducing overall pollutant loads. The site as well as recommended GI installations is illustrated in Figure 5.

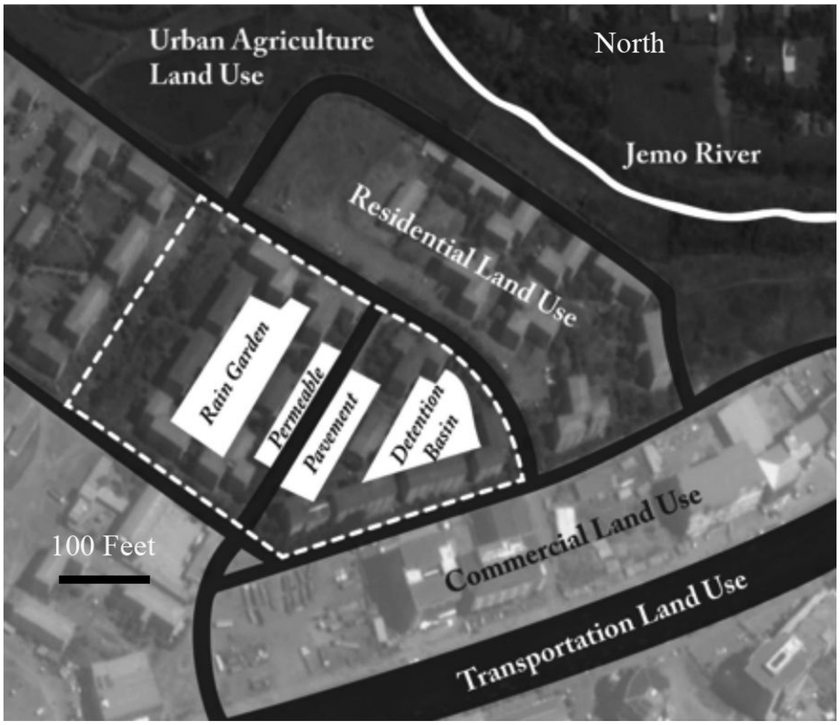


Figure 5. Biruh Tesfa Condominium Site, Addis Ababa, Ethiopia. This residential site includes a rain garden, retention area, and permeable pavement parking area.

A storm event was modeled in EPA SWMM (Figure 6) using a theoretical storm based on the heaviest monthly precipitation total from the Ethiopian Metrology Agency, which occurred in August 2012, as precipitation data for individual storm events is not yet reported. By implementing the detention basin, permeable pavement, and rain garden, the total runoff volume from the simulated storm event was reduced from 2.2 ft^3 to 0.84 ft^3 (0.062 m^3 to 0.024 m^3). This is a runoff volume reduction of approximately 63%. From the flash floods produced during the intense rainy season in this region, any reduction in peak flow is a success for the city. The SWMM model hydrograph validates that the proposed implementations will indeed reduce runoff on site, making this a safer and more enjoyable place to live for the residents.

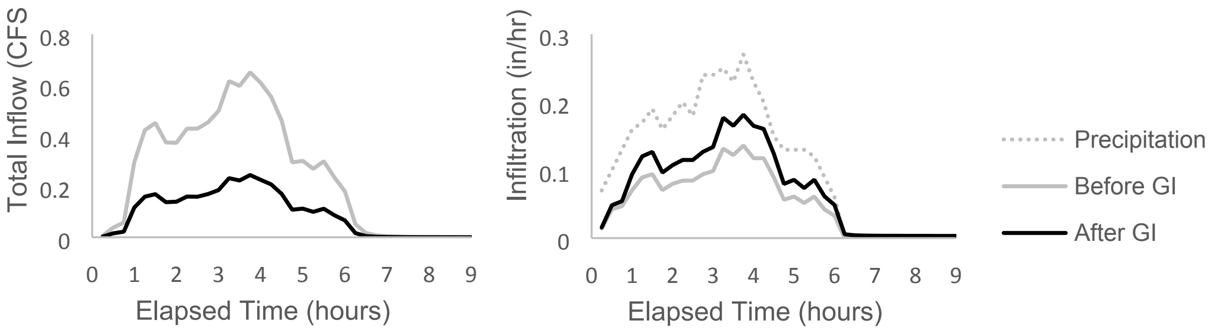


Figure 6. Hydrograph (left) and infiltration (right) of the Biruh Tesfa condominium site before and after implementing a rain garden, detention basin, and permeable pavement. Achieved a volume reduction of 2.2 ft^3 *to 0.84* ft^3*. Simulation in SWMM based on a theoretical storm from Addis Ababa's heaviest monthly precipitation total in 2016.*

The cost of GI in Addis Ababa is currently hindering more rapid implementation. Because the city does not regulate water quality strictly[123], there is little motivation to use GI for water quality improvement or it many other public benefits. However, water management officials in Addis Ababa acknowledge there would be associated cost savings such as reducing damage to public infrastructure (roads) due to stormwater. University scholars and researchers are urging the city to consider GI as a low-cost addition to the urban water management system that can slow flows and provide a contaminant buffer before entering the receiving rivers. Some research-associated GI systems are currently being implemented and monitored, with results intended to strengthen the argument for incorporating further GI throughout the city.[125]

5. Discussion

By identifying sites within Detroit, Michigan and Addis Ababa, Ethiopia, we can compare how our guidelines for selecting the type and location of GI installations consider watershed, urban water system, and site characteristics in addition to the city's natural conditions and existing built environment for stormwater management. In Detroit, the relatively flat site location in the lower watershed, as well as frequent CSO events, led us to prioritize water quantity over water quality concerns with a large permeable pavement installation. Because the site sits close to the Detroit River and thus Lake Erie, water quality was addressed to a lesser extent using a rain garden on site to provide preliminary runoff treatment before exiting the watershed into the Great Lakes network. Due to the gentle slope of the watershed, vegetation-based GI is likely to receive moderate runoff from the flat surrounding landscape, so GI failure is less of a concern.

In Addis Ababa, the watershed is steeply sloped. This makes the failure of GI systems a greater concern. However, our site in the central area of the Little Akaki watershed has a moderate slope. Water quantity and quality were equally considered for this middle-watershed site using a rain garden, a detention basin, and permeable pavement. In Addis Ababa, precipitation is concentrated. This city experiences two rainy seasons a year: the first lighter rains occur from February to May, while the second rainy season lasts from June to September and is when the city receives the majority of its annual precipitation.

In terms of GI, both Detroit and Addis will need to maintain their systems seasonally based on the amount of precipitation received as well as the flowrate of rainfall, because a more intense rain event will stress the GI systems. Maintenance of GI systems is critical for their continued performance. Some forms of maintenance, such as identifying and removing invasive plants, require trained individuals while other forms of maintenance, such as cleaning pervious pavement to retain its porosity, require special equipment. In our work with local decision-makers and residents in the two locations, maintenance has been a key discussion point. University faculty and students familiar with GI operations and native plant identification will conduct training sessions for volunteers. With the increasing popularity of GI in Detroit, the City has purchased special street cleaners. However, as these GI systems have yet to be installed, the maintenance regimes have not been finalized.

From an urban water system perspective, Detroit is experiencing the challenges of an oversized urban water network, where addressing general maintenance in addition to the problems of a CSS require significant financial investment yet local funds are limited. GI can help mitigate the stress on the current CSS and reduce CSO events. In Addis Ababa, the situation is opposite in several ways; the growing population does not have sufficient infrastructure or water supply to support all its residents. This leads to some residents going without access to proper drinking water sources or sanitation. Incorporating stormwater management in the urban water system specifically with GI can help create a safer environment. On-site in Addis Ababa, we considered both water quantity and water quality management. This decision was made in response to the residents' concerns about standing water affecting health and ability to play outdoors (quantity), as well as the site's proximity to the Jemo River (quality). The lack of a stormwater system means that all runoff passing over the ground directly conveys contaminants into the streams and rivers. Fortunately, many types of GI offer both water quality and quantity management, and these decentralized installations were beneficial for both the sites in Detroit and Addis Ababa.

The two specific case study sites have key differences. The Detroit site is 88% impervious and the proposed GI installations will serve as the only infiltration opportunity on site. Detroit's Holy Redeemer Church site is primarily a "public institution" and must maintain a significant area of parking. The contaminants stem from the heavy traffic within and along the site's boundaries with some potential contaminants from the adjacent commercial and residential areas. Therefore, we propose adding two types of GI: an area of permeable pavement in the secondary/overflow parking area and a rain garden near a main entrance. Based on our stormwater modeling, these proposed changes will reduce runoff volume from $0.49 ft^3$ to $0.14 ft^3$, reducing the total volume by 70% during the simulated storm event.

The Addis Ababa site, as a multifamily residential area, is 53% impervious. In this situation, we must balance our GI selections with residents' desire for safe year-round outdoor play for their children. Household waste and laundry surfactants are the main contaminants of concern on site, with adjacent land uses contributing nutrients form agriculture and heavy metals/synthetic organics from commercial and transportation effluents. Therefore, we propose adding a rain garden for water quality improvements, a detention area to reduce peak flow and allow for slow infiltration-based treatment of runoff, and pervious parking to reduce the runoff quantity on-site and keep the existing play areas free of standing water. Based on our stormwater modeling, these proposed changes will reduce runoff volume from $2.2 ft^3$ to $0.84 ft^3$, reducing the total volume by 65% during the simulated storm event.

6. Conclusion

We applied our guidelines to specific sites in two different urban locations and modeled the relative effectiveness of our proposed green infrastructure types on peak flow reduction and volume reduction. In creating our case studies, we summarized the watershed and water system characteristics of Detroit, Michigan, and Addis Ababa, Ethiopia. Detroit, Michigan, is a city with a significant amount open space due to population loss. With increasing precipitation intensity, Detroit's aging combined sewer/stormwater system is frequently overwhelmed, releasing untreated or partially treated wastewater into the adjacent Detroit and Rouge Rivers and Lake Erie. We selected a site at the bottom of this watershed that is particularly affected by intense storm events due to its large amount of impervious surface area, thus contributing to peak flow and exacerbating runoff volume issues. The proposed GI systems provides users with green space to enjoy as well as significant reductions in runoff quantity. GI in Detroit, Michigan, provides an opportunity to reduce stormwater runoff, rethink the use of vacant land for multiple GI benefits, and reduce Great Lakes' water pollution.

Addis Ababa, Ethiopia, on the other hand, is experiencing population growth at a rate that is not matched by water infrastructure growth. It currently lacks sufficient wastewater and stormwater systems to manage seasonal rains, contributing inconvenient flooding and high-contaminant runoff loads to the city's rivers. The site we selected, in the middle of the watershed with a moderate slope, uses GI to consider specific needs of the residents on-site as well as protecting the surrounding environment. By using these two case studies, we were able to balance these GI guidelines with three levels of contextual considerations for storwmater management and residents' desires.

Many communities are excited by the potential of using GI to supplement overwhelmed or absent stormwater management systems. In this guide, we summarized existing literature about how GI systems differ in their effectiveness to manage water quality and/or reduce water pollution and highlighted the array of important contextual variables at different scales.

7. Conflicts of Interest

There are no conflicts to declare.

8. Acknowledgements

We would like to thank Dr. Dagnachew Adugna, of the Ethiopian Institute of Architecture, Building Construction, and City Development at Addis Ababa University (EiABC), for providing us with data and a deeper understanding of the Jemo Condominium site. Sarah Clark, Director of Programs at Southwest Detroit Environmental Vision, conveyed the current status and concerns of Detroit, the Southwest Detroit neighborhood, and the Holy Redeemer Church site. McFarland was supported by a Graduate Research Fellowship from the U.S. National Science Foundation and a Doctoral Fellowship from the Dow Sustainability Fellows Program.

9. References

1 N. Kabisch, H. Korn, J. Stadler and A. Bonn, *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice*, Springer International Publishing, 2017.

2 S. Keesstra, J. Nunes, A. Novara, D. Finger, D. Avelar, Z. Kalantari and A. Cerdà, Science of the Total Environment The superior effect of nature based solutions in land management for enhancing ecosystem services, *Sci. Total Environ.*, 2018, **610–611**, 997–1009.

3 J. Chen, C. K. Van Den Bosch and T. B. Randrup, Nature-based solutions for resilient landscapes and cities, *Environ.* Research, 2018, **165**, 431–441.

4 Y. Xing, P. Jones and I. Donnison, Characterisation of Nature-Based Solutions for the Built Environment, *Sustainability MDPI*, 2017, 1–21.

5 S. Meerow and J. P. Newell, Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit, *Landsc. Urban Plan.*, 2017, **159**, 62–75.

6 M. Kuo, How might contact with nature promote human health? Promising mechanisms and a possible central pathway, *Front. Psychol.*, 2015, **6**, 1093.

7 G. Lindsey, L. Roberts and W. Page, Inspection and Maintenance of Infiltration Facilities, *J. Soil Water Conserv.*, 1986, **47**, 481–486.

8 J. a Foley, R. Defries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, M. T. Coe, G. C. Daily, H. K. Gibbs, J. H. Helkowski, T. Holloway, E. a Howard, C. J. Kucharik, C. Monfreda, J. a Patz, I. C. Prentice, N. Ramankutty and P. K. Snyder, Global consequences of land use, *Science*, 2005, **309**, 570–4.

9 M. J. Paul and J. L. Meyer, Streams in the Urban Landscape, *Annu. Rev. Ecol. Syst.*, 2001, **32**, 333–365.

10 A. Goonetilleke, E. Thomas, S. Ginn and D. Gilbert, Understanding the role of land use in urban stormwater quality management, *J. Environ. Manage.*, 2005, **74**, 31–42.

11 R. Wang, M. J. Eckelman and J. B. Zimmerman, Consequential environmental and economic life cycle assessment of green and gray stormwater infrastructures for combined sewer systems, *Environ. Sci. Technol.*, 2013, **47**, 11189–11198.

12 C. Kennedy, J. Cuddihy and J. Engel-Yan, The Changing Metabolism of Cities, *J. Ind. Ecol.*, 2007, **11**, 43–59.

13 M. A. Massoud, A. Tarhini and J. A. Nasr, Decentralized approaches to wastewater treatment and management: Applicability in developing countries, *J. Environ. Manage.*, 2009, **90**, 652–659.

14 G. Quezada, A. Walton and A. Sharma, Risks and tensions in water industry innovation: Understanding adoption of decentralised water systems from a socio-technical transitions perspective, *J. Clean. Prod.*, 2016, **113**, 263–273.

15 T. A. Larsen, K. M. Udert and J. Lienert, *Source Separation and Decentralization for Wastewater Management*, IWA Publishing, 2013.

16 N. K. Singh, A. A. Kazmi and M. Starkl, A review on full-scale decentralized wastewater treatment systems: Techno-economical approach, *Water Sci. Technol.*, 2015, **71**, 468–478.

17 L. Ma, J. Guo, G. L. Velthof, Y. Li, Q. Chen, W. Ma, O. Oenema and F. Zhang, Impacts of urban expansion on nitrogen and phosphorus flows in the food system of Beijing from 1978 to 2008, *Glob. Environ. Chang.*, 2014, **28**, 192–204.

18 United States Environmental Protection Agency, www.epa.gov, What is Green Infrastructure? 2016

19 H. Yang, W. a. Dick, E. L. McCoy, P. L. Phelan and P. S. Grewal, Field evaluation of a new biphasic rain garden for stormwater flow management and pollutant removal, *Ecol. Eng.*, 2013, **54**, 22–31.
20 Soil Society of America, www.soils.org, Rain Gardens and Bioswales, 2018
21 a. F. Speak, J. J. Rothwell, S. J. Lindley and C. L. Smith, Rainwater runoff retention on an aged intensive green roof, *Sci. Total Environ.*, 2013, **461–462**, 28–38.
22 D. Jurries, Biofilters (Bioswales, Vegetative Buffers, & Constructed Wetlands) for Storm Water Discharge Pollution Removal, *Dep. Environ. Qual. Northwest Reg.*, 2003, 1–52.
23 J. Foster, A. Lowe and S. Winkelman, The Value of Green Infrastructure for Urban Climate Adaptation, *Cent. Clean Air Policy*, 2011, 52.
24 United States Environmental Protection Agency, ofmpup.epa.gov, Watershed Protection Glossary, 2018.
25 C. Gaucherel, Regional watershed characterization and classification with river network analyses, *Earth Surf. Process. Landforms,* 2017, **2081**, 2068–2081.
26 B. Sivakumar, M. Asce, V. P. Singh, F. Asce, R. Berndtsson and S. K. Khan, Catchment Classification Framework in Hydrology: Challenges and Directions, *J. Hydrol. Eng.*, 2015, **20**, 1–12.
27 T. H. Snelder and B. J. F. Biggs, Multiscale river environment classification for water resources management, *J. Am. Water Res. Association*, 2003, **38**, 1225–1239.
28 T. Wagener, M. Sivapalan, P. Troch and R. Woods, Catchment Classification and Hydrologic Similarity, *Geography Compass*, 2007, **4**, 901–931.
29 J. E. Flotemersch, S. G. Leibowitz, R. A. Hill, J. L. Stoddard, M. C. Thoms and R. E. Tharme, A watershed integrity definition and assessment approach to support strategic management of watersheds, *River Res. Applic.*, 2016, **1671**, 1654–1671.
30 W. M. Marsh, *Landscape Planning: Environmental Applications*, Wiley, Hoboken, New Jersey, 2010.
31 R. Bannerman and E. Considine, dnr.wi.gov, Rain Gardens: A how-to manual for homeowners, 2003.
32 K. Hill, Urban Design and Urban Water Ecosystems, *Water Environ. Cities*, 2009, 1–307.
33 R. D. Klein, Urbanization and Stream Quality Impairment, *J. Am. Water Resour. Assoc.*, 1979, **15**, 948–963.
34 A. Mullapudi, B. P. Wong and B. Kerkez, Emerging investigators series: building a theory for smart stormwater systems, *Environ. Sci. Water Res. Technol.*, 2017, **3**, 66–77.
35 O. Lyandres and L. Welch, *Reducing Combined Sewer Overflows in the Great Lakes: Why Investing in Infrastructure is Critical to Improving Water Quality*, 2012.
36 S. De Toffol, C. Engelhard and W. Rauch, Combined sewer system versus separate system - A comparison of ecological and economical performance indicators, *Water Sci. Technol.*, 2007, **55**, 255–264.
37 R. J. Burm, D. F. Krawczyk and G. L. Harlow, Chemical and physical comparison of combined and seperate sewer discharges, *Water Environ. Fed.*, 1968, **40**, 112–126.
38 H. Brombach, G. Weiss and S. Fuchs, A new database on urban runoff pollution: Comparison of separate and combined sewer systems, *Water Sci. Technol.*, 2005, **51**, 119–128.
39 C. Palmer, Feasibility of Combined Sewer Systems, *Water Pollut. Control Fed.*, 1963, **40**
40 M. Peter-Varbanets, C. Zurbrugg, C. Swartz and W. Pronk, Decentralized systems for potable water and the potential of membrane technology, *Water Res.*, 2009, **43**, 245–265.

41 J. G. Hering, T. D. Waite, R. G. Luthy, J. E. Drewes and D. L. Sedlak, A changing framework for urban water systems, *Environ. Sci. Technol.*, 2013, **47**, 10721–10726.

42 P. Mguni, L. Herslund and M. B. Jensen, Sustainable urban drainage systems: examining the potential for green infrastructure-based stormwater management for Sub-Saharan cities, *Nat. Hazards*, 2016, **82**, 241–257.

43 J. Sansalone, S. Raje, R. Kertesz, K. Maccarone, K. Seltzer, M. Siminari, P. Simms and B. Wood, Retrofitting impervious urban infrastructure with green technology for rainfall-runoff restoration, indirect reuse and pollution load reduction, *Environ. Pollut.*, 2013, **183**, 204–212.

44 USEPA, Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure, *Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure*, 2010.

45 Y. Li, G. Zhu, W. J. Ng and S. K. Tan, A review on removing pharmaceutical contaminants from wastewater by constructed wetlands: Design, performance and mechanism, *Sci. Total Environ.*, 2014, **468–469**, 908–932.

46 J. Parkinson, Decentralized wastewater management in peri-urban areas in low-income countries, *Environ. Urban.*, 2003, **15**, 75–90.

47 United States Department of Agriculture, Soil Properties and Qualities, *National Soil Survey Handbook*, 2004.

48 W. C. Lucas and M. Greenway, Nutrient Retention in Vegetated and Nonvegetated Bioretention Mesocosms, *J. Irrig. Drain. Eng.*, 2008, **134**, 613–623.

49 S. A. Shannak, F. H. Jaber and B. J. Lesikar, Modeling the effect of cistern size, soil type, and irrigation scheduling on rainwater harvesting as a stormwater control measure, *Water Resour. Manag.*, 2014, **28**, 4219–4235.

50 D. L. Herrmann, L. A. Schifman and W. D. Shuster, Widespread loss of intermediate soil horizons in urban landscapes, *PNAS*, 2018, **115**, 6751–6755.

51 S. J. Gaffield, R. L. Goo, L. A. Richards and R. J. Jackson, Public Health Effects of Inadequately Managed Stormwater Runoff, *Am. J. Public Health*, 2003, **93**, 1527–1533.

52 O. Yagi, Biodegradation of halogenated organic compounds., *Japan J. Water Pollut. Res.*, 1985, **8**, 289–295.

53 A. J. Ebele, M. Abou-Elwafa Abdallah and S. Harrad, Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment, *Emerg. Contam.*, 2017, **3**, 1–16.

54 J. Y. M. Tang, R. Aryal, A. Deletic, W. Gernjak, E. Glenn, D. McCarthy and B. I. Escher, Toxicity characterization of urban stormwater with bioanalytical tools, *Water Res.*, 2013, **47**, 5594–5606.

55 M. López, M. Soliva, F. X. Martínez-Farré, A. Bonmatí and O. Huerta-Pujol, An assessment of the characteristics of yard trimmings and recirculated yard trimmings used in biowaste composting, *Bioresour. Technol.*, 2010, **101**, 1399–1405.

56 C. Ferguson, A. M. De Roda Husman, N. Altavilla, D. Deere and N. Ashbolt, Fate and transport of surface water pathogens in watersheds, *Crit. Rev. Environ. Sci. Technol.*, 2003, **33**, 299–361.

57 M. F. Chow, Z. Yusop and S. M. Shirazi, Storm runoff quality and pollutant loading from commercial, residential, and industrial catchments in the tropic, *Environ. Monit. Assess.*, 2013, **185**, 8321–8331.

58 H. Ha and M. K. Stenstrom, Identification of land use with water quality data in stormwater using a neural network, *Water Res.*, 2003, **37**, 4222–4230.

59 K. Kümmerer, Drugs in the environment: Emission of drugs, diagnostic aids and disinfectants into wastewater by hospitals in relation to other sources - A review, *Chemosphere*, 2001, **45**, 957–969.

60 T. F. O. Brien, D. G. Ross, M. A. Guzman, A. A. Medeiros, R. W. Hedges and D. Botstein, Dissemination of an Antibiotic Resistance Plasmid in Hospital Patient Flora, *Antimicrobial Agents and Chemptherapy*, 1980, **17**, 537–543.

61 P. Verlicchi, M. Al Aukidy and E. Zambello, What have we learned from worldwide experiences on the management and treatment of hospital effluent? - An overview and a discussion on perspectives, *Sci. Total Environ.*, 2015, **514**, 467–491.

62 X. Guo, Z. Liu, M. Chen, J. Liu and M. Yang, Decentralized wastewater treatment technologies and management in Chinese villages, *Front. Environ. Sci. Eng.*, 2014, **8**, 929–936.

63 F. Meinzinger and M. Oldenburg, Characteristics of source-separated household wastewater flows: A statistical assessment, *Water Sci. Technol.*, 2009, **59**, 1785–1791.

64 A. Wik and G. Dave, Occurrence and effects of tire wear particles in the environment - A critical review and an initial risk assessment, *Environ. Pollut.*, 2009, **157**, 1–11.

65 C. H. Vane, A. W. Kim, D. J. Beriro, M. R. Cave, K. Knights, V. Moss-Hayes and P. C. Nathanail, Polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB) in urban soils of Greater London, UK, *Appl. Geochemistry*, 2014, **51**, 303–314.

66 K. Kumar, S. C. Gupta, S. K. Baidoo, Y. Chander and C. J. Rosen, Antibiotic uptake by plants from soil fertilized with animal manure, *J Env. Qual*, 2005, **34**, 2082–2085.

67 G. K. MacDonald, E. M. Bennett and S. R. Carpenter, Embodied phosphorus and the global connections of United States agriculture, *Environ. Res. Lett.*, 2012, **7**, 044024.

68 D. R. Montgomery, Soil erosion and agricultural sustainability., *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 13268–72.

69 C. P. L. Grady, N. G. Love, G. T. Daigger and C. D. M. Filipe, *Biological Wastewater Treatment*, CRC Press, Boca Raton, FL, 2011.

70 J. Peng, Y. Cao, M. A. Rippy, A. R. M. N. Afrooz and S. B. Grant, Indicator and pathogen removal by low impact development best management practices, *Water (Switzerland)*, 2016, **8**, 1–24.

71 G. A. Burton and R. E. Pitt, *Stormwater Effects Handbook*, Lewis Publishers, Boca Raton, FL, 2001.

72 T. Heberer, Occurrence, fate, and removal of pharmaceutical residues in the aquatic environment: a review of recent research data., *Toxicol. Lett.*, 2002, **131**, 5–17.

73 D. Fischer, E. G. Charles and A. L. Baehr, Effects of Stormwater Infiltration on Quality of Groundwater Beneath Retention and Detention Basins, *J. Environ. Eng.*, 2003, **129**, 464–471.

74 L. Chelleri, T. Schuetze and L. Salvati, Integrating resilience with urban sustainability in neglected neighborhoods: Challenges and opportunities of transitioning to decentralized water management in Mexico City, *Habitat Int.*, 2015, **48**, 122–130.

75 B. C. Ferguson, R. R. Brown, N. Frantzeskaki, F. J. de Haan and A. Deletic, The enabling institutional context for integrated water management: Lessons from Melbourne, *Water Res.*, 2013, **47**, 7300–7314.

76 A. Boger, L. Ahiablame, E. Mosase and D. Beck, Effectiveness of Roadside Vegetated Filter Strips and Swales at Treating Roadway Runoff: A Tutorial Review, *Environ. Sci. Water Res. Technol.*, 2018, **4**, 478–486.

77 A. Deletic and T. D. Fletcher, Performance of grass filters used for stormwater treatment - A field and modelling study, *J. Hydrol.*, 2006, **317**, 261–275.
78 M. E. Dietz and J. C. Clausen, A field evaluation of rain garden flow and pollutant treatment, *Water. Air. Soil Pollut.*, 2005, **167**, 123–138.
79 J. Czemiel Berndtsson, Green roof performance towards management of runoff water quantity and quality: A review, *Ecol. Eng.*, 2010, **36**, 351–360.
80 B. O. Brattebo and D. B. Booth, Long-term stormwater quantity and quality performance of permeable pavement systems, *Water Res.*, 2003, **37**, 4369–4376.
81 T.-T. Fong and E. K. Lipp, Enteric viruses of humans and animals in aquatic environments: Health risks, detection, and potential water quality assessment tools, *Microbiol. Mol. Biol. Rev.*, 2005, **69**, 357–371.
82 S. Richards, E. Paterson, P. J. A. Withers and M. Stutter, Septic tank discharges as multi-pollutant hotspots in catchments, *Sci. Total Environ.*, 2016, **542**, 854–863.
83 D. E. Meeroff, F. Bloetscher, T. Bocca and F. Morin, Evaluation of water quality impacts of on-site treatment and disposal systems on urban coastal waters, *Water. Air. Soil Pollut.*, 2008, **192**, 11–24.
84 N. D. Wolfe, C. P. Dunavan and J. Diamond, Origins of major human infectious diseases, *Nature*, 2007, **447**, 279–283.
85 V. B. Richini-Pereira, S. D. M. G. Bosco, J. Griese, R. C. Theodoro, S. A. D. G. Macoris, R. J. Da Silva, L. Barrozo, P. M. E. S. Tavares, R. M. Zancopé-Oliveira and E. Bagagli, Molecular detection of Paracoccidioides brasiliensis in road-killed wild animals, *Med. Mycol.*, 2008, **46**, 35–40.
86 M. Klavarioti, D. Mantzavinos and D. Kassinos, Removal of residual pharmaceuticals from aqueous systems by advanced oxidation processes, *Environ. Int.*, 2009, **35**, 402–417.
87 J. Davies and D. Davies, Origins and Evolution of Antibiotic Resistance, *Micro. and Molec. Bio. Reviews*, 2010, **74**, 417–433.
88 Y. Eklind and H. Kirchmann, Composting and storage of organic household waste with different litter amendments: Nitrogen turnover and losses, *Bioresour. Technol.*, 2000, **74**, 125–133.
89 D. Q. Zhang, S. K. Tan and R. M. Gersberg, Municipal solid waste management in China: Status, problems and challenges, *J. Environ. Manage.*, 2010, **91**, 1623–1633.
90 M. P. Bernal, J. A. Alburquerque and R. Moral, Composting of animal manures and chemical criteria for compost maturity assessment: A review, *Bioresour. Technol.*, 2009, **100**, 5444–5453.
91 R. T. T. Forman and L. E. Alexander, Roads and Their Major Ecological Effects, *Annu. Rev. Ecol. Syst.*, 1998, **29**, 207–231.
92 H. E. Muga and J. R. Mihelcic, Sustainability of wastewater treatment technologies, *J. Environ. Manage.*, 2008, **88**, 437–447.
93 J. Lobos, C. Wisniewski, M. Heran and A. Grasmick, Continuous and sequencing membrane bioreactors applied to food industry effluent treatment, *Water Sci. Technol.*, 2007, **56**, 71–77.
94 J. Peigné and P. Girardin, Environmental impacts of farm-scale composting practices, *Water. Air. Soil Pollut.*, 2004, **153**, 45–68.
95 Y. Zheng, Z. Lin, H. Li, Y. Ge, W. Zhang, Y. Ye and X. Wang, Assessing the polycyclic aromatic hydrocarbon (PAH) pollution of urban stormwater runoff: A dynamic modeling approach., *Sci. Total Environ.*, 2014, **481**, 554–63.

96 J. N. Brown and B. M. Peake, Sources of heavy metals and polycyclic aromatic hydrocarbons in urban stormwater runoff, *Sci. Total Environ.*, 2006, **359**, 145–155.

97 C. J. Diblasi, H. Li, a P. Davis and U. Ghosh, Removal and Fate of Polycyclic Aromatic Hydrocarbon Pollutants in an Urban Stormwater Bioretention Facility Removal and Fate of Polycyclic Aromatic Hydrocarbon Pollutants in an Urban Stormwater Bioretention, *Environ. Sci. Technol.*, 2009, **43**, 494–502.

98 A. Parkinson, C. D. Klaasen and J. B. Watkins, Biotransformation of xenobiotics, *Casarett & Doull's Essentials of Toxicology*, 2001, 133–144.

99 M. Maurer, P. Schwegler and T. A. Larsen, Nutrients in urine: Energetic aspects of removal and recovery, *Water Sci. Technol.*, 2003, **48**, 37–46.

100 S. R. Smith, A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge, *Environ. Int.*, 2009, **35**, 142–156.

101 P. M. Vitousek, J. D. Aber, R. W. Howarth, G. E. Likens, M. P. A, D. W. Schindler, W. H. Schlesinger and D. G. Tilman, Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen, *Ecol. Soc. Am.*, 1997, **7**, 737–750.

102 D. Pimental, C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri and R. Blair, Environmental and economic costs of soil erosion and conservation beneits, *Science*, 1995, **267**, 1117–1122.

103 A. R. Boger, L. Ahiablame, E. Mosase and D. Beck, Effectiveness of roadside vegetated filter strips and swales at treating roadway runoff: A tutorial review, *Environ. Sci. Water Res. Technol.*, 2018, **4**, 478–486.

104 T. B. Councell, K. U. Duckenfield, E. R. Landa and E. Callender, Tire-wear particles as a source of zinc to the environment, *Environ. Sci. Technol.*, 2004, **38**, 4206–4214.

105 D. A. Bright and N. Healey, Contaminant risks from biosolids land application: Contemporary organic contaminant levels in digested sewage sludge from five treatment plants in Greater Vancouver, British Columbia, *Environ. Pollut.*, 2003, **126**, 39–49.

106 M. A. Barakat, New trends in removing heavy metals from industrial wastewater, *Arab. J. Chem.*, 2011, **4**, 361–377.

107 J. Mortvedt, Heavy metal contaminants in inorganic and organic fertilizers, *Fertil. Res.*, 1995, **43**, 55–61.

108 A. H. Roy, L. K. Rhea, A. L. Mayer, W. D. Shuster, J. J. Beaulieu, M. E. Hopton, M. Morrison and A. St Amand, How much is enough? Minimal responses of water quality and stream biota to partial retrofit stormwater management in a suburban neighborhood, *PLoS One*, 2014, **9**, e85011.

109 C. G. Daughton and T. A. Ternes, Pharmaceuticals and Personal Care Products in the Environment: Agents of Subtle Change?, *Environ. Toxicol.*, 2009, **28**, 2663–2670.

110 Detroit Water and Sewerage Department, www.detroitmi.gov, DWSD Fact Sheet, 2014.

111 M. Pirnie, CH2MHilll, TYJT and Hazen & Sawyer, www.detroitmi.gov, Water Treatment Plant Needs Assessment, 2013.

112 C. Williams, Leaky government: Detroit's water supply wasted by ravaged pipes, *NBC News*, 2015.

113 Wikipedia, List of largest wastewater treatment plants, 2016.

114 B. Laitner, Help is available for Detroiters with backed-up basements from storms, *Detroit Free Press*, 2016.

115 N. R. M. R. Laboratory, EPA Storm Water Management Model (SWMM), 2016.

116 United States Geological Survey, waterdata.usgs.gov, USGS Current Water Data for Michigan, 2016.
117 The World Bank, www.worldbank.org, Ethiopia Overview, 2016.
118 E. Yard, T. Bayleyegn, A. Abebe, A. Mekonnen, M. Murphy, K. L. Caldwell, R. Luce, D. R. Hunt, K. Tesfaye, M. Abate, T. Assefa, F. Abera, K. Habte, F. Chala, L. Lewis and A. Kebede, Metals Exposures of Residents Living Near the Akaki River in Addis Ababa, Ethiopia: A Cross-Sectional Study, *J. Environ. Public Health*, 2015, 1–8.
119 ESIA, Rainfall and Climate Station: Addis Ababa Observatory, Addis Ababa, Ethiopia, 2004.
120 D. A. Belete, Road and urban storm water drainage network integration in Addis Ababa: Addis Ketema Sub-city, *J. Eng. Technol. Res.*, 2011, **3**, 217–225.
121 B. Debele, The Vertisols of Ethiopia: their properties, classification and management, in *Fifth Meeting of the Eastern African Sub-Committee for Soil Correlation and Land Evaluation*, World Soil Resources Reports, Rome, 1983.
122 B. Basel, *Lessons of Informality: Architecture and Urban Planning for Emerging Territories - Concepts from Ethiopia*, Beltz Bad Langensalza GmbH, Basel, Switzerland, 2016.
123 A. Awoke, A. Beyene, H. Kloos, P. L. M. Goethals and L. Triest, River Water Pollution Status and Water Policy Scenario in Ethiopia: Raising Awareness for Better Implementation in Developing Countries, *Environ. Manage.*, 2016, **58**, 694–706.
124 A. Backhaus, D. Adugna, G. J. Mhina, L. B. Herslund and O. Fryd, *Water Resilient Green Cities in Africa*, Addis Ababa, 2016.
125 D. Adugna, L. Larsen, B. Lemma, G. Sahilu, Low-Cost Stormwater Filtration System to Improve Urban Water Quality: The Case of Addis Ababa, Ethiopia, *J. Water Res. and Protect.*, 2017, **9**, 692–705.

10. Appendices

APPENDIX 1: Explanation of SWMM Modeling

The Environmental Protection Agency's Stormwater Management Model (SWMM) is free software that permits the comparison of stormwater run-off before and after interventions. Typical applications of SWMM include designing and sizing drainage system components, flood plain mapping, control of combined sewer overflows, generating non-point source pollutant loadings, and evaluating green infrastructure for sustainability goals. The resolution of SWMM output data is dependent on user input. In our application of SWMM, we quantified stormwater runoff from a single rain events in two distinct urban environments before and after implementing GI systems. Inputs included a storm event with total precipitation in 5-minute increments, total site area, impervious surface area from the site, slope of the site, permeability of the site, and GI systems (referred to as LID controls in SWMM) that we wanted to implement. Using Google Earth and its embedded measuring tool, we calculated the area of each site and divided the area into pervious and impervious surface to determine the total percent impervious area of the site. Using ArcGIS, we calculated the average slope of each site. LID control parameters were inputted after we designed the desired area, depth, and permeability of materials of each rain garden, detention basin, and permeable pavement installation. We obtained the precipitation and hydrograph of each site using government resources. The rainfall data for Wayne County was acquired through the United States Geological Survey Current Water Data for Michigan, waterdata.usgs.gov.[116] Using the weather station at Recovery Park in Detroit, the 5-minute incremented precipitation data from the 6-hour storm that produced the largest amount of rainfall in 2016 (24 March) was selected as the simulated storm for the paper. The rainfall data for Addis Ababa was acquired through the Ethiopian Metrology Agency, www.ethiomet.gov.et. Using the data of the most current year posted, the heaviest rainfall of 2012 was in August. Unlike Detroit, the Ethiopian Metrology Agency does not yet provide 5-minute incremented precipitation data of a storm event. Instead, a storm event was theoretically generated by dividing the total rainfall volume by the number of days it rained in August to get the average precipitation of each storm event, and then using past precipitation data to estimate 5-minute increment precipitation measurements for the simulated storm.

APPENDIX 2: These guidelines presented in Table 5 were constructed by combining Table 3 with Table 4. Each table is labeled by a GI implementation. Looking at row one listing contaminants, Table 3 was used in row two to give a rating of high, medium or low considering the effectiveness of the title GI against the stated contaminant. Looking at row one listing contaminants and column one listing land uses, Table 4 was used to give a rating of high, medium or low considering the amount of stated contaminant that the stated land use contributes to the environment. After assigning a rating, a number was assigned to each contaminant-land use pair: if the match was high-high, med-med, or low-low, the pair was assigned the number 2. If the match was high-med, med-high, med-low or low-med, they pair was assigned the number 1. If the match was high-low or low-high, the pair was assigned the number 0. The final recommendations were based on the sum of the rows. Values from 10 to 14 were categorized as excellent(**). Values between 5 and 9 were categorized as good (*). Values less than 5 were considered poor (blank cell).

RETENTION BASIN

TABLE 3

TABLE 4

	Pathogens		NOM		SOCs		Nutrients		Heavy Metals		Sediments		PPCPs		SUM OF ROWS
	med		high		high		med		med		med		med		
residential	high	1	high	2	med	1	high	1	med	2	med	2	high	1	10
transportation	low	1	low	0	high	2	low	1	high	1	high	1	low	1	7
public	high	1	med	1	med	1	high	1	med	2	med	2	high	1	9
industrial	low	1	low	0	high	2	low	1	high	1	med	2	med	2	9
urban ag	high	1	high	2	med	1	high	1	med	2	med	2	high	1	10
open space	med	0	med	1	low	0	med	2	low	1	med	2	low	1	7
commercial	med	0	med	1	med	1	low	1	med	2	high	1	med	2	8

RAINWATER HARVEST

	Pathogens		NOM		SOCs		Nutrients		Heavy Metals		Sediments		PPCPs		
	low		low		low		low		low		med		low		
residential	high	0	high	0	med	1	high	0	med	1	med	2	high	0	4
transportation	low	2	low	2	high	0	low	2	high	0	high	1	low	2	9
public	high	0	med	1	med	1	high	0	med	1	med	2	high	0	5
industrial	low	2	low	2	high	0	low	2	high	0	med	2	med	1	9
urban ag	high	0	high	0	med	1	high	0	med	1	med	2	high	0	4
open space	med	1	med	1	low	2	med	1	low	2	med	2	low	2	11
commercial	med	1	med	1	med	1	low	2	med	1	high	1	med	1	8

CONSTRUCTED WETLAND

	Pathogens		NOM		SOCs		Nutrients		Heavy Metals		Sediments		PPCPs		
	med		high		high		high		high		high		med		
residential	high	1	high	2	med	1	high	2	med	1	med	1	high	1	9
transportation	low	1	low	0	high	2	low	0	high	2	high	2	low	1	8
public	high	1	med	1	med	1	high	2	med	1	med	1	high	1	8
industrial	low	1	low	0	high	2	low	0	high	2	med	1	med	2	8
urban ag	high	1	high	2	med	1	high	2	med	1	med	1	high	1	9
open space	med	2	med	1	low	0	med	1	low	0	med	1	low	1	6
commercial	med	2	med	1	med	1	low	0	med	1	high	2	med	2	9

DETENTION BASIN

	Pathogens		NOM		SOCs		Nutrients		Heavy Metals		Sediments		PPCPs		
	med		high		high		med		med		med		med		
residential	high	1	high	2	med	1	high	1	med	2	med	2	high	1	10
transportation	low	1	low	0	high	2	low	1	high	1	high	1	low	1	7
public	high	1	med	1	med	1	high	1	med	2	med	2	high	1	9

industrial	low	1	low	0	high	2	low	1	high	1	med	2	med	2	9
urban ag	high	1	high	2	med	1	high	1	med	2	med	2	high	1	10
open space	med	2	med	1	low		med	2	low	1	med	2	low	1	9
commercial	med	2	med	1	med	1	low	1	med	2	high	1	med	2	10

BIOSWALE

	Pathogens		**NOM**		**SOCs**		**Nutrients**		**Heavy Metals**		**Sediments**		**PPCPs**		
	low		med		med		med		low		med		med		
residential	high	0	high	1	med	2	high	1	med	1	med	2	high	1	8
transportation	low	2	low	1	high	1	low	1	high	0	high	1	low	1	7
public	high	0	med	2	med	2	high	1	med	1	med	2	high	1	9
industrial	low	2	low	1	high	1	low	1	high	0	med	2	med	2	9
urban ag	high	0	high	1	med	2	high	1	med	1	med	2	high	1	8
open space	med	1	med	2	low	1	med	2	low	2	med	2	low	1	11
commercial	med	1	med	2	med	2	low	1	med	1	high	1	med	2	10

RAIN GARDEN

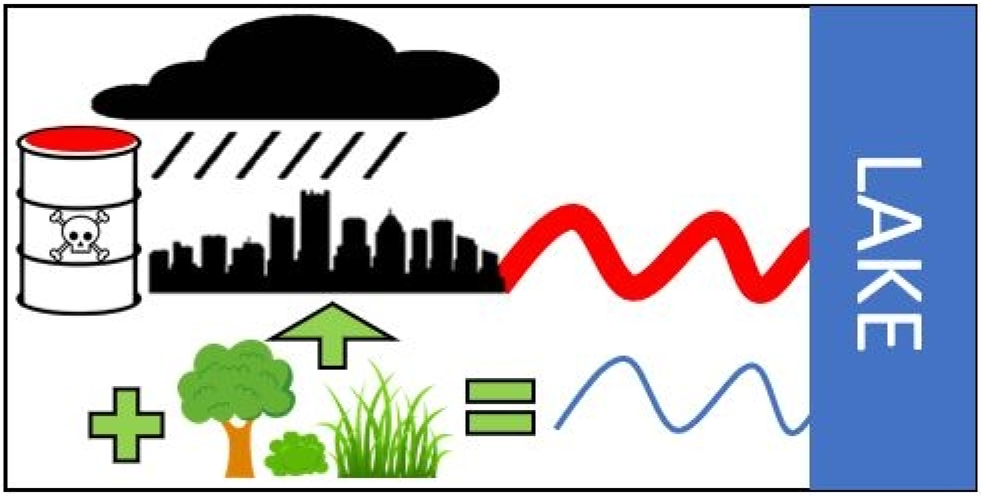
	Pathogens		**NOM**		**SOCs**		**Nutrients**		**Heavy Metals**		**Sediments**		**PPCPs**		
	low		med		med		high		med		high		med		
residential	high	0	high	1	med	2	high	2	med	2	med	1	high	1	9
transportation	low	2	low	1	high	1	low	0	high	1	high	2	low	1	8
public	high	0	med	2	med	2	high	2	med	2	med	1	high	1	10
industrial	low	2	low	1	high	1	low	0	high	1	med	1	med	2	8
urban ag	high	0	high	1	med	2	high	2	med	2	med	1	high	1	9
open space	med	1	med	2	low	1	med	1	low	1	med	1	low	1	8
commercial	med	1	med	2	med	2	low	0	med	2	high	2	med	2	11

GREEN ROOF

	Pathogens		**NOM**		**SOCs**		**Nutrients**		**Heavy Metals**		**Sediments**		**PPCPs**		
	low		med		med		high		med		high		med		
residential	high	0	high	1	med	2	high	2	med	2	med	1	high	1	9
transportation	low	2	low	1	high	1	low	0	high	1	high	2	low	1	8
public	high	0	med	2	med	2	high	2	med	2	med	1	high	1	10
industrial	low	2	low	1	high	1	low	0	high	1	med	1	med	2	8
urban ag	high	0	high	1	med	2	high	2	med	2	med	1	high	1	9
open space	med	1	med	2	low	1	med	1	low	1	med	1	low	1	8
commercial	med	1	med	2	med	2	low	0	med	2	high	2	med	2	11

PERMEABLE PAVEMENT

	Pathogens		**NOM**		**SOCs**		**Nutrients**		**Heavy Metals**		**Sediments**		**PPCPs**		
	low		med		low		low		low		high		low		
residential	high	0	high	1	med	1	high	0	med	1	med	1	high	0	4
transportation	low	2	low	1	high	0	low	2	high	0	high	2	low	2	9
public	high	0	med	2	med	1	high	0	med	1	med	1	high	0	5
industrial	low	2	low	1	high	0	low	2	high	0	med	1	med	1	7
urban ag	high	0	high	1	med	1	high	0	med	1	med	1	high	0	4
open space	med	1	med	2	low	2	med	1	low	2	med	1	low	2	11
commercial	med	1	med	2	med	1	low	2	med	1	high	2	med	1	10



Selecting and locating Green Infrastructure systems for stormwater management based on containment removal potential, land use, and watershed context.

130x99mm (96 x 96 DPI)