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Green Stormwater Infrastructure in an Informal Context: Feasibility and Potential Stormwater Impacts of Implementing Rain Gardens and Rain Barrels in Peri-Urban Santo Domingo

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Green Stormwater Infrastructure in an Informal Context: Feasibility and Potential Stormwater Impacts of Implementing Rain Gardens and Rain Barrels in Peri-Urban Santo Domingo

by

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Report

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Abstract

Green Stormwater Infrastructure in an Informal Context: Feasibility and Potential Stormwater Impacts of Implementing Rain Gardens and Rain Barrels in Peri-Urban Santo Domingo

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Latin America is the most urbanized region in the developing world, with much of this urbanization occurring informally. The pressure of increasing impervious cover without the provision of adequate stormwater infrastructure frequently leads to urban flooding in informal contexts. This study investigates the feasibility and potential benefits of implementing a network of decentralized green stormwater infrastructure controls in the subwatersheds of three channelized creeks that contribute to flooding in Los Platanitos, an informal settlement in Santo Domingo Norte, Dominican Republic. Through a mixed-methods research design including interviews with institutional actors and residents, as well as detailed field mapping with local experts, a Stormwater Management Model (SWMM) model was developed to estimate the potential runoff and storage impacts of the construction of a network of rain gardens and rain barrels throughout the contributing subwatersheds. The model predicts a 20% reduction in flooding for a 5-year storm, and a lengthening of the time it takes for the system to start flooding. These benefits, albeit small, are substantial when floodwaters are highly contaminated and pose a significant health risk.

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CHAPTER ONE: Introduction

With 80% of its population living in cities, Latin America is the second most urbanized region after North America, and the most urbanized region in the developing world (IDB, 2012). Much of this urbanization occurs informally—nearly 15% of the population of the Dominican Republic lives in informal settlements, with more than half of the population lacking formal land titles (Torres, 2014; MEPyD, 2013). Due to neoliberal reforms that have devolved planning power to weak and underfunded local governments, large portions of the population do not have access to the most basic of services. Thirty-five percent of the population do not have access to clean tap water, 22% have no indoor plumbing, and only 11.4% are connected to adequate stormwater infrastructure. The pressure of increased informal urbanization and its concomitant addition of impervious surfaces without the provision of adequate stormwater infrastructure frequently leads to urban flooding problems (COPDES and UNCT, 2004).

The informal settlement of Los Platanitos is located in Santo Domingo Norte, one of the five municipalities that compose Greater Santo Domingo, Dominican Republic. The community was founded by rural-to-urban migrants on land deemed unsuitable for formal development due to its steep slopes, proximity to a natural drainage way, and the fact that it was previously used as a landfill. A large portion of the neighborhood is situated in a steep canyon, traversed by three major channelized creeks that drain into the Yaguasa River. Due to the large volume of runoff originating from the upstream communities of Los Trinitarios, Santa Cruz, and the arterial Avenida Hermanas Mirabal, the channel frequently overflows during periods of heavy rainfall and floods the nearby homes. Nearly 75% of structures adjacent to the channel have experienced flooding, and 58% had flooding severe enough to force residents to leave their homes. As the community has low incomes and high levels of unemployment, underemployment, and informal employment, its residents are particularly vulnerable to these flood impacts (Sletto, ed. 2010).

Stormwater professionals in the Dominican Republic, as well as many other developing countries, rely on the sanitary model to manage urban stormwater. Under this model, stormwater is piped as quickly as possible to outfalls to rivers or the sea, causing downstream flooding, erosion, and water quality degradation. Because these centralized systems are costly to construct and maintain, public entities are largely unable to expand the system—only 16% of the Distrito Nacional (the central municipality of Greater Santo Domingo) is served by the current system (Auding-Watson, 1997). The intersection of the hydrologic consequences of increased urbanization, informality, and neoliberal governance in Santo Domingo produces a situation in which those populations most vulnerable to flood impacts are also the most likely to live in flood-prone areas. At the same time, the overall lack of technical, administrative, and financial capabilities in local governments brought about by decentralization has greatly diminished the possibilities for effective flood mitigation in informal settlements. This combination of local, national, and global forces that exacerbate vulnerability in Los Platanitos are reproduced throughout the entire city.

This study investigates the feasibility and potential benefits of implementing a network of decentralized green stormwater infrastructure controls in the subwatersheds of the three channelized creeks that contribute to flooding in Los Platanitos. The emerging paradigm of decentralized stormwater management is based on the dispersal of small stormwater controls throughout a watershed to manage stormwater quality and quantity at the source of runoff production. These source-control strategies attempt to restore natural hydrologic processes to the greatest extent possible. Instead of managing stormwater as a waste product that must be eliminated immediately, which is the current predominant practice throughout the developing world, stormwater is seen as a resource that can provide multiple benefits to a watershed (Green et al. 2012; Thurston et al., 2003).

A review of the green stormwater infrastructure literature suggests that a decentralized approach is potentially well-suited to informal settlements due to its ability to be implemented incrementally, at low cost, and utilizing the human and social capital of the community itself rather than relying on outside actors (Brewer & Fisher, 2004; ECONorthwest, 2007; Thurston et al., 2003, USEPA, 2007). In one notable study, the Environmental Protection Agency (EPA) evaluated the public participation and stormwater effects of an incentive-based approach to “citizen-based stormwater management” in an urbanized watershed in Cincinnati, Ohio (Green et al., 2012, p. 1669). After an education campaign and the establishment of local demonstration rain gardens and rain barrels, the researchers held reverse auctions in which eligible landowners placed bids on how much they desired to be paid to receive a rain garden or barrel. Overall, 81 rain gardens and 165 rain barrels were installed on 75 properties within the 1.8 km^2 watershed. The overall impact of the installations was a small, but statistically significant decrease in stormwater volume at the subcatchment scale (Shuster et al., 2013; Mayer et al., 2012).

This project explores the following, related questions: 1) Would an incentive- or community-based provision model similar to that in the EPA’s Cincinnati, Ohio study be feasible in an informal context? 2) What are some resources to be leveraged or barriers to the implementation of such a program? 3) Given the predominant urban form of the channels’ subwatersheds, how many rain gardens and rain barrels can reasonably be expected to be installed throughout the community? 4) Taking into account the soils, regional rainfall patterns, the capacity of current stormwater infrastructure, and the percentage of impervious cover within the channels’ subwatersheds, what are the potential runoff and storage implications of the construction of these controls?

In order to investigate these questions, I employed a mixed-methods research design including a literature review, semi-structured interviews with institutional actors, structured interviews with neighborhood residents, detailed field mapping of the creeks' subwatersheds with local experts, and field testing of soil infiltration rates. Finally, this information was used to develop a Stormwater Management Model (SWMM) model to estimate the potential stormwater impacts of rain garden and rain barrel implementation in the channels' subwatersheds. This mixed-methods approach was chosen to both identify the geophysical parameters of the area that would inform the subsequent modeling of each intervention, but also to better understand the sociocultural, political, and economic realities that could facilitate or hamper implementation of those interventions.

After estimating the total number of rain gardens and rain barrels that would be constructed given the number of households with sufficient space, coupled with the rate of adoption in the Cincinnati, Ohio study (230 rain gardens and 299 rain barrels), the model predicts a 20% reduction in flood volumes for a 5-year storm, and a lengthening of the time it takes for the system to start flooding. These benefits, albeit small, can have a substantial impact on human security and quality of life, given that floodwaters are highly contaminated and therefore pose a significant health risk. The community would see a small decrease in flood frequency, depth, and duration, meaning less exposure to contaminated floodwaters and more time to prepare for flooding.

Given these findings, it is highly unlikely that the use of green stormwater infrastructure alone can meaningfully reduce flooding in Los Platanitos. This report recommends that the community adopt some combination of green and traditional "grey" infrastructure. While green infrastructure can handle small storms and provides multiple ancillary benefits, upgrades to "La Piscina" storage area are needed to protect vulnerable residents from larger storm events. In the short-term, the community can implement some rain gardens and rain barrels immediately, but it will also need to collaborate with the local government to enact longer-term regulatory solutions that can influence the land-development activities of upstream landowners. It is important to note that the existence of ready-made, well-developed social networks may make community-based stormwater management more viable in Los Platanitos than in the developed world. The capacity and connections of existing community groups such as Mujeres Unidas and the Fundación Los Platanitos (FUMPLA) should be utilized to establish a green stormwater infrastructure demonstration site. This would introduce the concept to homeowners and serve as a training site for potential local technicians, building the human capital the community needs to ensure rain barrels and rain gardens are properly constructed and maintained.

After this introduction, Chapter Two gives an overview of the current literature regarding green stormwater infrastructure, stormwater practices in developing countries, and the potential advantages of implementing green stormwater infrastructure in developing countries. Chapter Three explains the trajectory of planning in the Dominican Republic, including the move from a centralized to decentralized planning paradigm. Chapter Three also describes current stormwater practices in Santo Domingo, and the current state of stormwater, potable water, and sanitary services in Los Platanitos. Chapter Four documents the methods employed in this study, including model development procedures and the models input parameters. Chapter Five describes the results of modeled stormwater impacts of rain gardens and rain barrels, and discusses community capacity to implement a community-based service provision model. Finally, Chapter Six provides conclusions and recommendations for flood solutions.

CHAPTER TWO: Decentralized Sustainable Stormwater Management in Developing Countries

Green Stormwater Infrastructure: A New Paradigm for Stormwater Management

Urbanization, and the associated increase in impervious surfaces in the form of rooftops, roads, and parking lots, is changing hydrological processes worldwide. The installation of impervious surfaces, soil compaction, and tree and vegetation removal involved in conventional land development practices alter the natural hydrology of the land. Instead of being intercepted by tree canopies, evapotranspirated by vegetation, or infiltrated into the soil to eventually feed stream baseflow, precipitation runs off impervious surfaces and is converted to overland flow. Runoff reaches streams faster and in greater volumes, causing higher peak flows that cause channel erosion and habitat alteration. While flood frequency and magnitude increases, less infiltration means less groundwater water is available to the stream during dry periods. This reduction in baseflow, coupled with the increased pollutant and sediment loadings from impervious surfaces, leads to a subsequent degradation of aquatic habitat. The benthic macroinvertebrates that form the building blocks for the entire riparian ecosystem cannot survive (Thurston et al., 2003).

In the conventional centralized drainage systems common throughout the U.S., excess runoff is captured, conveyed, and discharged untreated into receiving water bodies through a separated municipal storm sewer system. In older communities, stormwater is combined with sanitary sewage, conveyed to a wastewater treatment facility, treated, and discharged into a receiving water body (Green et al., 2012). In municipalities that have the resources and desire to engage in watershed protection measures, the negative externalities of urbanization are ameliorated by control and treatment strategies that capture excess runoff to control downstream flooding, peak flow rates, and suspended solids concentrations before water is discharged into a water body. While these practices result in less risk of flooding, erosion, and pollutant loadings in urban streams, they do not address all the widespread and cumulative effects of hydrological modification. These "end-of-pipe" water quality and quantity solutions reduce the downstream impacts of excessive runoff, but they cannot fully mitigate upstream effects of the loss of sufficient infiltration. Even though such practices frequently occupy high-value community open space and require costly maintenance with heavy equipment to maintain functionality, urban streams continue to be turned into stormwater conveyances, largely losing their ecological function.

While conventional stormwater conveyance practices have a high degree of reliability and acceptance by municipalities and consumers, such practices are not resilient to the uncertainties brought about by climate change, they damage the natural hydrological function of the land, and they require constant influxes of capital resources to maintain. In the past few decades, control and treatment strategies have had limited success in preventing further degradation of urban streams, but water quality and habitat degradation continue. A new paradigm has emerged in stormwater management, however, that promises to restore natural functioning to a watershed while also enhancing resiliency to climate change and drought, reducing energy costs, enhancing carbon sequestration, and improving quality of life for nearby residents (Kuo & Sullivan, 2001). Decentralized stormwater management is based on the dispersal of stormwater management practices throughout a watershed to manage stormwater quality and quantity at the source of runoff production. These source-control strategies attempt to restore, to the greatest extent possible, natural hydrologic processes. Instead of managing stormwater as a waste product that must be eliminated immediately, it is seen as a resource (Green et al., 2012) that can provide multiple benefits to a watershed.

Collectively, this emerging paradigm of stormwater practices that use soil and vegetation or engineered capture technologies to control runoff at its source by replicating natural drainage systems is referred to as sustainable stormwater management (Green et al., 2012). As a relatively new approach to stormwater management, various overlapping terms are used in the literature. While closely related and often used interchangeably with the terms Low Impact Development, environmental site design, or conservation design, which are more often used regarding greenfields development—this project sees sustainable stormwater management as a broader term that can apply to retrofits, the redevelopment of existing sites, and practices that stretch over multiple scales (MacMullan and Reich, 2007; Shaver, 2009). Green stormwater infrastructure is a collective term for the suite of stormwater control measures (SCMs) that support the control of runoff near its source. Named in opposition to conventional, unifunctional "grey" infrastructure, such practices are multifunctional, multiscalar, and provide multiple ancillary benefits. While the opportunities to integrate green stormwater infrastructure into new development and retrofits is almost endless, this project concentrates on the flood mitigation capability of those SCMs that can be easily deployed in an incremental fashion throughout a watershed: privately-maintained rain gardens to capture runoff from homes and businesses and rainwater harvesting systems.

Aside from the ecological benefits of sustainable stormwater management, the most important advantage to this emerging approach is that green stormwater infrastructure has the unique ability to *appreciate* in ecological value and function over time (Green et al., 2012). Although properly designed and maintained grey infrastructure can efficiently convey and store runoff, such systems are in a continual state of decay and depreciation after they are constructed. Green infrastructure approaches to stormwater management use soil pore space as an alternative volume for runoff storage. Because plant-soil systems support their own ecosystem, they are by design inherently capable of responding to a range of climate conditions and may therefore exhibit enhanced resilience, compared to grey infrastructure systems. And while grey infrastructure only depreciates in value and functionality over time, this ecosystem dynamic actually can enhance a stormwater control measure's functioning over time. For example, the soil ecosystem properties of a properly-maintained rain garden can induce positive feedbacks that improve both plant health and soil structure. The soil macrofaunal activity that promotes nutrient cycling also creates large biopores, which allow water to flow more freely than through compacted soils. Along with structural porosity from seasonal soil heaving and ongoing root penetration, this growth of biopores enhances the infiltration capacity of the rain garden. As the rain garden ages and its ecosystem advances, it is able to infiltrate a broader range of rainfall depths and frequencies.

A green stormwater infrastructure approach is of course not a panacea for urban flooding problems. The City of Austin Watershed Protection Department recently concluded a three-year study which modeled the large-scale application of decentralized green stormwater infrastructure in the Brentwood Neighborhood to assess the potential impacts on localized flooding caused by undersized drainage infrastructure. Overall, the study showed that even if a decentralized program achieved the maximum possible coverage of green stormwater controls throughout the neighborhood, these controls could only mitigate flooding up to a 7-year storm. A combination of green stormwater infrastructure and targeted traditional infrastructure improvements, however, completely eliminated local flooding up to 10-year storms, and significantly reduced the number of structures subject to flooding in somewhat larger storms. While these traditional infrastructure upgrades added approximately one million dollars to the projected costs, bringing the total costs to $17 million, these projected costs were still significantly lower than the traditional infrastructure scenario ($190 million) (City of Austin, 2014).

The green stormwater infrastructure approach is also not without its own distinct disadvantages. By their nature, dispersed stormwater systems are distributed throughout an entire watershed and over many properties, making continued monitoring and maintenance a monumental task for conventional top-down, command-and-control stormwater management strategies. Evidence and practice suggests that rain gardens also require more frequent maintenance than larger control and treatment structures, as smaller structures can easily become clogged with sediment or trash (Vesely et al., 2005). For infiltration-based SCMs, the soil is very vulnerable to disturbances—it needs to be cared for to ensure continued functionality and the soil also must be replaced periodically to prevent the accumulation of pollutants. But most maintenance does not have to be carried out with heavy equipment by professionals, nor are ongoing costs high.

Stormwater Management in Developing and Informal Contexts

While developed countries are beginning to embrace the paradigm shift towards sustainable stormwater management as a way to restore runoff quantity *and* quality to that of natural land cover, lower income countries mostly still struggle with problems of excess runoff quantity due to uncontrolled urbanization. The immediate threat to lives and property that urban flooding poses lends itself to quickly-implemented and familiar solutions over untested ones, and the 19th century sanitary model of urban drainage is still the overwhelmingly predominant practice in developing countries. The object of the sanitary model is to convey excess stormwater as rapidly as possible away from settled areas to waterbodies via open channels and buried conduits. Even though stormwater is often mixed with sewage and solid waste, it is largely discharged directly into waterbodies untreated (Goldenfum et al., 2007). While the sanitary approach causes a multitude of negative environmental consequences, it has the advantage of being simple to design and implement—it is concerned with one design goal and can be carried out by civil engineers alone. The prevalence and entrenchment of the sanitation model of urban drainage is one of many barriers facing the implementation of sustainable stormwater management in developing countries, but recent research has shown that the potential exists for the implementation of more sustainable stormwater management strategies (Armitage, 2011; Button et al., 2010; Goldenfum et al., 2007; Silveira, 2002)

Academic and practitioner literature related to urban stormwater management in developing contexts is still relatively scarce and largely introductory. Most authors simply document the challenges to providing any sort of urban drainage, sustainable or otherwise, in a developing context. The root causes of these problems can be reduced to two main categories: 1) the rapid population growth of developing-world cities, and 2) the inability of governments to adequately respond to that population growth.

The social and ecological problems associated with the rapid and uncontrolled urban expansion common to developing countries are many—including increased levels of air pollution, urban heat island effect, overcrowding, unemployment, noise pollution, and deforestation. Past research has demonstrated that the most hydrologically devastating effects of this migration to cities is the explosive expansion of impervious cover and incursion of vulnerable populations into areas unsuitable to land development (Silveira, 2002; Reed, 2013; Tucci, 2001; Parkinson, Tayler, and Mark, 2007). As low-income rural migrants flow into developing-world cities, they frequently settle in areas of cities that have been deemed unsuitable to intensive land use because these areas are cheap, unoccupied, and close to job opportunities (Silviera, 2002; Reed, 2013). The site of these informal settlements are often areas of flow conveyance, floodplains, steep slopes, and unsuitable soils; i.e. areas which are either at already at risk of flooding or highly sensitive to hydrological changes. These settlements are virtually always built without the consent of planning authorities and rarely conform to official planning guidelines, building regulations, and construction standards. Because these settlement are not part of the formal city, they have also not been provided services such as stormwater, household wastewater (greywater), and sanitary (blackwater) infrastructure (Tucci, 2001; Silveira, 2002). Furthermore, the use of the sanitary model of stormwater management in the formal city frequently exacerbates flooding problems in informal areas. The expansion of drainage works such as pipes and channels to increase conveyance of ever-expanding runoff volumes frequently just creates new flooding problems downstream. The combination of increased upstream impervious cover, incursions into flood-prone areas, and a lack of proper stormwater conveyance infrastructure produces a situation in which very vulnerable populations are frequently subject to the highest flood risk (Armitage, 2011).

Past research has also demonstrated that multiple interrelated factors contribute to the tendency of local governments to largely ignore drainage problems in informal settlements. By far the most commonly mentioned limiting factor is the lack of adequate economic resources and technical skills to respond to the pressures that informal settlements place on local government, mostly due to small tax bases and lack of trained staff (Tucci, 2001; Silveira, 2002; Armitage, 2011). Local governments are also reluctant to extend services to illegal settlements, both because of their illegality and also because the residents of such settlements have a low percentage of rate payers for water-related services. Local governments and utilities are more inclined to make investments in formal neighborhoods with a higher percentage of rate payers (Tucci, 2001). Unfortunately, the increased pressure that informal settlement place on limited government resources often results in lower levels of maintenance of existing systems and reduced performance across the entire municipality (Armitage, 2011). Most local governments also lack the legal instruments and enforcement capabilities necessary to effectively regulate development, so drainage problems caused by the private sector must be solved and paid for by the public sector (Goldenfum et al., 2007).

Even when local governments do decide to extend stormwater services to informal settlements, Goldenfum (2007) and Armitage (2011) observed that local governments have a limited capacity to effectively address problems. Local governments in developing contexts frequently suffer from data deficiencies, an incomplete record of the existing drainage network, lack of records updating, and a lack of water quantity and quality monitoring of the natural or man-made drainage network. Armitage (2011) observed that local and national officials in developing countries also tend to focus on clientelistic, short-term projects that can secure re-elections, rather than long-term projects that can better serve the populace (Armitage, 2011). This short-term mentality, coupled with a fragmentation of responsibility for water-related service delivery among various actors, frequently results in a piecemeal response to highly interrelated problems (Goldenfum et al., 2007).

While middle income countries such as Chile and Malaysia have already begun to implement source-control methods for stormwater management (Parkinson and Mark, 2005), there has been limited research into the potential for green stormwater infrastructure in developing countries other than Brazil. Having recognized that urban drainage must be integrated with planning, Brazil is transitioning towards a drainage paradigm that more closely resembles that of developed nations (Goldenfum et al., 2007; Silveira, 2002). Detention basins have been introduced in some Brazilian cities, but the widespread adoption of detention techniques has been limited due to resistance to new concepts and ideas on the part of stormwater engineers (Baptista et al., 2005; Goldenfum et al., 2007).

The lack of technical knowledge regarding infiltration, storage, or water quality also limits their use, and frequently leads to a lack of proper maintenance of ponds that are built (Goldenfum et al., 2007). Dense urban environments also provide limited space for larger-scale practices such as detention basins. Planners and engineers are also understandably reluctant to install costly detention ponds given the real or potential threat of contamination with fecal matter and other forms of solid waste (Silveira, 2002). Attempts to bring smaller controls to developed contexts will likely face similar problems.

Like most research covering urban drainage in developing countries, Goldenfum et al. (2007) and Silveria et al.'s (2002) contribution to the literature is largely focused on documenting the barriers to implementation of more environmentally sound stormwater management practices. While they do cite general solutions such as institutional integration, long-range planning, implementation of laws to enforce the construction and proper maintenance of detention basins, and the education of designers, legislatures, and the general public (Goldenfum et al., 2007), the timeframe of potential gains from these solutions is long-term. The large-scale control and treatment strategies they examine also continue to ignore the root causes of excess runoff—impervious cover and inadequate infiltration capacity. Research into short and medium range solutions is needed to immediately improve the quality of life of the most vulnerable residents of developing countries—those living in informal settlements.

Potential Advantages of Green Stormwater Infrastructure in Developing Countries

Potentially lower retrofit and lifecycle costs

Due to the limited resources available to local governments, cost considerations are frequently the driver of local government decisions in developing contexts. This is especially true for the costs of upgrades to informal communities—while informal settlements place a great strain on existing infrastructure and services, they typically do not contribute a high proportion of taxes or rates to pay for the expansion of those services. Grey infrastructure investments are costly for all governments, especially those that are chronically overextended by unplanned development. Local governments in a developing context also must consider the potential relocation costs incurred due to the displacement of residents that is often necessary to make room for large grey infrastructure projects in dense informal communities. Any strategy that could reduce costs while retaining functionality could greatly enhance local government's ability to address flood risk in informal communities. Decentralized approaches to stormwater retrofits have been shown to remedy the negative consequences of stormwater runoff more cost-effectively than upgrading traditional centralized systems (Thurston et al., 2003), and they can be implemented without disrupting large tracts of land. The multifunctional nature of green stormwater infrastructure also adds to its efficiency, potentially reducing public expenditures on other infrastructure such as potable water, water treatment, and sanitary sewers.

In an EPA (2007) review of 17 projects that include Low Impact Development Practices (LID), the total capital cost of construction savings ranged from 15 – 80%, with one exception in which costs were greater for the LID development. Because the current study investigates the feasibility of installing green stormwater infrastructure LID in a densely urban context, the costs associated with retrofits are more relevant to the current study. While the case studies predominantly compared the costs of implementing LID versus conventional development practices on an undeveloped tract, three cases compared the costs of retrofitting an existing urbanized area with LID practices versus upgrading the existing conventional stormwater infrastructure. While Vancouver, Canada's Crown Street redevelopment cost an estimated 9% more than upgrading the existing conventional system, Seattle's Street Edge Alternative (SEA) redesign of a residential block cost 25% less while retaining an impressive 99% of surface runoff. Another notable retrofit is the case study of two parking lot retrofits in Bellingham Washington, in which installing rain gardens saved an estimated 77% over installing conventional underground vaults. Because underground vaults are frequently used in dense urban contexts common to developing countries, and are used throughout Santo Domingo, such a drastic cost reduction suggests that LID retrofits could be viable in developing contexts as well. A separate review of installation costs associated with LID development conducted by ECONorthwest (2007) found modest cost savings across the board for retrofit projects.

From the perspective of a private developer, the up-front installation costs associated with a particular development approach are far and away the most important cost metric. From the perspective of the municipal decision-makers that would carry out a retrofit project in a developing context, however, such an examination excludes key considerations of cost-effectiveness and operations and maintenance costs over time. The existing literature suggests that these lifecycle costs are also smaller or comparable to conventional stormwater systems. Brewer and Fisher (2004) modeled the cost-effectiveness of installing LID stormwater controls in varying contexts. Their analysis found that while the LID scenario cost more for the school and commercial context, all four of the modeled scenarios managed a larger volume of stormwater than the conventional design scenario, extending the useful life of the infrastructure. Using data on the national average of construction costs per cubic feet of stormwater detention, ECONorthwest (2007) further analyzed the Brewer and Fisher's results to calculate the future construction costs avoided due to the LID scenarios' additional storage capacity. In both the school and commercial development models, the LID scenario's future cost savings surpassed its up-front cost overruns by a margin of at least $38,000. While the

Brewer and Fisher study did not include future operations and maintenance costs in its analysis, Vesely et al. (2005) conducted an analysis comparing the life cycle costs of a conventional versus low impact retrofit of a residential development experiencing frequent localized flooding due to inadequate drainage infrastructure in North Shore City, New Zealand. The LID retrofit consisted of an engineered system of gravel ditches, trenches, bioswales, and rainwater cisterns. Their analysis concluded that the cisterns and pumps must be replaced more frequently than pipes, leading to 6% higher lifecycle costs than a conventional system upgrade. Notably, this analysis also found that maintenance costs associated with the gravel trenches and channels was considered insignificant, suggesting that LID approaches relying solely on such systems could see considerably lower life cycle costs.

Human capital can be leveraged immediately for short- and medium-term gains

In the absence of large investments of physical capital from overstretched local governments, a decentralized approach is also advantageous in that it can be implemented more or less immediately and by communities themselves. Individual SCMs can be constructed incrementally as time, space, and availability of materials allows. Many infiltration-based SCMs can be constructed of cheap and commonly-found materials such as sand, gravel, compost, and PVC pipe, and no special equipment is needed. What is needed, however, is the human and social capital necessary to construct and ensure the continuing functionality of a large number of individual small-scale stormwater controls. Human capital is the knowledge, skill, and experience of an individual, whereas social capital is when individuals share and bring these capabilities to coordinated activity (Coleman, 1988). In informal communities, human and social capital is often the only form of capital readily available—as a result, these communities often have robust networks of formal and informal social ties that can be leveraged for a community-based, decentralized stormwater management system.

While Reed (2013) found that delegating the maintenance of traditional grey infrastructure to community groups was rarely successful, a decentralized approach differs from traditional approaches in that each SCM contributes to runoff retention largely independently of other SCMs in the network. Whereas a centralized network must be managed as a whole in order to preserve function, a failure in one decentralized SCM does not affect the functioning of the other parts of the network. Because of the dispersed nature of the urban runoff problem, in fact, sustainable stormwater solutions are significantly hamstrung without the engagement of private landowners. Such a bottom-up, incremental stormwater management program is also advantageous in that it can operate within the extant legal framework, without the need for new governmental authority or regulatory action.

Since 1999, the EPA has recognized that community engagement is particularly important to decentralized stormwater management because issues of private property rights, land access, and community acceptance of an unfamiliar technology pose significant barriers to implementation and long-term functionality of the program (USEPA, 2007). Since that time, requirements for municipalities that discharge stormwater directly into receiving water bodies have included public education and outreach and public participation and involvement among the menu of measures that communities must use to reduce the discharge of polluted stormwater (Green et al., 2012). For example, as part of their compliance with the EPA's Combined Sewer Overflows (CSO) regulations, the City of Portland implemented a Downspout Disconnection Program (City of Portland, 2015). The program gave homeowners in selected neighborhoods the opportunity to disconnect their downspout from the combined sewer system, allowing their roof runoff to drain to gardens and lawns. Residents earned $53 per downspout if they did the work themselves, or community groups or local contractors performed the disconnection—community groups earned $13 for each downspout. When the program was ended in 2011, over 56,000 downspouts had been disconnected, removing more than 1.3 billion gallons of stormwater annually from the combined sewer system. (USEPA, 2007; City of Portland, 2015).

In order to investigate the effectiveness of a decentralized, public-engagement focused stormwater management strategy, the EPA conducted a six-year study on the public participation and stormwater effects of an incentive-based approach to "citizen-based stormwater management" in an impaired urbanized watershed in Cincinnati, Ohio (Green et al., 2012, p. 1669). After a direct mailing education campaign and the establishment of demonstration rain gardens and rain barrels at the local arboretum, the researchers held reverse auctions in which eligible landowners placed bids on how much they desired to be paid to receive a 16 m^2 rain garden or 75 gallon rain barrel. This reverse action quantifies the homeowner's valuation of the opportunity cost of losing the portion of their yard occupied by the SCM. In two rounds of reverse auctions in 2007 and 2008, 81 rain gardens and 165 rain barrels were installed on 75 properties within the 1.8 km^2 watershed. The overall impact of the installations was a small, but statistically significant decrease in stormwater volume at the subcatchment scale—resulting in an estimated 360 m^2 (360,000 liters) increase in detention capacity for excess stormwater runoff (Shuster et al., 2013; Mayer et al., 2012). In one micro-watershed area of around 50 houses with particularly high participation rates, this increase in detention was enough to decrease stormwater quantity relative to pre-management conditions at the neighborhood outfall for smaller rain events. It is also notable that over half of the bids were for $0, meaning that many property owners were willing to participate in the program for no financial compensation.

Another potential mechanism for an increased suitability of this model for informal contexts is seen in Woodward, Hunt, & Hartup's (2008) evaluation of the North Carolina Backyard Rain Garden Program, in which the homeowner's reasons for adopting the rain garden appeared to correlate with how well the rain garden was functioning two years later. The program conducted a series of "How to Rain Garden" training workshops to avid gardeners, environmentalists, school groups, homeowners who lived on the lake that the rain gardens were intending to protect, and homeowners who were required by law to build a rain garden; the program then shared the costs of constructing the rain garden with the homeowner. The rain garden sites were revisited two years after installation to evaluate their condition. Good condition meant the rain garden was functioning as designed, had been maintained, and adequate storage volume had been maintained. Fair rain gardens had not received maintenance, but retained at least some functionality. Both the avid gardeners and the homeowners that lived within sight of the lake had high levels of maintenance, with 93% and 100% of rain gardens in good or fair condition after two years, while the other groups maintained only 67% in good or fair condition.

This increased attention to maintenance for avid gardeners and households with a direct connection to the resource suggests that rain garden adopters in Los Platanitos may also be, on average, more conscientious caretakers of rain gardens and rain barrels. As documented in Sletto ed. (2014), the residents of Los Platanitos have a high level of household plant production, and take great pride in their green spaces. Most households in Los Platanitos, Los Trinitarios, and Santa Cruz also have a direct connection to someone that lives *abajo*, or in the lower portion of Los Platanitos that is susceptible to flooding. Perhaps as a result of this daily engagement with those affected by flooding, any potential rain garden adopters with be more likely to keep them in working condition.

Given the limited capacity of many developing countries to provide adequate stormwater infrastructure to all of its citizens, this model of providing small incentives and/or support to private landowners to construct and maintain green stormwater infrastructure deserves attention. Especially in informal settlements that are facing immediate flooding problems, such a community-based provision of decentralized stormwater infrastructure could serve as a way to quickly leverage limited resources and human capital for short- and medium-term gains. In fact, the existence of ready-made, well-developed social networks and the lack of adequate public infrastructure may make community-based stormwater management *more* viable in informal contexts than in the developed world.

CHAPTER THREE: Planning, Urban Governance, and Stormwater Management in Santo Domingo

Planning and Urban Governance in Santo Domingo

Urban drainage problems in Santo Domingo are primarily the result of rapid population growth due to massive rural-to-urban migration during the mid to late twentieth century (Torres, 2014). The pressure that rural-to-urban migration puts on growing municipalities, and the stress that this population growth puts on environmental systems, is compounded by the consequences of the shift to neoliberal forms of governance in the 1990s.

The history of urban planning—and by extension stormwater management planning—in the Dominican Republic (DR) has been largely driven by national political and economic developments. During the administration of the dictator Rafael Trujillo from 1930 to 1961, planning was characterized by a highly modernist and centralized approach. The country saw a rapid economic growth under Trujillo, and with it, the construction of the major street grid, government complexes, housing complexes for evicted residents of informal communities, and the expansion of the highway system (Torres, 2014). Trujillo's planners also oversaw the construction of centralized stormwater system. With less population and the city covering less area, the system functioned with 6 inch connection tubes and 1 meter by 1 meter storm sewers (*colectores*), using gravity to send the water to the Rio Osama or the sea (A. Miceli, personal communication, August 2014). In the words of Alfonzo Miceli, a stormwater engineer for Santo Domingo Distrito Nacional:

> *In the era of Trujillo there was less population…Trujillo never thought that there would be trucks carrying soft drinks, plantains, concrete, etc., and the streets functioned very well—the drainage functioned well. But the population grew, with a lack of awareness, and the people began to take the tops off the sewers.*

After Trujillo's assassination in 1961 and the ensuing years of instability, Joaquín Balaguer's election and establishment as a "strongman"(caudillo) in 1966 largely marked a return to the centralized, modernist planning carried out by Trujillo. Balaguer's administration established a National Planning Office (Oficina Nacional de Planificación) and continued to expand the highway system, construct new public administration complexes, and build 5,000 new public housing units. During this time period, rural-to-urban migration greatly increased due to rural underdevelopment and expulsions by foreign landowners to accommodate more sugar plantations (Torres, 2014; Muraya, 2006). With an inadequate supply of formal housing despite the construction of public housing units, many rural migrants settled on the edges of the Ozama River. Following the common trend of establishing informal settlements in areas that are publicly owned, unoccupied, and close to job opportunities, this area became site of the first large-scale informal settlements in the city. Other informal settlements developed in other parts of the city, many of which were similarly unsuitable for intensive land development due to flood risk. Situated at the confluence of two major rivers, Santo Domingo is home to hundreds of natural drainageways, known in Santo Domingo as cañadas. With 55 urban creeks throughout Santo Domingo Norte alone and numerous other creeks draining to the Rivers Osama and Isabela from the other districts of the metropolitan area, there are countless flood-prone informal settlements throughout Santo Domingo. By 1977, informal settlements contained 74% of the city's population (Muraya, 2006).

The 1970's also saw the rise of neoliberal economic theory as well as the issuance of loans to the DR through the International Monetary Fund (IMF). The consequences of these two developments would result in an eventual shift in the national governance and planning paradigm towards a decentralized, horizontal approach. The beginning of this shift was prompted by the "Volker Shock" in 1981, when the Federal Reserve raised US interest rates to over 20% in order to curb high inflation. Because much of Latin American external debt, including that of the DR, had been contracted at floating interest rates, this shock led many Latin American countries to the brink of default, setting off what is now known as the "third world debt crisis." (Ocampo, 2014). In response to this crisis, President Salvador Jorge Blanco approved an IMF package in 1984 that renegotiated the DR's external debt, but this renegotiation was contingent on several structural adjustments aimed at deregulating and opening the Dominican economy to foreign markets (Torres, 2014). Through the 1990s and 2000s, the Dominican government was pressured to undertake fiscal reform aimed at cutting government spending and borrowing, increasing tax revenues, cutting public works projects, dismantling subsidies on staples, and lowering trade barriers (Greenberg 1997).

The emergence and eventual embrasure of this neoliberal economic model has resulted in a "rollback" of investment in the provision of basic services, as well as a decentralization of planning authority to underfunded local governments. With the restructuring of the Comisión de Asuntos Urbanos (Urban Issues Commission, CONAU) into a consultant role as the Dirección General de Ordenamiento y Desarrollo Territorial (DGODT) within the Ministerio de Economía, Planificación, y Desarollo (Ministry of Economy, Planning, and Development, MEPyD), planning power has effectively devolved from national to local governments. At the same time, public spending cutbacks have led to a persistent lack of technical, administrative, and financial capabilities in local governments (Sletto, 2014), as well as a privatization of many basic services such as solid waste removal and potable water. In 2001, the decentralization effort resulted in the creation of the new municipality of Santo Domingo Norte, in which Los Platanitos is located, as part of the division of Santo Domingo into five municipalities (Sletto ed., 2014; SDN, 2013). As a completely new public entity lacking technical and economic resources, Santo Domingo Norte faced significant challenges in governing the primarily informal and new residential development.

The privatization of most basic services, coupled with spending cutbacks, has largely left the poorest segments of society out of the recent economic rebound. Although the DR is now classified as an upper-middle income country by the World Bank, 40% of the population lives below the poverty line while 20% of the population account for fully half of the nation's income (World Bank, 2013; Torres, 2014). Nearly 15% of the population lives in informal settlements, and more than half of the population lacks land titles (Torres, 2014; MEPyD, 2013). This unemployed, underemployed, and informally employed segment of society largely live in inaccessible areas and provide little in the way of tax revenues. As a result, they are largely ignored by private service providers and local governments alike (Sletto, 2014). Large portions of the population do not have access to the most basic of services—35% of the population does not have access to clean tap water, 22% have no indoor plumbing, and only 11.4% are connected to adequate stormwater infrastructure. From 1990 to 2000, the portion of urban residents with sustainable access to safe drinking water actually decreased by 2.5% (COPDES and UNCT, 2004).

In the 1990s and 2000s, public discontentment with neoliberal policies grew, and protest was loudest in those sections of the populace most affected by inadequate provision of public services. The public protested, at times violently, about lack of security in public places, inadequate access to education, lack of waste collection services, and poor preparation in the face of hurricanes. Especially after the DR joined the Central American Free Trade Agreement, civil society groups and intellectuals called for improved public administration and greater attention to the needs of the urban poor (Torres, 2014). In 2009, the government responded to growing criticism by adopting the Law of Participatory Budgeting, which gave further autonomy to municipalities and required them to dedicate a certain percent of their tax revenues to projects developed through a participatory process. Ostensibly, participatory budgeting both reduces the clientelism that has characterized politics in the DR since Trujillo and directly satisfies needs of the public. And while this model seems to be functioning well in the Distrito Nacional, very few other municipalities comply with the law's requirements (Chantada, 2014). According to Juan Torres, a former Senior Planner who was responsible for the participatory budgeting process in the Distrito Nacional until March 2015, "the relevance of the participatory budgeting process and the extent of local influence depend to a large degree on the capacities and commitments of the mayors and city councils." (Torres, 2014, p. 572). In other words, those municipalities that are already weakened due to a lack of technical and economic capacity are rarely able to effectively wield the tool of participatory budgeting. In Santo Domingo Norte, the process has been described as "opaque" (Sletto et al., 204, p. 576), "haphazard, politicized, or not implemented at all" (Torres, 2014, p. 572).

In response to the devolution of planning authority to local municipalities and the increased availability of resources for civil society groups through the participatory budgeting process, new types of planning actors have emerged in Santo Domingo. Civil society groups that initially protested neoliberal reforms have taken advantage of the participatory budgeting process to present alternative, community-based planning solutions to urban problems. For example, the Fundación de Saneamiento Ambiental de la Zurza (Fundsazurza) has partnered with the Distrito Nacional to conduct household solid waste collection their community, a service that was not previously provided by the municipality. As a part of an agreement that provides US$25 to the organization for each ton of solid waste collected, Fundsazurza is also responsible for other services such as tree trimming, maintenance of street lighting, removal of animal carcasses, and the cleaning and beautification of public places (Mendoza, 2014). This community-based service provision model could potentially be replicated for stormwater management.

The intersection of the hydrologic consequences of increased urbanization, informality, and neoliberal governance in Santo Domingo produces a situation in which those populations most vulnerable to flood impacts are also the most likely to live in flood-prone areas. At the same time, the overall lack of technical, administrative, and financial capabilities in local governments brought about by decentralization has greatly diminished the possibilities for effective flood mitigation in informal settlements. This combination of local, national, and global forces that exacerbate vulnerability in Los Platanitos are reproduced throughout the city.

City-wide Stormwater Management Practices

As discussed above, high rates of rural-to-urban migration to informal settlements and the devolution of planning authority to local governments has produced a situation in which virtually all natural drainageways pose a flood hazard to vulnerable residents, and municipalities are ill-equipped to effectively deal with this hazard. The stormwater management practices reflected in the following section are derived from interviews with stormwater engineers from the Distrito Nacional, which, as the seat of the capital, is by far the most well-funded and technically advanced municipality in the country.[1] These strategies and opinions that follow, therefore, represent the best practices of the Dominican Republic as a whole, rather than practices particular to Santo Domingo Norte where Los Platanitos is located. However, in conversations with the Director of Planning it became clear that the stormwater management practices of the Distrito Nacional represented the

[1] The stormwater engineers and planning professionals all gave their consent for their names to be used in this document. The resident interviewee have been given a pseudonym to protect their privacy and confidentiality.

model for Santo Domingo Norte. Because Santo Domingo Norte has a much smaller workforce and technical capacity than the Distrito Nacional, drainage concerns are typically handled by the Public Works Department as a part of road construction or a participatory budgeting project (J. De la Cruz, personal communication, August 2014). Without a stormwater engineer dedicated specifically to drainage infrastructure, Santo Domingo Norte's stormwater approach draws heavily on the practices in the Distrito Nacional described here.

Like many developing countries, stormwater managers in Santo Domingo are too preoccupied with problems of excess runoff quantity to consider water quality and stream health a top priority. The immediate threat to lives and property that urban flooding poses occupies most of their time, leaving little time to question the preeminence of the sanitary model of urban drainage. As discussed earlier, the object of the sanitary model is to convey excess stormwater as rapidly as possible away from settled areas to waterbodies via open channels and buried conduits. The absolute acceptance of this institutional philosophy was reinforced many times in my conversations with stormwater engineers and planners throughout the Distrito Nacional and Santo Domingo Norte. Numerous interviewees spontaneously cited the massive tunnel that was built to ensure that the Metro does not flood as the ideal urban drainage solution (J. Torres, A. Miceli, Y. Batista, J. De la Cruz, personal communication, August 2014). Besides this overarching stormwater paradigm, the other main drivers of stormwater decisions include a desire to keep roads clear of flooding (J. De la Cruz, personal communication, August 2014), as well as a preference for avoiding the relocation of residents (J. Torres, personal communication, August 2014).

Even though the Distrito Nacional is the best-equipped to deal with urban stormwater problems, the decentralization of power without the allocation of sufficient resources to effectively wield that power has resulted in a highly reactive approach to stormwater management. The aging infrastructure built during Trujillo's administration only covers the old city center, with 59 km of storm sewers serving 16% of the area between the Haina River, Arroyo Guzman, Arroyo Manzano, the Isabela River, Ozama River and Avenida Charles de Gaulle. While a consultant completed a stormwater plan in 1997, it has not been implemented by the municipality. Unsurprisingly, it is a traditional plan composed of centralized system of covered sewers that discharge stormwater directly into a river or the sea (Auding-Watson, 1997; J. Diaz Anderson, personal communication, August 2014). Rather than implement a comprehensive stormwater plan, stormwater engineers respond to complaints from citizens and implement projects that emerge out of the participatory budgeting process. Far from proactively providing a network of stormwater solutions that serves current needs and future population growth, this reactive approach can barely keep up with acute flooding problems, nor can it prevent stormwater systems from negatively impacting influencing other water systems such as natural water bodies, potable water systems, and sanitary disposal systems (Y. Batista, personal communication, August 2014).

The technologies that are used to implement this reactive approach include sewers, inlet filters, oil/grit separators, and inlet registers aimed at preventing trash from entering and clogging the drainage system. Sewers are built and maintained by the city, but larger tunnels are outside of the financing capabilities of the municipality (Y. Batista, personal communication, 2014). With over 2,400 installed in Distrito Nacional alone, one common practice in the DR that is not widely used in the US is *filtrantes* (filters). *Filtrantes*, known as infiltration boreholes in the US, consist of simple 4 – 8 inch boreholes that perforate the aquifer (60 ft – 170 ft). Stormwater then directly recharges the aquifer and eventually reaches the sea. *Filtrantes* can be bored directly into the ground wherever there are ponding problems, or the Distrito Nacional will also drill them under inlet filters or oil/grit separators to alleviate pressure on the undersized sewer system. This use of *filtrantes*, widespread in Santo Domingo because of its low cost, only resolves localized ponding. They are only effective when the receiving soils have a high permeability and the well is properly preserved during its lifetime. These conditions are rarely met—*filtrantes* frequently clog with debris, trash, and sediments, and many households also use them to dispose of human waste. Fecal matter not only clogs the *filtrantes*, but this practice has led to contamination of the aquifer (Auding-Watson, 1997).

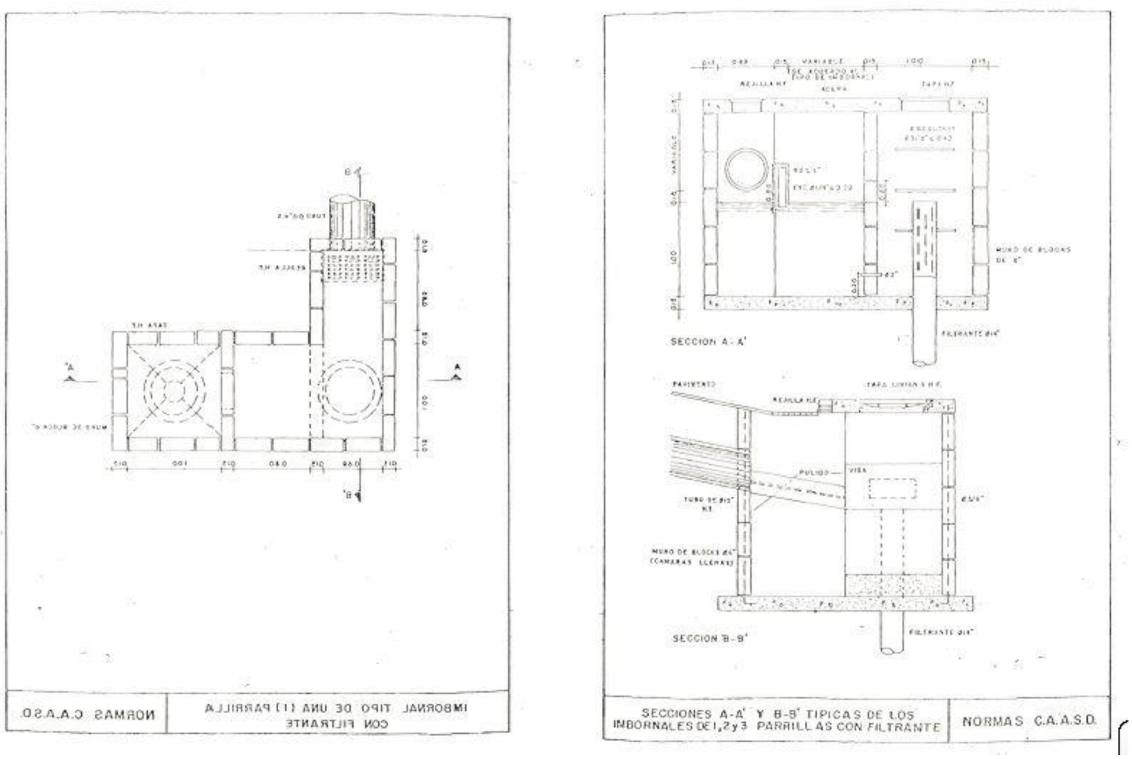


Figure 1 Two-Chambered Trash and Oil-Grit Separator

According to the stormwater engineers I interviewed, by far the most pressing challenge to effective stormwater management in Santo Domingo is trash accumulation in the streets and gutters. Far from being a problem only in marginal communities such as

Los Platanitos, trash inhibits the free flow of stormwater throughout the capital. Even in areas where household trash is collected regularly, bags of trash are often simply left on the side of the road until the truck comes to pick them up because there is no alternative location or facility such as a dumpster. In a climate characterized by short periods of intense rainfall, these bags are rapidly carried into the stormwater system during storm events. Furthermore, public trash bins are rare outside of tourist areas and people frequently throw trash into the street. All of this trash eventually obstructs stormwater controls, which greatly increases maintenance costs. Inlet filters and registers must then be cleaned out after every major rain event to preserve their functionality. If a *filtrante* becomes clogged, it is usually just allowed to fill up and cease functioning; it is more expensive to clean them out than to simply drill a new borehole. The root cause of this problem, of course, is a lack of proper solid waste disposal services and sanitation services, which were largely privatized in the shift to neoliberal governance. The stormwater engineers tend to make a more proximal attribution for the trash problem, however, citing a lack of education on the part of the public.

> *In our country, in order to do the easiest thing that have the most functionality, we first have to educate the citizenry. Because they throw trash in the street, the trash travels down the gutters, and it travels through the oil/grit separator, into the sewers, and into the filters—and it clogs the filters. The cost of unclogging a filter is the same as constructing another one...So, in order to make our technical work more efficient, to do what has to be done to manage stormwater, we have to first educate the public. (A. Miceli, personal communication, August 2014)*

While a lack of public education and conscientiousness certainly plays a part, many simply do not have any alternative to placing their trash on the side of the road.

The second most pressing problem identified by the stormwater engineers is a lack of financial resources, which, along with the massive maintenance burden due to trash accumulation, forces management to be reactionary instead of planning for the future. Ing. Yadira Batista explains the problem: “Apart from the trash, the biggest problem is that there aren’t a lot of resources to work with. When we work at a site and construct a stormwater system, it takes a long time to return to maintain it because we focus on other problems throughout the city. So when we do return to the site, the previous work is already totally deteriorated” (Y. Batista, personal communication, August 2014). This same dynamic has played out in Los Platanitos, where numerous small fixes have been made to add capacity to the channel, but most of these fixes are no longer functional. This lack of resources also forces the stormwater engineers to choose short-term solutions that they know are less effective than other solutions on the basis of cost. Both Alfonzo Miceli and Yadira Batista agree on the solution—“[Sewers] would be the definitive solution, for the filters don’t have a very long life—they are a short-term solution” (Y. Batista, personal communication, August 2014)

Thirdly, it is important to note that while the stormwater engineers that I interviewed were not familiar with the overarching paradigm of decentralized stormwater management, they did have an understanding of its underlying principles (J. Torres, A. Miceli, Y. Batista, J. De la Cruz, personal communication, August 2014). Ing. Yadira Batista was very aware of the relationship of impervious cover to increasing stormwater volumes: “Before, there were lots of green areas. There weren’t as many buildings and the soil absorbed the water and filtered it. But now since they have made so many buildings, and the natural soil is no longer there.” Furthermore, the concept of infiltration-based stormwater controls is not foreign to any stormwater engineer in Santo Domingo: they are commonplace in the form of an infiltration boreholes. Ing. Yadira Batista and Juan Torres were also familiar with infiltration trenches, which use gravel and a perforated pipe to serve as a storage volume as the surrounding soil infiltrates stormwater. This understanding of the basic building blocks of a decentralized stormwater management network suggests that, if convinced of its efficacy and provided sufficient resources, Dominican stormwater engineers could rapidly learn to implement such a system.

While this familiarity with basic green stormwater infrastructure concepts is encouraging, there are still many barriers to implementing a decentralized stormwater management model in Santo Domingo. First and foremost, none of the engineers I interviewed thought it was a particularly good idea. Most expressed the opinion that it wouldn't work in the DR and that large tunnels would be a better solution. Even though Yadira Batista and Juan Torres were both familiar with infiltration trenches, neither recommend this system because the water remains on the site as it slowly infiltrates into the soil. This aversion to standing water is common among those who are newly introduced to green stormwater infrastructure (Earles et al., 2009), and it is true that poorly maintained controls can become clogged and cause nuisance ponding. Similarly, the notion that massive tunnels would be the ideal solution reveals a lack of familiarity with the negative water quality and wildlife externalities of such solutions, as well as a lack of knowledge about the comparative costs. This following response from Ing. Yadira Batista reveals a misunderstanding of the relationship between stormwater and water pollution: "What I think they should [use] are the sewers, because water in those is well-treated. They conduct stormwater—stormwater doesn't contaminate; it is just rainwater" (Y. Batista, personal communication, August 2014). Stormwater running off clean impervious surfaces such as roofs can be very clean, it is true, but the vast majority of impervious surfaces throughout Santo Domingo are covered in contaminants of all forms.

Another challenge to implementing infiltration-based methods for stormwater management is that the drainage department is limited in what it can do because it has no authority to regulate impervious cover, urban form, or the streetscape. Planning in Santo

Domingo, and the DR as a whole, is highly fragmented—the Planning Department regulates greenspace on a site, while Public Works designs and constructs all the streets and gutters, and Drainage performs maintenance on the roadside controls. Each department is funded though separate processes, interdepartmental coordination is uncommon, and what is essential to one department may not be highly valued by another. For example, Ing. Yadira Batista relayed to me the typical evolution of an urban parcel, and how this process produces illegal subdivisions and a subsequent high degrees of impervious cover:

> *"The planning department is in charge of regulating the amount of green space on a site—the permits and things like that. It would be good to work together with the planning department and to develop a solution…What happens is that everyone has their little house, and they go buying land to construct a building, and they put down money to build an apartment, and [the planning department] doesn't say no to that."*

And even if stormwater managers could limit impervious cover, change the streetscape to better accommodate infiltration trenches, or get the Planning Department to abide by its own existing regulations, it is very difficult to enforce building codes in Santo Domingo. According to Alfonzo Miceli, lax and corrupt enforcement results in developments where the building plans have little relation to what actually gets built.

> *When the planning department is reviewing the plans, they have to have their sanitary and stormwater systems, but I will tell you, here in this country the rules are almost never followed. It is that same lack of awareness, and also the [inspectors] are for sale. There are some that are very serious, but others that aren't—just like all the countries on their way to development.*

Without adequate supporting regulations and enforcement, it is virtually impossible to introduce sustainable stormwater management practices from the top-down. The controls will simply not get built. However, another alternative is to approach the problem from the bottom-up—with a community-based stormwater management model.

Water-Related Infrastructure in Los Platanitos, Los Trinitarios, and Santa Cruz

I initially only set out to investigate how stormwater infrastructure is planned and implemented in Santo Domingo and specifically in Los Platanitos, as well as the potential for incorporating a decentralized stormwater managagement approach into the existing framework. As I conducted interviews with professionals and residents, however, it became apparent that in a developing context, stormwater infrastructure cannot be examined in a vacuum. Because of a lack of formal planning and the predominant reliance on the self-procurement of most water-related services in informal settlements, the stormwater infrastructure, potable water systems, household water systems, and sanitary systems are all interrelated. The following section outlines how the stormwater system currently functions in the informal settlement of Los Platanitos, but it also highlights the intersections of potable water provision and sanitary disposal.

Los Platanitos is composed of largely rural migrants and situated on land deemed unsuitable for formal development due to its steep slopes, proximity to a natural drainage way, and the fact that it had been previously used as a landfill. Is it located on the southeastern extremis of the Rio Isabela watershed, just northwest of where it meets the Ozama River and flows into the Caribbean Sea. The neighborhood is situated in a steep canyon, traversed by two major and three smaller channelized creeks that converge at a natural low-lying collection and retention area called La Piscina. La Piscina drains into the Yaguasa River, which then flows into the Isabela River. The capacity of the formerly natural channel has been expanded through piecemeal municipal projects over the course of several years, but this capacity has largely been lost due to sedimentation, trash accumulation, and degradation of the infrastructure. Due to the lack of capacity and the large volume of runoff coming from the communities of Los Trinitarios, Santa Cruz, and the arterial Avenida Hermanas Mirabal, the channel frequently overflows during periods of heavy rainfall and floods the nearby homes. In interviews with residents directly adjacent to the principal channel, Sletto ed. (2010) found that 75% of residents' homes had flooded within the past year, and 58% had flooding severe enough to force them to leave their homes. This problem is only exacerbated by the accumulations of uncollected trash that are swept from the curb to clog the inlets that drain to the channel. Much of this trash eventually makes its way into the channel, which causes blockages downstream.

Figure 2 Stormwater Management in Los Platanitos. Clockwise from top left: a) A child sweeps runoff from Hermanas Mirabal to an inlet that drains to the channel. b) An inlet to the channel. c) High levels of impervious cover. d) Trash accumulations in the channel frequently block the free-flow of water. e) Trash and contaminated water is carried into an inlet that drains to the channel. f) Illegal connections to the household water system. Photographs by Kelly Strickler.

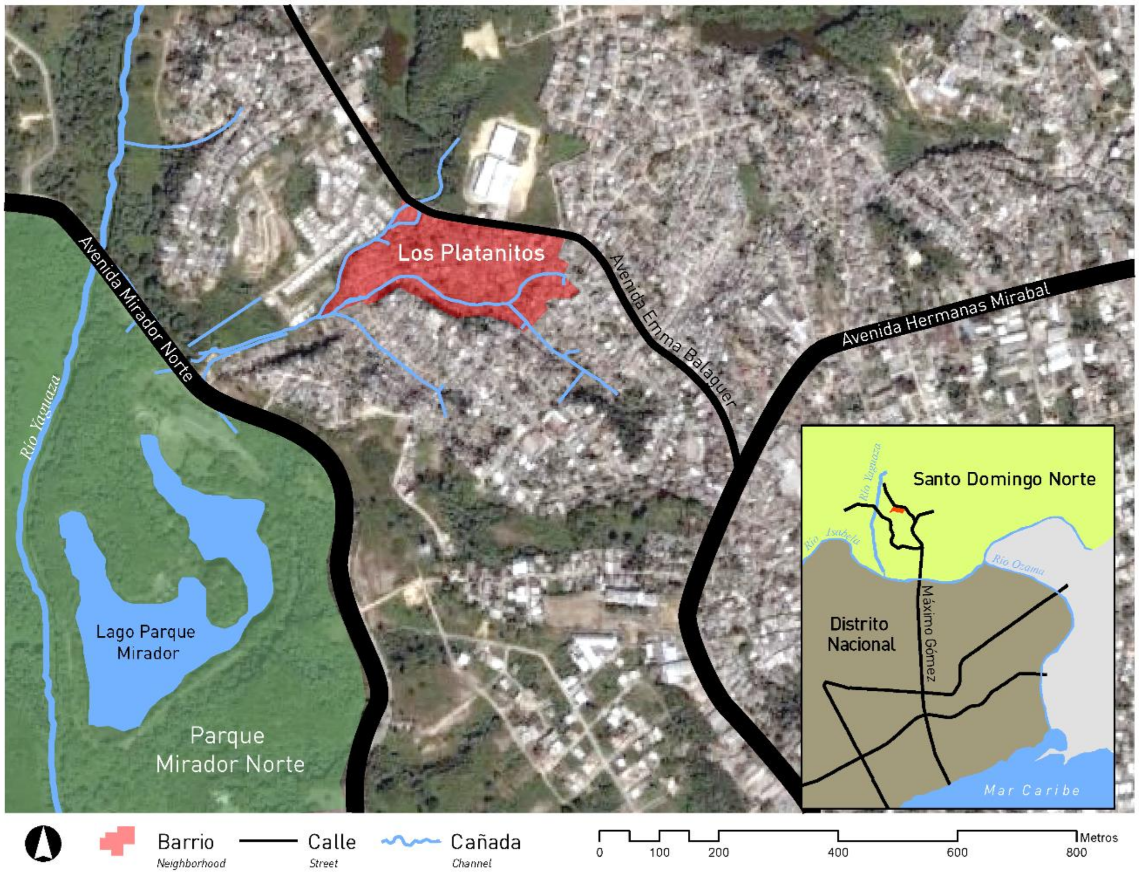


Figure 3 Santo Domingo Norte and Los Platanitos

As the community of around 2,000 residents has low incomes and high levels of unemployment, underemployment, and informal employment, the residents are particularly vulnerable to flood impacts (Sletto, ed. 2010). Residents who live at lower elevations near the channel, and who are therefore subject to more frequent flooding, tend to have lower incomes than those who live at higher elevations. As indicated by a vulnerability and risk assessment carried out by UT students in 2008, residents of the lower portion of the neighborhood have an estimated median income between USD $60-100, whereas upper portion has an estimated median income between USD $200-$345 (Sletto, ed. 2010). Thirty-nine percent of adults in all elevations of Los Platanitos work in the informal sector, while 48% of working-age adults are unemployed (Sletto, ed. 2010). These low income and employment levels make residents of the neighborhood more vulnerable to flood impacts, for they lack the necessary resources to mitigate the problems associated with flooding such as sickness, loss of income, and loss of property.

In addition to the hazard posed by periodic flooding, the channel also presents a threat to residents' health and quality of life because here is no functional separation between stormwater and sanitary sewers in Los Platanitos, nor in any other informal settlements in Santo Domingo Norte. Indeed, sanitary systems for the safe disposal of human waste are very limited in Santo Domingo Norte—only 27% of the population is connected to a separated sanitary system, and many of these systems were constructed by independent organizations. There are 16 water-treatment plants throughout the metropolitan area, but most of these are not in service (SDN, 2013). For the most part, these dedicated sanitary systems discharge wastewater containing fecal matter directly into the river or sea—only three percent of wastewater is processed by a wastewater treatment plant (J. Diaz Anderson, personal communication, August 2014; SDN, 2013). Under these circumstances, stormwater not only has the potential to damage property and pose an inconvenience to residents in these marginal communities—it also poses an imminent public health threat.

Because Los Platanitos and the upland neighborhoods of Trinitarios and Santa Cruz are not serviced by dedicated sanitary systems, human waste disposal becomes entirely the responsibility of individual households. Of the 11 interviewees from the communities surrounding the channelized creek, no one reported that their homes were connected to a system provided by the local municipal government; i.e. the *Ayuntamiento* of Santo Domingo Norte. The methods used for disposing of human waste vary depending on the resident's proximity to the creek and level of income. For residents with lower incomes, who tend to live in the steepest slopes of the valley or in the floodplain, the only feasible option for removing human waste from the area is to connect their toilets to the creek via a run of 3 inch PVC pipe. Residents living in the uplands of the creek (i.e. in higher elevations) are able to employ a more varied mix of sanitary solutions. Some can afford septic systems that trap solid wastes while allowing bacteria-laden water to travel into the creek. Others drill infiltration boreholes to deposit their waste in the aquifer. While the wealthier can marginally treat their waste or hide their contamination by perforating the aquifer, all of these practices are hugely damaging to water quality. Sletto ed. (2010) documented that the principal channel had levels of biologic oxygen demand between 15 and 36 mg/l; measurements above 6 mg/l are considered unacceptable. These results, coupled with high levels of ammonia, indicate that the water in the channel is highly contaminated by organic waste. As a result, the fecal matter in the open channel poses an imminent health hazard to those who live near the creek. Because the presence of *E. Coli* and *Leptospira interrogans* (among other bacteria) is a chronic health hazard rather than an infrequent, albeit serious occurrence, one prominent member of Fundación Los Platanitos (FUMPLA) thinks that the contaminated water surpasses flooding in terms of priorities for neighborhood improvements (M. Rodriguez, personal communication, August 2014; Sletto, ed. 2012). Furthermore, the cumulative effect of the disposal of such vast quantities of human waste into the urban hydrologic system has significantly degraded the water quality of the Osama, Iguaza, and Isabela Rivers, leading to a loss of aquatic species and the overgrowth of algae and water hyacinths (Consultores Ambientales y Pesqueros, 1998).

Another consequence of the lack of separation between water supply and wastewater disposal in Los Platanitos is that access to sustainable sources of potable water has diminished as the area has seen increased urbanization. This is a common occurrence throughout the metropolitan area—according to the Millennium Development Goals Needs Assessment, sustainable access to safe drinking water actually decreased in urban areas from 1990 to 2000 (COPDES and UNCT, 2004). In Los Platanitos, this decreased access to safe drinking water is largely due to contamination of groundwater sources and the unreliable provision of potable water. While Los Platanitos was founded as a peri-urban settlement that relied on groundwater sources, the aquifer has since become highly contaminated due to thousands of infiltration boreholes that have been drilled into the aquifer to mitigate localized flooding. Unfortunately, because most of these wells are also used as sewage outlets, the aquifer is highly contaminated and water must be provided from upstream parts of the aquifer or river (Gilboa, 1980). Residents must now rely on the Corporación del Acueducto y Alcantarillado de Santo Domingo (CAASD) to bring in potable water from upstream portions of the rivers Osama and Isabela. This increased pressure on CAASD from rapid urban development without concurrent public investment, as well as the high number of illegal connections, has in turn resulted in a lower level of service. Almost no one I spoke with received potable water with any regularity, and everyone had to rely on bottled water or trucked-in water for at least some portion of their potable water requirements.

As uncontrolled development continually adds impervious surfaces upstream, flooding will only worsen in Los Platanitos without some sort of solution. The *Ayuntamiento* of Santo Domingo Norte currently lacks the capabicity to adequately address the problem. Since the Mayor's bid to upgrade the channel in 2006 was not approved and funded by the central government (J. De la Cruz, personal communication, August 2014), representatives of the municipal administration have on various occasions suggested that the *Ayuntamiento* would soon develop a flood-mitigation project, but no actions have been taken yet. Unfortunately, Los Platanitos is still not officially recognized as a separate neighborhood, and as a result, it is poorly represented in the participatory planning process. Despite all of these barriers, however, there exists local capacities to develop a community-based storm water management system from the bottom up.

Santo Domingo's rapid population growth during the mid to late twentieth century, coupled with the shift to neoliberal forms of governance, has placed immense strain on both the environment and local governments. Consequentially, water-related services such as potable water, sanitary sewers, and drainage are provided in a highly reactive fashion, if they are provided at all. Services are rarely extended to informal settlements such as Los Platanitos, leading to a situation in which the most vulnerable populations live in those areas most likely to experience frequent flooding. Due to its ability to be employed incrementally, at a low cost, and by citizens themselves, a green stormwater infrastructure approach to stormwater management warrants consideration as a way to alleviate flooding in informal settlements. Concentrating on modeling the potential flood impacts and evaluating the community's capacity to carry out such a program, this study investigates the feasibility of implementing source-control methods such as rain gardens and rain barrels to reduce flooding in Los Platanitos.

CHAPTER FOUR: Research Design and Methods

Antecedents

The community of Los Platanitos is part of an ongoing participatory research effort in which students from UT Austin School of Architecture collaborate with residents to address challenges facing the community, largely concentrating on issues surrounding solid waste disposal. These collaborative research projects were carried out in January and March of 2008, 2010, 2012, and 2014. Previous research has been largely confined to the immediate area around the channel, but investigators have identified drainage into the community from other neighborhoods as a significant contributor to flooding (Sletto, ed. 2010). I participated in the research efforts during two weeks in January and nine days in March of 2014, in which our research team conducted an investigation of the spatial distribution and cultural significance of plants within the community. Before I spent any time in the community, however, I decided to first familiarize myself with the area through geospatial analysis as a part of my coursework in CRP 386, Introduction to Geographic Information Systems.

In the months preceding my first visit to Santo Domingo, I conducted a desktop study that aimed to explore my personal interest in the multifunctional nature of green infrastructure while also familiarizing myself with the geography and hydrology of the area that I was going to be working in. Through a combination of geospatial analysis and hydrological modeling using the ArcMap 10.2 and the EPA's System for Urban Stormwater Treatment, and Analysis INtegratration (SUSTAIN) and Stormwater Management Model (SWMM) modeling software, this project quantified the possible decreases in runoff through the upstream implementation of three types of green infrastructure. Because I knew the residents of Los Platanitos had lower incomes on average and received only limited support from the local government, I chose to investigate the storm water impacts of small-scale interventions that could be implemented quickly, relatively cheaply, and with little reliance on actors outside of the neighborhood. The following table outlines the three scales of intervention that were investigated using the hydrological modeling tools.

Table 1 Green Stormwater Infrastructure Models Used in 2013 Desktop Study

	Operationalization within the model	*Scale*	*Cost*	*Constraints*
Model 1	1 ft x 1 ft x 2 ft planters	Individual to household level	Very low	Availability of compost
Model 2	Rooftop gardens/Green roofs	Household level	Medium	Costs and maintenance
Model 3	Bioretention cells	Neighborhood level	High	Need to obtain land-use rights

After determining the feasible placement and number of these types of intervention based on a suitability analysis within the modeled subwatershed, the stormwater impacts of these interventions were projected using the EPA's SWMM modeling software. Out of the three intervention types, the model showed that only the large-scale bioretention cell had any detectable effect on overall subwatershed runoff and system flooding. These results influenced my decision to more closely examine a distributed network of rain gardens, because, when functioning together, such a network should approximate the volume reduction of one larger cell. While the preliminary geospatial analysis certainly informed the direction of the present project, I had to make many assumptions to construct the model and any statements about the feasibility of implementation lacked a grounding in the environmental, political and economic realities of Santo Domingo Norte.

After completing the geospatial analysis in December of 2013, I traveled to Los Platanitos in January and March of 2014 to participate in the UT Austin School of Architecture community-based research project. Building upon previous research efforts which helped to establish a vermicomposting project in the community, our research focused on investigating whether adaptive capacities surrounding household plant production could enhance community resilience and potentially serve as a foundation for a reconceptualization of the vermiculture project as a source of integrated, community-based development. During my time in Los Platanitos, I was struck by how community members took great care to make sure that even the smallest piece of outdoor space always looked presentable and beautiful—the path in front of a house was swept multiple times a day, a single potted plant was prominently displayed, or a dilapidated house was brightly painted. This obvious attention to neatness and aesthetics in turn informed my choice of proposed SCMs, for community members would not be interested in implementing solutions in their personal space that they found ugly or untidy.

Overall Research Design and Justification

During the planning phase of this project I selected a mixed-methods research design that utilized semi-structured interviews with institutional actors, structured interviews with middle-income neighborhood residents, detailed field mapping of the creek's watershed with local experts, and field testing of soil infiltration rates. This mixed-methods approach was chosen to both identify the geophysical parameters of the area that drive the selection of potential interventions as well as understand the sociocultural, political, and economic realities that could influence the implementation of those interventions.

In addition to these primary data collection methods, supplementary materials such as previous studies, legal documents, observed rainfall volumes, plans, maps, and historical aerial photography were obtained from participants and relevant institutions. Concurrent with a review and analysis of this secondary data, I also conducted a literature review of current practices and theory in stormwater control to develop an understanding of the geophysical limitations, design considerations, maintenance requirements, and costs associated with each potential stormwater control measure.

Institutional Actors Interviews

I conducted semi-structured interviews with institutional actors from the Corporación del Acueducto y Alcantarillado de Santo Domingo (CAASD) and the *Ayuntamientos* of Santo Domingo Norte and the Distrito Nacional. These interviews were intended to provide details regarding current stormwater practices, the potential for alternative practices, and institutional barriers to implementing a green infrastructure approach stormwater management in the informal settlements of Santo Domingo. Participants were recruited through two primary means: 1) personal contacts from my previous visits to Santo Domingo, and 2) the personal and professional contacts of the engineer Juan Torres, a longtime local partner of UT's research efforts. The interview questions were constructed to be open-ended to allow participants to answer freely, encouraging unanticipated responses and covering issues that participants found most relevant and important. If time constraints allowed, I discussed interview questions with Juan Torres beforehand in order to ensure that the questions were understandable and appropriate to the context. I also formulated alternative wordings and explanations to standardize how certain concepts were described to participants.

Interview questions were tailored to the expertise of the participants. For example, questions for the stormwater engineers covered practical matters regarding current stormwater controls such as materials costs, labor inputs, effectiveness, maintenance requirements, and institutional barriers to implementing a green infrastructure framework for stormwater control. I first read the participants a verbal informed consent and then asked if they would permit me to make a voice recording of the interview. Participants were largely allowed to direct the conversation, and supplemental questions were frequently spontaneously interjected to clarify any topics that had not been included in the original interview questions. Participants were allowed to refuse to answer questions or stop the interview at any time. At the end of the interview, I asked if they could provide any additional written or electronic materials such as plans, maps, or previous studies.

Santa Cruz/Los Trinitarios Interviews

I also conducted a purposeful interview questionnaire with residents in the middle income communities surrounding Los Platanitos about their perceptions of flooding, their knowledge and interest in stormwater control practices, and the form and efficacy of potential incentives for implementing such practices. Interviews were concentrated in these communities because they are situated in the most promising area for the implementation of SCMs due to the larger prevalence of private outdoor space and the homes' location in the flat, upland areas of the creek's watershed. These interviews were aimed at developing an understanding of the feasibility of implementing SCMs in the private yards of this community, as well as the potential community-level barriers and resources that could be leveraged to carry out such a plan.

Participants were largely recruited through the contacts and knowledge of my guide and local expert, Elias Brito Reynoso. Mr. Reynoso was integral to my research activities in the communities surrounding Los Platanitos—he served as a guide and local expert on topography and hydrology, ensured my safety, and connected me with knowledgeable residents. Interviews took place in the participant's yard, place of business, or home. I first read the participants a verbal informed consent and then asked if they would permit me to make a voice recording of the interview. While the line of questioning was more structured than the institutional actors' interviews in that each resident was asked the same series of questions using the exact same wording, residents were encouraged to direct the conversation towards topics they deemed most relevant and important. Depending on the participant's perceived level of interest and patience with the process, supplemental questions were sometimes spontaneously interjected to clarify any topics that had not been included in the original interview questions. Finally, I asked the participant if I could take pictures of their yard and home.

Field Mapping

While limited topographic and digital elevation models are available for the area, these resources are not highly detailed and cannot account for the modifications to the natural hydrology as a result of man-made features such as roads, gutters, and pipes. For this reason, field mapping with knowledgeable residents was required to develop a detailed representation of the subwatersheds of the three arms of the channelized creek. I enlisted two area residents as local experts and research assistants: Elias Brito Reynoso, a member of the Fundación Los Platanitos and resident of Santa Cruz, and Juan Francisco Correa, a resident of Los Platanitos who lives in the uplands to the north of the creek. Each local expert was interviewed separately during the field mapping of their respective neighborhoods.

After I explained the purpose of the exercise and oriented the local expert on a map that I had prepared using ESRI's ArcMap 10.2, the local expert first led me around their neighborhood while pointing out where storm flows came from and to which arm of the creek they were directed. With the help of the local expert, I marked these locations and directions of flow on a map I had created based on the work of previous UT research groups. This map had major roads, alleys, and a limited number of building footprints superimposed over georeferenced aerial photography obtained from Google Earth. On major roads and alleys, the local experts were often able to articulate the exact location where storm water begins to flow from the streets and into the creeks. In other words, they were able to define the watershed boundary within a few feet. This process of purposefully walking the entirety of the neighborhood also provided an opportunity for the local experts to explain other important locations within the community. For example, Juan Francisco Correa pointed out a natural lagoon that had previously stored a large amount of rainfall before draining to the northwest channel, but that is now being systematically filled-in by the mattress factory to the north of the community.

After finishing this walk of the neighborhood, I sat down with each local expert to draw a continuous line that divided up the subwatersheds of the principal channel and its two tributaries. This line connected the various reference points, using the local experts' knowledge of the topography to fill in any gaps. Both local experts were unsure of the location of the northern limit of the northwest channel's watershed due to the complexity of the lagoon system and the fact that the border extends outside of their immediate neighborhood. For this northern boundary, I made a conservative estimate based on my previous desktop study and other topographical information at my disposal (this process is further described in the Watershed Modeling section of this chapter). The final product was a georeferenced map with a detailed representation of the subwatersheds of each arm of the channelized creek that runs through Los Platanitos.

On a separate walk of each local expert's neighborhood, I quickly walked down each street recording the number of houses with no visible unpaved outdoor space and those with sufficient unpaved outdoor space for the installation of a rain garden. The purpose of this exercise was to extrapolate the percentage of homes in each neighborhood that could potentially support a privately-maintained rain garden or rain barrel.

Field Testing

In order to evaluate the feasibility of the use of infiltration-based SCMs and to establish design infiltration rates to calculate the potential impact on stormwater volumes, it was necessary to estimate a representative infiltration rate of the soils in the upland areas that contribute to the channelized creek. I adapted the field testing method from the City of Austin Environmental Criteria Manual (ECM) section 1.6.7.4, Infiltration Rate Evaluation. This section provides various methods of determining the design value for an infiltration rate, depending on the type of SCM proposed and the resources available to the designer. Because of the limited availability of accurate soil survey maps, other geotechnical information, and the heavy equipment needed for other testing methods, I chose the Percolation Test for its simplicity and cost effectiveness. Meant for investigating infiltration facilities with drainage areas less than two acres and with maximum ponding depths of 12 inches, the Percolation Test as described in the ECM can be conducted using simple tools and manual labor, and does not require extensive excavation. Before leaving for Santo Domingo, I accompanied an engineer from the City of Austin Watershed Protection Department as he performed a percolation test in order to learn the technique.

Ideally, the percolation test should be performed at the site of each proposed rain garden or other infiltration-based SCM site. In the case of this investigation, it would have been preferable to test multiple sites across Santa Cruz and Los Trinitarios to account for potential variability in soil composition. Unfortunately, it was infeasible to organize a large number of percolation tests due to the necessity of returning over the period of two days and the unease that many residents felt at the idea of digging a hole in their yard. For these reasons, I performed only one infiltration test at the home of Elias Brito Reynoso, one of the participatory researchers.

I dug the test hole in a location that was deemed most suitable for a rain garden—it could easily capture runoff from the house's roof with a minimum amount of tubing and its position close to the exterior wall of the yard made for a short, direct path for excess water to the existing street gutters. The ECM specifies that the test hole should be between 8 and 12 inches in diameter, with a depth that corresponds to the proposed bottom elevation of the control. Because I used a conventional shovel to excavate the soil rather than a post-hole digger, the resulting hole was irregular and I had to estimate an approximate diameter. The hole was dug to 12 inches, a common rain garden depth. Because the design infiltration rate is based on saturated conditions to obtain the most conservative estimation, the test hole must be pre-soaked to approximate saturated conditions. I poured water into the hole to pre-soak it, and testing was commenced after all of the water had percolated. In cases of slow percolation or time constraints, the test is typically performed between 15 and 26 hours after the pre-soak. I placed a piece of wood over the top of the hole to serve as a datum from which depth measurements were made. I then filled the hole with water, and recorded this water elevation and the time it was taken. This process was repeated until all the water had percolated. I calculated the steady-state percolation rate as the change in water elevation (in inches) by the corresponding time interval (in hours). Finally, I converted the steady-state percolation rate (p) to a representative infiltration rate (i) using the reduction factor (Rf) as follows, which accounts for water losses through the sides of the percolation hole:

$i = p/Rf$

The reduction factor (Rf) is given by:

$Rf = ((2d1 - \Delta d)/D) + 1$

Where:

D1 = water depth at start of representative time interval (in.)

Δd = water level drop during representative time interval (in.)

D = diameter of percolation hole (in.)

Watershed Modeling

Upon my return the United States, I used information obtained from field mapping and field testing to create a model of the watersheds of the principal channel and its two tributaries using EPA's Stormwater Management Model (SWMM) 5.1 software. After constructing the model, I conducted an analysis of potential runoff reductions due to the implementation of rain gardens and rain barrels. SWMM 5.1 uses watershed properties such as percent impervious cover, slope, and soil infiltration rate to estimate the runoff generated from a watershed during a simulated rain event (or series of rain events). This runoff is then routed through a modeled conveyance network of conduits and junctions, where it is eventually discharged at an outfall. When the runoff inflow from the upstream conduit is within the design capacity of the downstream conduit, the inflow simply drains through the downstream conduit. If the inflow exceeds the design capacity of the downstream conduit, however, only a part of discharge can be drained by the outflow conduit. This portion of the discharge which exceeds the design capacity surcharges onto the ground surface, causing flooding.

SWMM can account for various hydrologic processes that produce runoff from urban areas, including the capture and retention of rainfall and runoff with various types of decentralized stormwater control measures (called LID practices by the model) (USEPA, 2010). It does not explicitly model spatial variability, but spatial variability can be mimicked by partitioning of the study area into individual subcatchments based on land feature characteristics (Pathirana; USEPA, 2009). Table 2 summarizes the source of each model parameter and how it was estimated, and the estimation methodologies are further explained below. Because this study is intended to estimate the flood impacts of the proposed system of rain gardens, SWMM's ability to estimate the production of pollutant loads associated with runoff was not utilized at this time.

Table 2 Principal Model Elements, Estimation Methods, and Sources

Required Elements	*Estimation Methods*	*Sources*
Watershed Boundaries	Field mapping	Interviews and walks with knowledgeable community members
	ArcMap's Hydrology toolset + 30 meter ASTER Global Digital Elevation Model	USGS Earth Explorer, 2013.
	Analysis of 2008 team's watershed boundary	Sletto ed., 2008.
	Analysis of SRTM Level 2 Synthetic Drainage Network	USGS Center for Earth Resources Observation and Science (EROS), 2007.
Percent Impervious Cover	Digitization of aerial imagery	Google Earth and ArcMap Basemap
Soil Infiltration Rate (Saturated Hydraulic Conductivity, or k_{sat})	Field testing	City of Austin Environmental Criteria Manual, section 1.6.7.4
	Analysis of soil maps + consulting with a biofiltration pond engineer	Ministry of the Environment and Natural Resources, 2015. Rodríguez and Pineda, 1981. Tom Franke, personal communication, March 2015.
Rainfall Parameters	Synthetic storm generation using the Intensity-Duration-Frequency curves provided in the Santo Domingo Drainage Plan.	Keifer and Chu, 1957 Auding-Watson, 1997
Existing Drainage System	Based on principal channel measurements taken during initial vulnerability and risk assessment.	Sletto et al., 2008.
Rain Garden and Rain Barrel Parameters	Potential rain garden size estimation	Interviews and walks with knowledgeable community members
	Number of homes with sufficient pervious area estimation	Sletto et al., 2014
	Number of rain garden adopters from pool of eligible households estimation	Mayer et al., 2012 Green et al., 2012
	Model conceptuazlization	Simpson, 2010. Tom Franke, personal communication, March 2015.

Watershed boundaries

The watersheds of the principal channel and its two tributary channels were estimated using a combination of multiple sources of information: 1) field mapping with knowledgeable residents, 2) ArcMap's Hydrology toolset and a 30 meter Digital Elevation Model (DEM) obtained from NASA and Japan's Ministry of Economy, Trade, and Industry (METI) Shuttle Radar Topography Mission, 3) results of previous UT researchers' attempts to identify the channel's watershed, and 4) the SRTM Level 2 Synthetic Drainage Network obtained from the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS). Because the watersheds derived from each of these sources of information conflicted with each other and urban watershed boundaries are highly dependent on human modifications of the landscape, the watershed divisions used in the final analysis are a conservative estimate that placed the most value on local knowledge. When knowledgeable community members were unsure about watershed boundaries, I retained the information that was consistent across all of the supplementary data sources.

In Figure 4 below, watershed divisions based on local knowledge are represented as solid lines, while those that are based on less reliable information are represented as dashed lines. The "potential drainage areas"polygons, represented as black dashed lines, are areas that could potentially also contribute to flooding problems in Los Platanitos. Whereas the community members interviewed in 2008 indicated that Residencia Vista del Parque discharged its stormwater into the northern tributary, this was not confirmed during my interviews. The community members that I interviewed believe that the most of the runoff generated from the housing development, situated to the northeast of the community, drains directly to the river. This seems to be corroborated by the presence of a ridgeline roughly along the green dotted line in Figure 4, but it is entirely possible that the community members I interviewed were mistaken and the development's runoff drains directly to the northern tributary. There are numerous stormdrains from the development to the northern tributary. Similarly, the runoff from Hermanas Mirabal north of the metro station very likely drains to the principal channel. Runoff from Hermanas Mirabal was frequently cited as a major contributor to flooding. Because the community member I interviewed could only confirm that it came from "around the bend" (E. Reynoso, personal communication, August 2014), however, I could only be confident in extending the watershed boundary to that point.

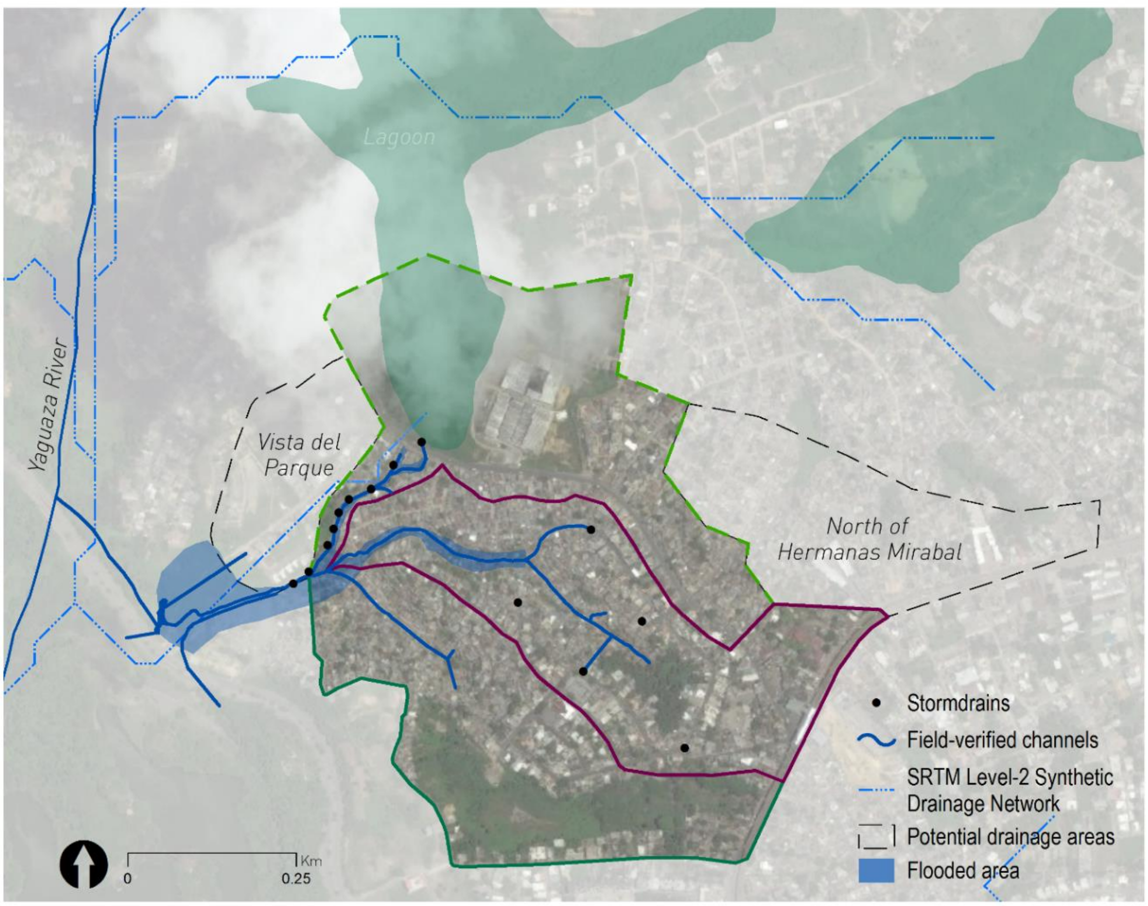


Figure 4 Estimated Watershed Boundaries

The uncertainty regarding the watershed boundaries depicted in Figure 5 are largely due to the unavailability of high-resolution topographical information and the high degree of urbanization within the watershed. Although the METI Shuttle Radar Topography Mission has produced the highest resolution, global elevation data to date, multiple attempts to use it to delineate channel subwatersheds have proved that it is not detailed enough to delineate watersheds at this scale. Important topographical details that would be provided by a high-resolution (1.5 m) LiIght Detection And Ranging (LIDAR) dataset, which is typically used for this purpose in the United States, are lost. The watershed delineation process from the desktop study produced a singular channel that does not correspond to the known channels. Even after reconditioning the DEM to "burn" the field-verified stream channels into the DEM, the output watersheds significantly overlapped with a nearby USGS synthetic stream, the presence of which was verified using Google Earth. Because this USGS synthetic stream is much longer than the study channel and crosses the largest portion of the lagoon, it is likely that this larger stream drains the majority of the lagoon system, with the study channel draining the southern lagoon (this interpretation of the area's hydrology is a refinement of Sletto ed.'s initial assessment of risk and vulnerability in 2008, which provided a highly generalized estimate of the channel's watershed based on limited data and rapid field observations; see Figure 5). For this reason, I chose to estimate the northern boundary (represented by a green dashed line in Figure 4) based on all the information at my disposal.

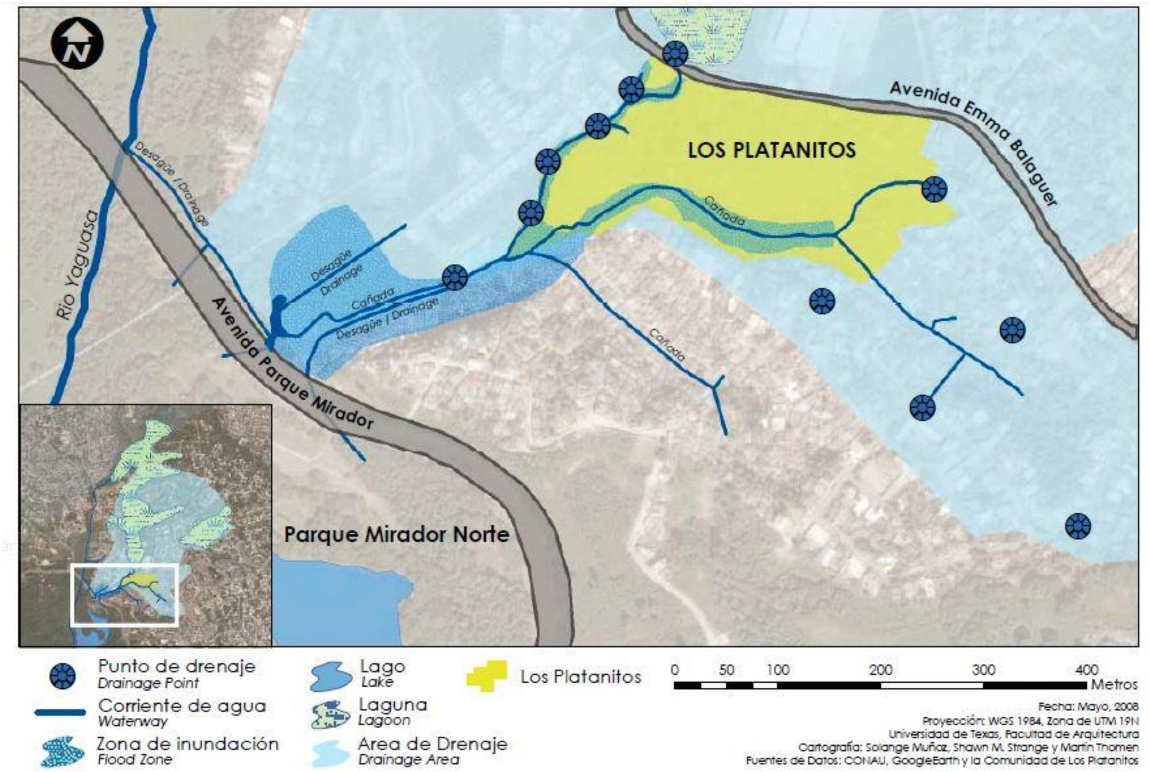


Figure 5 The University of Texas Researchers' Estimate of the Principal Channel's Watershed (Sletto ed. 2008)

Percent directly connected impervious cover

The percent impervious cover of each subwatershed was developed from Google Earth and ArcMap's Basemap imagery using ArcMap's editing toolset. Areas that appeared to be impervious were traced and added to the building footprints shapefile developed by Sletto ed. (2008) and modified by subsequent community-based research efforts. The resolution of this imagery was sufficient to detect road and buildings in conventionally developed areas. In the informally developed areas, however, roofs are constructed of whatever material is available, and are not usually constructed as one cohesive unit. With low-resolution imagery, it is difficult to tell between an irregular dark piece of zinc and tree canopy. The limitations of the imagery likely lead to mistakes in the digitization of impervious cover. In addition to the imagery limitations, the soil is very compacted in many areas by foot and motorized traffic, rendering the soil effectively impervious. For this reason, the total impervious cover estimation is likely an underestimation due to soil compaction and imagery limitations.

SWMM uses directly connected impervious area (DCIA) as its model input, which is the impervious area that drains directly to the stormwater conveyance system without flowing over pervious surfaces. This value is typically less than the total impervious area (IA), and is a function of the predominant land uses (and their concomitant drainage practices) in a watershed. I used the total impervious area estimations to derive DCIA for each watershed using the Sutherland Equations (USEPA, 2009; USEPA, 2011). The Sutherland Equation differs for average, highly connected, totally connected, somewhat connected, and mostly disconnected watersheds. Based on the "Watershed Selection Criteria" for the equation below, I chose the "Average" watershed equation because of the areas relatively high density and the fact that almost none of the rooftops are directly connect to the conveyance system (see Table 3).

Table 3 Estimating Directly Connected Impervious Cover Equations

Watershed Selection Criteria	*Assumed Land Uses*	*Equation (where IA(%) >1)*
Average: Mostly storm sewered with curb & gutter, no dry wells or infiltration, residential rooftops not directly connected	Commercial, Industrial, Institutional/ Urban public, Open land, and Med. density residential	$DCIA=0.1(IA)^{1.5}$

Source: USEPA, 2011

Soil infiltration rate

Urban soils, and especially the soils of Los Platanitos, are very variable—soil maps are not detailed enough for the design or planning of infiltration-based controls. Prior to the design of any rain garden, field tests must be performed to determine the soil's infiltration rate, the depth of ponding that will be allowed, and the excavated area needed to capture and infiltrate the desired volume of rainfall (Tom Franke, personal communication, June 2014). Unfortunately, the percolation test that I performed in the field produced erroneous results, and I did not realize this fact until I returned to the United States. Using the methodology described in the "Field Testing" section, the infiltration rate was estimated to be 5.59 inches per hour. This infiltration rate is only found in very sandy soils, which is inconsistent with the available soil information. These erroneous results are likely due to a failure to adequately presoak the hole to depth of the bottom of the proposed rain garden.

According to the Ministry of Environment and Natural Resources webviewer, the study area is predominated by the Jalonga – Marmolejos – Caliché soil association, although those areas closest to the Yaguaza river are composed of alluvial soils (Ministerio de Medioambiente y Recursos Naturales, 2015). Although the available soil data is not detailed enough to specify where each of the three series are located, the Jalonga series is the most common in this association and has been identified as the primary soil type in Villa Mella, which is just north of the study area (Rodríguez & Pineda, 1981). Formed largely from limestone and calcerous and noncalcerous sandstone, the Jalonga series is characterized as highly friable, calcerous, rocky, shallow, and with high potential for erosion (Rodríguez & Pineda, 1981; Tirado, 2003). Its texture has been described as *franco arcilloso*, meaning loam clay with 20-45% sand, 15-52% silt, and 27-40% clay (Fernández, 2001). Infiltration rate estimates for this type of soil range from 0.03 to 0.09 inches/hour, which is not ideal for infiltration-based controls (Rawls, Gimenez, & Grossman, 1998; T. Franke, personal communication, March 2015). Due to its rockiness, however, its drainage properties have been described as "very good," and actually borders on "excessive" for agricultural purposes (Tirado, 2003). For this reason, I have chosen to use the higher estimation of 0.09 inches/hour for the hydrologic conductivity parameter of the model.

Rainfall values

Because SWMM is a dynamic rainfall-runoff model, it requires a hyetograph of rainfall over time in 5 minute to 1 hour intervals to generate runoff values (USEPA, 2010). While this information is usually obtained from rain gages or the National Weather Service in U.S. applications, the Dominican Republic's National Meteorological Office (ONAMET) only reports rainfall in a highly aggregated form (daily values). In order to develop a usable rainfall time series from available data, I obtained the intensity-duration-frequency (IDF) values in the existing Stormwater Drainage Plan of Santo Domingo. Because intensity-duration-frequency values simply reflect average rainfall intensity over the specified duration, and do not represent actual time histories, it was also necessary to generate design storm hyetographs for 5, 10, and 25 year storms using the "Chicago Method" described in Keifer and Chu (1957). The Chicago Method uses a series of equations and two constants (generated from the IDF curve) to turn the constant intensity into a peaked shape over the duration of the storm, which more closely models actual rainfall patterns (Keifer and Chu, 1957). The Chicago Method uses the following equations to generate the 5, 10, and 25 year synthetic storms depicted in Table 4.

When:

t = time

t_p = time to peak

r = rainfall fraction before peak

D_{es} = Design Storm Duration

Time to Peak = $\mathbf{t_p = r * D_{des}}$

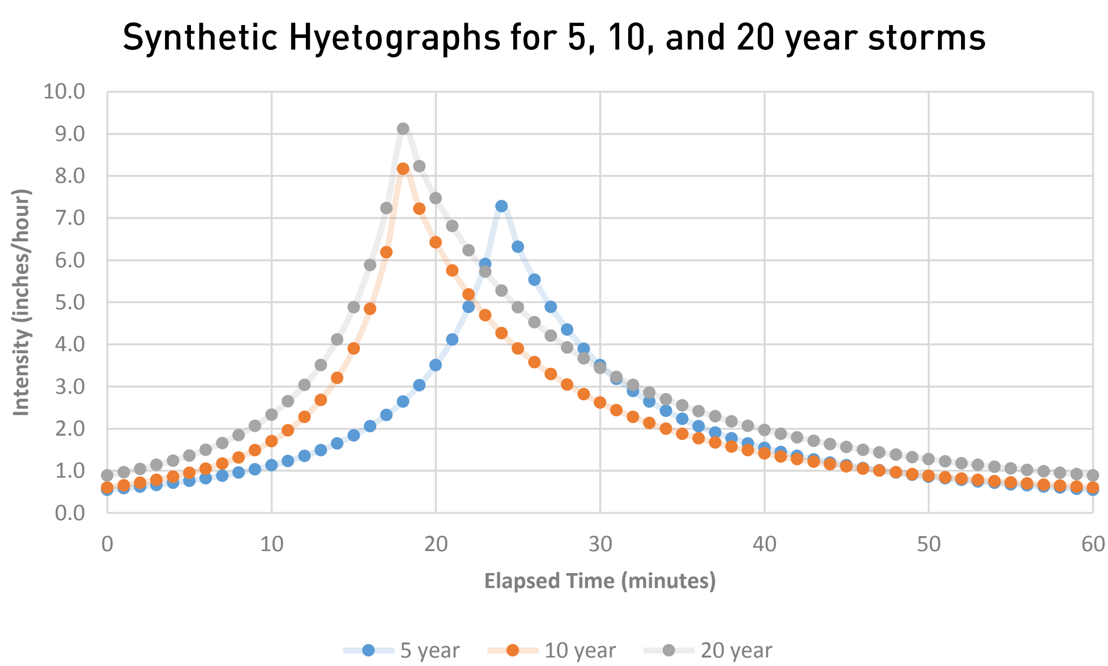
For $t < t_p$:

$$i = \frac{a\left[(1-c)(t_p - t)/r + b\right]}{\left[(t_p - t)/r + b\right]^{1+c}}$$

For $t > t_p$:

$$i = \frac{a\left[(1-c)\frac{(t - t_p)}{1-r} + b\right]}{\left[\frac{(t - t_p)}{1-r} + b\right]^{1+c}}$$

Table 4 Synthetic Hyetographs for 5, 10, and 20-year Storms



Existing drainage system

Average depth and width values for the drainage system were obtained from the detailed CAD model of the principal channel developed during the initial 2008 vulnerability and risk assessment (Sletto ed. 2008). Because depth of tributary channels were not measured in 2008, I applied the depth values of the principal channel where it joined each tributary. An estimate of Manning Roughness is also needed for open channel flow calculations. A Manning Roughness estimate for channel as a whole was determined using the method described in McCuen (1998), which uses a base n value determined by the general type of channel and then modifies the base value on the basis of various descriptors of the channel and its surface.

Table 5 Existing Drainage System Parameters

Drainage System Link	*Modeled Dimensions (meters)*			*Manning Roughness*
	Width	*Depth*	*Length*	
Principal Channel – Section 1	1.5	0.9	85.5	0.052
Principal Channel – Section 2	1.5	1.0	152.1	0.052
Principal Channel – Section 3	1.3	0.6	125.1	0.052
Principal Channel – Section 4	2.0	0.15	123.7	0.052
Principal Channel – Section 5	1.3	0.9	111.2	0.052
Northwest Tributary	0.9	0.9	415.9	0.052
Southern Tributary	1.0	0.9	682.6	0.052

CHAPTER FIVE: Rain Garden and Rain Barrel Implementation in Los Platanitos, Santa Cruz, and Los Trinitarios

Through an analysis of both primary and secondary sources, I conducted a feasibility study for the implementation of rain gardens and rain barrels in the watersheds of each of the three channels that cut through the communities of Los Platanitos, Santa Cruz, and Los Trinitarios. Given past research in the area and the geophysical parameters identified through field mapping exercises with knowledgeable residents, I estimated the potential form and number of rain gardens and rain barrels that could be expected to be installed under a potential incentive- or community-based program. Using methods derived from a review of current stormwater modeling techniques, I then estimated the potential impact on runoff volumes and flooding. I also identified resources within the community that can be leveraged to implement the stormwater control measures.

Stormwater Controls Measures Tested

Borrowing from the structure of the earlier desktop study, I had initially planned to investigate the feasibility of several SCMs which varied by the typical scale, level of public oversight, and resources required. For example, green roofs represent a medium-scale, resource-intense, and typically privately-maintained typology (New York City Department of Environmental Protection, 2010). In contrast to green roofs, roadside bioswales are usually larger scale, extending the entire length of the road, but they are also less complex to construct and maintain (Vesely et al.,2005). Roadside bioswales also require a high degree of coordination with the public sector due to their integration with the public right-of-way. Rain gardens are small to medium-sized, and require a moderate level of technical expertise and resources to construct and maintain. Rain barrels have small capture volume (55 gallons is common), but they are also the simplest to implement and maintain. Due to their small scale and limited capture volume, both rain gardens and rain barrels are typically privately-maintained.

Under ideal conditions, I would conduct a full-scale modeling and feasibility analysis for the entire suite of source-control stormwater control measures in an informal context. Given the limited timeframe of my fieldwork, however, it became necessary to narrow the focus of modeling efforts to one source-control typology. To this end, I dedicated a portion of the exploratory phase of my fieldwork to selecting the most-promising avenue. Along with other exploratory task such as verifying my understanding of the flooding problem, building relationships, and testing my interview questions, I also made several observations that led me to exclude green roofs and roadside biowales from the analysis. Their exclusion does not mean that their implementation is unwise or infeasible, however, just that the barriers to their implementation appear to be more intractable than those of rain gardens and rain barrels. Further investigation of other source control technologies could be conducted according to the same basic methodology that is described for rain gardens and rain barrels below.

Green roofs require a minimum soil volume to function effectively, and any structure must be capable of safely supporting the weight of the saturated soil and any vegetation (if vegetation is desired). Although the homes of Santa Cruz are solidly built by experienced local contractors, even the largest structures would be considered informally constructed in the United States. Construction in this area largely does not go through any sort of permitting or inspection process, and if an inspector is involved, they typically just accept the payment of the associated fees without conducting the inspection (E. Reynoso, personal communication, August 2014). It would be unwise to implement a green roof under these conditions without a site specific analysis of the roof's load-bearing capacity.

Publically-maintained roadside bioswales were also excluded during the exploratory phase. While they were initially considered because Avenida Hermanas Mirabal has been identified by community members as a primary source of excess runoff, during the field mapping exercise, I did not see any sections of Hermanas Mirabal that were not already curb-and-guttered with a 4 to 10 ft sidewalk between the road and a building frontage. With buy-in from the local government, roadside swales could potentially be implemented in the more "peri" portions of this periurban environment. In already built-out areas such as Los Platanitos, however, bioswales cannot alleviate immediate urban flooding problems without both a massive retrofit effort and a drastic change in Santo Domingo Norte's institutional approach to stormwater management.

Whereas the exploratory phase led me to exclude green roofs and publically-maintained roadside bioswales from the analysis, it also revealed that introducing rain gardens and rain barrels for flood mitigation would potentially be well-received by the community. Many residents of Los Platanitos already use a rainwater harvesting systems for non-potable household use and gardening (see Figure 6). Furthermore, it was apparent from the arrangement of household patios that many Santa Cruz homeowners took great care to tend to their yards and create interesting plant assemblages (see Figure 6). If rain gardens were successfully marketed as beautiful patio amenities, there is the potential for both widespread adoption by residents and fastidious maintenance ensuring their functionality. Thus, I chose to invest my limited time in the community exploring the feasibility of implementing rain gardens and rain barrels in Los Platanitos, Trinitarios, and Santa Cruz.

Figure 6 Existing Rain Barrel and Well-Maintained Patios in Los Platanitos and Santa Cruz. Photographs by Kelly Strickler.

Study Approach and Model Assumptions

In addition to traditional grey conveyance and storage infrastructure, SWMM is capable of modeling the runoff implications of several types of source controls such as vegetated swales, biofiltration cells, rain cisterns, green roofs, permeable pavements, and rain gardens. The feasibility study uses field observations, remote sensing, interviews with knowledgeable residents, and assumptions based on the existing literature to construct three models: existing conditions, a rain garden scenario, and a rain barrel scenario (see Chapter 3 for a more extensive discussion the development of model parameters).

The model of existing conditions in Los Platanitos, Santa Cruz, and Los Trinitarios is based on the best estimation given data and time limitations, and should not be considered an exact representation. However, while the model is not well-developed enough to accurately predict exact flood volumes, it is capable of estimating rough proportions of runoff reduction resulting from rain garden and rain barrel implementation. For modeling purposes, the watersheds of the three channels are conceptualized as the three subcatchments depicted in Figure 7. As discussed previously, these watersheds likely underestimate the influence of runoff from Hermanas Mirabal and the storage capacity of the lagoon in the Northwest. The model also does not account for the storage volume or blockage of The Piscina. When the box culvert that drains The Piscina is blocked by accumulations of trash, the capacity of the principal channel is seriously compromised, exacerbating upstream flooding (Sletto ed., 2008).

The watersheds range from 36 to 43 acres, with impervious cover percentages ranging from 32% to 52%. The principal channel watershed is the most highly urbanized, and subsequently has the most severe flooding. Those living along the channel and near the confluence of the channel arms are the most impacted by flooding—even a small reduction in flood volumes or frequency could result in significant quality of life and health improvements in those very vulnerable populations.

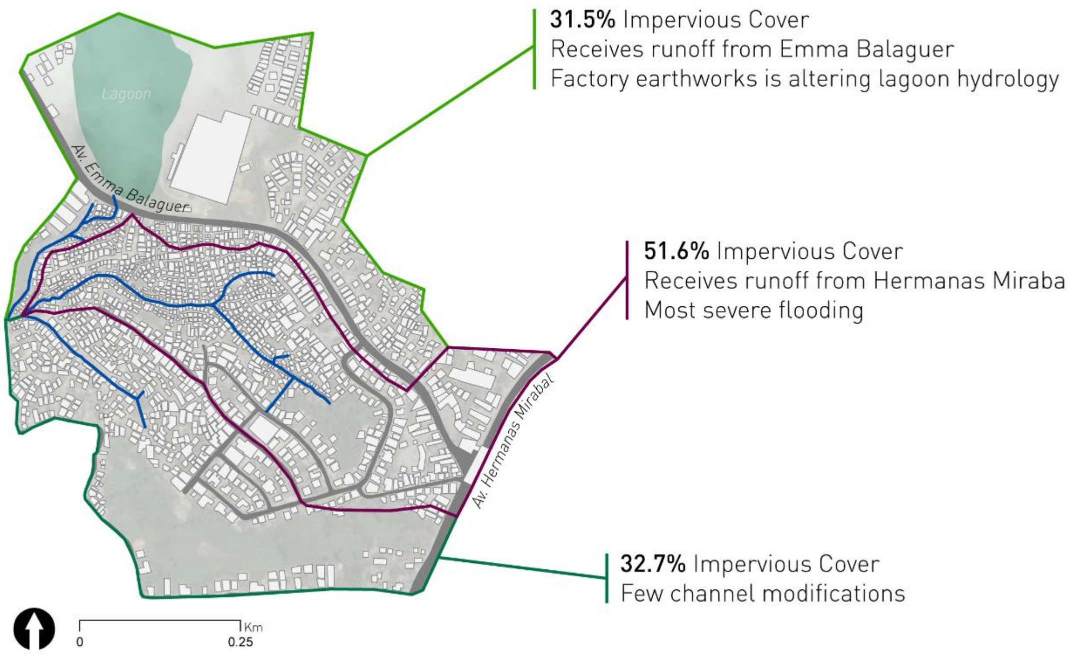


Figure 7 Study Watersheds

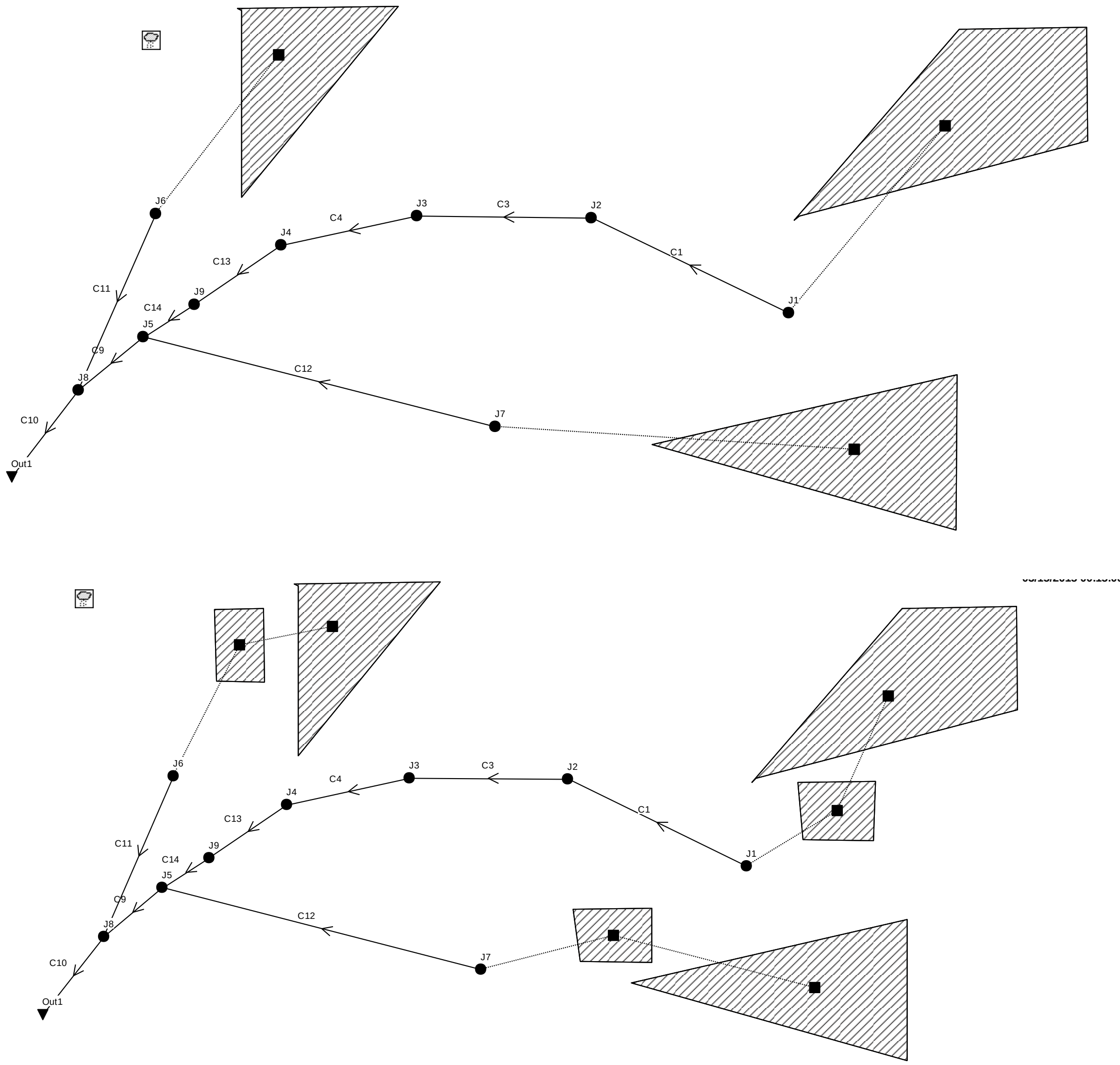


Figure 8 Existing Scenario Model (top) and Rain Gardens Scenario (bottom). SWMM does not model spatial relationships—catchments and conduits are not to scale.

To measure the potential stormwater impact of implementing rain gardens and rain barrels in the study area, I used interviews, remote sensing, field survey, past research in the area, and insights from relevant literature to estimate the number of controls that could be expected to be implemented under a potential incentive- or community-based program. From research conducted as part of our 2014 survey of household plant production practices in Los Platanitos, I was able to estimate how many households in each subwatershed have sufficient pervious area available to install a rain garden. This survey resulted in the identification of four basic patio typologies in Los Platanitos: Low-space/No-space, Small, Large, and Conuco (Sletto ed., 2014). The latter two typologies, which represent 43% of the surveyed patios (n = 14), both include sufficient pervious cover to install a rain garden, as well as sufficient space to install a rain barrel. Because the surrounding areas are of a similar or higher socioeconomic status than Los Platanitos, it was assumed that the percent of "eligible" properties applied to unsurveyed areas as well. This assumption is justified because higher socioeconomic areas were observed to have larger patios than those of Los Platanitos, giving a conservative estimate of eligible properties. Because my field survey of Santa Cruz showed that all houses had large patios, all households in Santa Cruz were considered eligible. Using the number of structures in each watershed obtained from digitizing building footprints from aerial imagery, I was able to estimate the number of total eligible households in each watershed.

Since a property owner may be using their patio space for other purposes or simply may not want to install a stormwater control, the number of eligible properties that could be expected to adopt a rain garden or rain barrel was estimated using the results of Mayer et. al (2012) and Green et al. (2012), who found that 23% and 30% percent of eligible households chose rain gardens and rainwater harvesting systems in a reverse-auction, respectively (see Chapter 1 for a discussion of this study). This assumes that any prospective program will provide the materials at no cost to the homeowner, and that some incentive will be offered to homeowners if they desire one. If these assumptions are not met, the number of controls in each watershed is likely to drop by half (half of the reverse auction bids were for $0).

Table 6 Estimated Number of Eligible and Stormwater Control Adopting Households

Watershed	Neighborhood	Total Households	Eligible Households	Rain Garden Adopters (23% of eligible)	Rain Barrel Adopters (30% of eligible)
Principal	LP + unsurveyed	883	379	87	114
	Santa Cruz	152	152	35	46
	Total	1035	531	122	160
Northwest	LP + unsurveyed	432	185	43	55
	Santa Cruz	36	36	8	10
	Total	468	221	51	65
South	LP + unsurveyed	124	124	28.5	37
	Santa Cruz	289	124	28.5	37
	Total	413	248	57	74
Total		**1,916**	**1,000**	**230**	**299**

With these estimations of the number of rain gardens and rain barrels that could be expected to be installed under an incentive program, the controls were added to the existing scenario model to estimate their stormwater impact (see Chapter 3 for a discussion of the existing scenario model). Rain gardens were conceptualized in the model as a single storage subcatchment with the combined dimensions of the estimated number of rain gardens in each subcatchment (see Figure 8) (Adams and Pappa; Simpson, 2010). The general assumptions for the stormwater control models as a whole and the parameters for each control are listed below and in in Table 7:

General Model Assumptions

1. Green Ampt infiltration model
2. The rain gardens are terraced to maximize infiltration and provide rectangular storage volumes.
3. All rain gardens are on the subcatchment level (as opposed to receiving runoff from the conduit)
4. There is no surface flow from external watersheds (run-on) (run-on from Hermanas Mirabal is likely, but it cannot be quantified)

5. Free outfall and no storage at the Piscina.
6. Rain barrels are emptied before the next rain event.
7. Rain gardens are properly installed and well-maintained

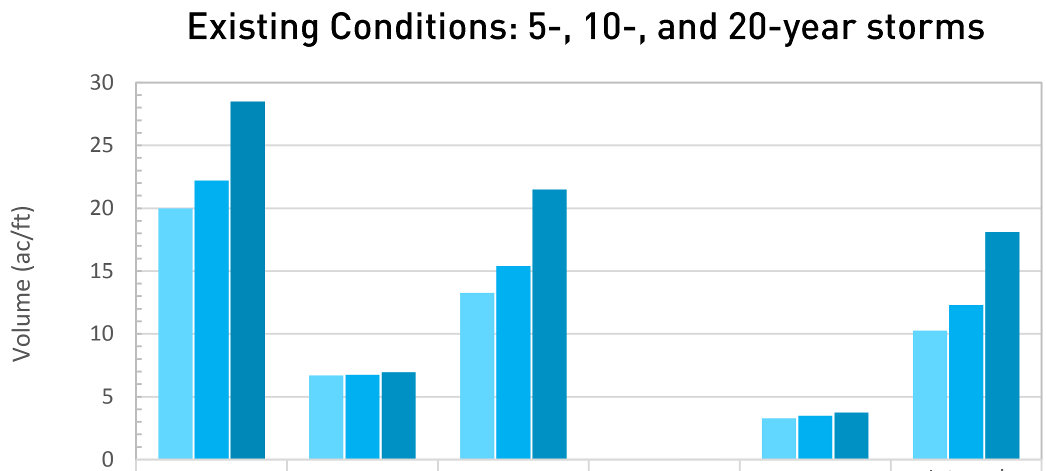
Table 7 Rain Garden and Rain Barrel Model Parameters

Parameter	*Assumption*		*Source*
	Rain Gardens	*Rain Barrels*	
Number of eligible properties	43% of structures (LP+) 100% of structures (Santa Cruz)	43% of structures (LP+) 100% of structures (Santa Cruz)	Sletto ed., 2014 Field survey
Number of eligible properties that will install control	23% of eligible properties	30% of eligible properties	Mayer et al., 2012 Green et al., 2012.
Size	13.3 ft x 3.3 ft x 0.5 ft (8 cement blocks by 2 cement blocks)	35 in tall 24 in diameter (standard oil drum)	Interviews with knowledgeable community members Tom Franke, personal communication, March 2015
Side slope	3:1	N/A	Tom Franke, personal communication, June 2014
Volume	70 ft^3	9.2 ft^3	Adams and Pappa
Rain garden slope	0.05% (assumes terracing)	N/A	N/A
Soil type	Clay loam with high gravel content	N/A	N/A
Infiltration rate (hydraulic conductivity)	0.09 in/hr		N/A
Suction head	8.27 inches		N/A
Initial deficit	0.124		N/A

The resulting mass continuity errors indicate that the models have high internal validity. The mass continuity errors for runoff and flow routing represent the percent difference between initial storage + total inflow and final storage + total outflow for the entire drainage system. If the error exceeds 10%, then the validity of the analysis results may be questioned. According to the SWMM Knowledge Base, less than 1% error is considered "excellent," less than 2% is "great," and less than 5% is acceptable (SWMM Knowledge Base forum answer, 2010). The models had continuity errors ranging from 0.03 to 3.64, all with the acceptable range. It is important to note that this measure of internal validity does not relate to whether the model accurately reflects actual conditions. Future research could enhance external validity by calibrating the parameters to values measured in the field, but this was not possible given the limited time available in the field.

Existing Conditions Results

The existing conditions modeling results are presented in Figure 9. These runoff and flooding predictions for 5-, 10-, and 20- year storms appear reasonable; as the volume of total precipitation increases from 20 acre/feet to 28.5 acre/feet, there is a proportional increase in the volume of surface runoff and internal outflow, which is flow that leaves the conveyance system through flooding at non-outfall nodes (see Figure 9). The internal outflow, hereafter referred to as flooding, is significantly greater than the external outflow (flow that leaves through the outflow node) for all three storms. While this situation is not impossible, the flooding is most likely overestimated due to an underestimation of flood storage in the lagoon and The Piscina (see Study Approach and Model Assumptions). The outflow stays relatively constant over the three storms, reflecting the limited capacity of the conveyance infrastructure, while the flooding increases with the size of the storm.



	Total Precipitation (ac/ft)	Infiltration Loss (ac/ft)	Surface Runoff (ac/ft)	Final Surface Storage (ac/ft)	External Outflow (ac/ft)	Internal Outflow - Flooding (ac/ft)
5-year storm	20.00	6.70	13.25	0.05	3.29	10.26
10-year storm	22.19	6.75	15.39	0.06	3.48	12.29
20-year storm	28.50	6.94	21.48	0.08	3.75	18.10

Figure 9 Existing Conditions: Runoff and Outflow Results for 5-, 10-, and 20-year Storms

Given the fact that many in the community flood in relatively frequent 1-, 2-, and 5-year storms, and the results of past investigations of green stormwater infrastructure that have shown the limitations of the decentralized approach to flood mitigation for larger storms (City of Austin, 2014), the subsequent analysis has largely been restricted to 5-year storms. These small and more frequent storms will see the most flood volume reduction benefit from any green stormwater controls. For the 5-year storm, a brief analysis of the runoff by subcatchment also yields predictable results, with the watershed with the highest percentage of impervious cover producing the largest runoff volumes and lowest infiltration rates (see Figures 10 and 11).

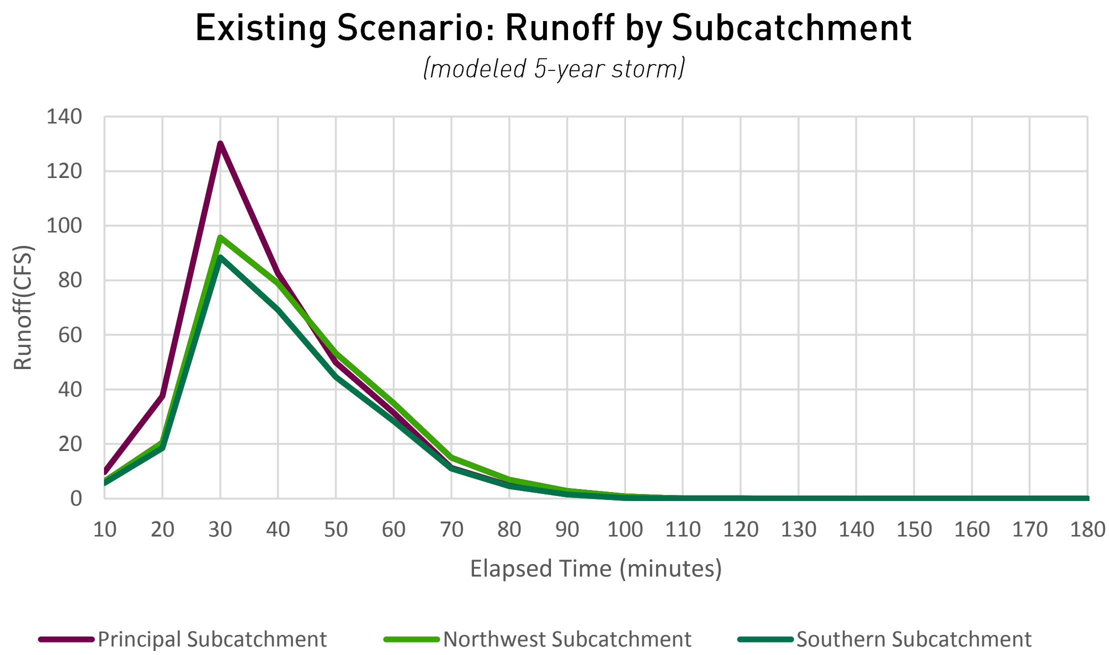


Figure 10 Existing Scenario: Runoff by Subcatchment

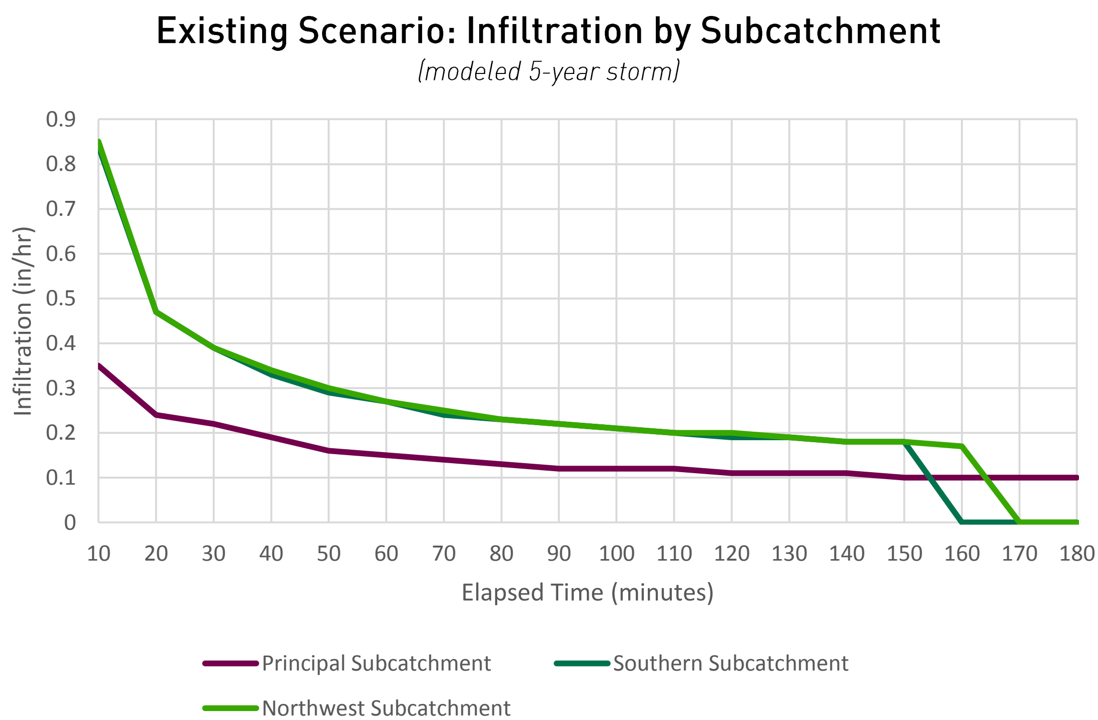
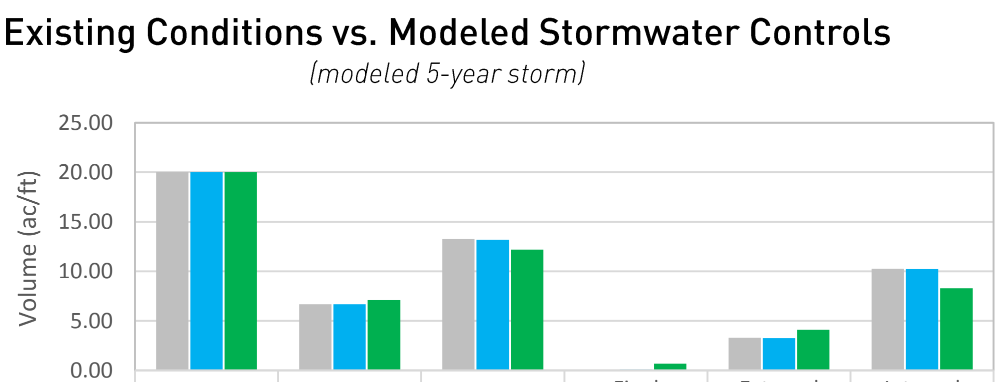


Figure 11 Existing Scenario: Infiltration by Subcatchment

Potential Stormwater Impact of Rain Garden and Rain Barrel Implementation

According to the model results, neither the implementation of rain gardens nor rain barrels has a drastic effect on runoff or flood volumes for the 5-year storm. While the addition of nearly 300 rain barrels nearly doubles the storage capacity of the system, this storage only amounts to a 0.5% reduction in runoff and a 0.4% reduction in flood volumes. The addition of 230 moderately sized (70 ft^3) rain gardens throughout the three watersheds, however, does reduce runoff by 8% and flood volumes by 19% (see Figure 12). In addition to the reduction in flooding, the rain gardens scenario also produces a 25% increase in the external outflow through the outfall node. This means that as the rate of runoff slows due to the storage and infiltration capacity of the rain gardens, more stormwater is able to discharge through the outflow instead of leaving the system via flooding.



	Total Precipitation (ac/ft)	Infiltration Loss (ac/ft)	Surface Runoff (ac/ft)	Final Surface Storage (ac/ft)	External Outflow (Conveyance) (ac/ft)	Internal Outflow (Flooding) (ac/ft)
Existing Conditions	20.00	6.70	13.25	0.05	3.29	10.26
Rain Barrels	20.00	6.70	13.19	0.12	3.28	10.23
Rain Gardens	20.00	7.11	12.21	0.69	4.10	8.29

Figure 12 Runoff and Outflow Results for Existing Conditions, Rain Gardens Scenario, and Rain Barrels Scenario

The reduction in runoff peaks for rain gardens scenario can be seen in Figure 13 below. The peak runoff rate is reduced from 130 to 50 CFS for a 5-year storm. With significantly reduced 5-year peaks and the extension of the hydrograph, the rain garden scenario can be assumed to help reduce flooding by giving the channel more time to convey flows through the system (an assertion supported by the increase in external outflows seen in Figure 12 above). Because many residents adjacent to the channel flood during smaller rain events, even this small reduction can have a large effect on quality of life. For comparison with a larger storm, Figure 14 displays the system runoff for a 20-year storm. While the peak runoff rate is moderately reduced from 450 to 300 CFS, this reduction is unlikely to have an effect on flooding in the community. The volumes and runoff rates from larger storms are simply too large for the rain gardens to handle.

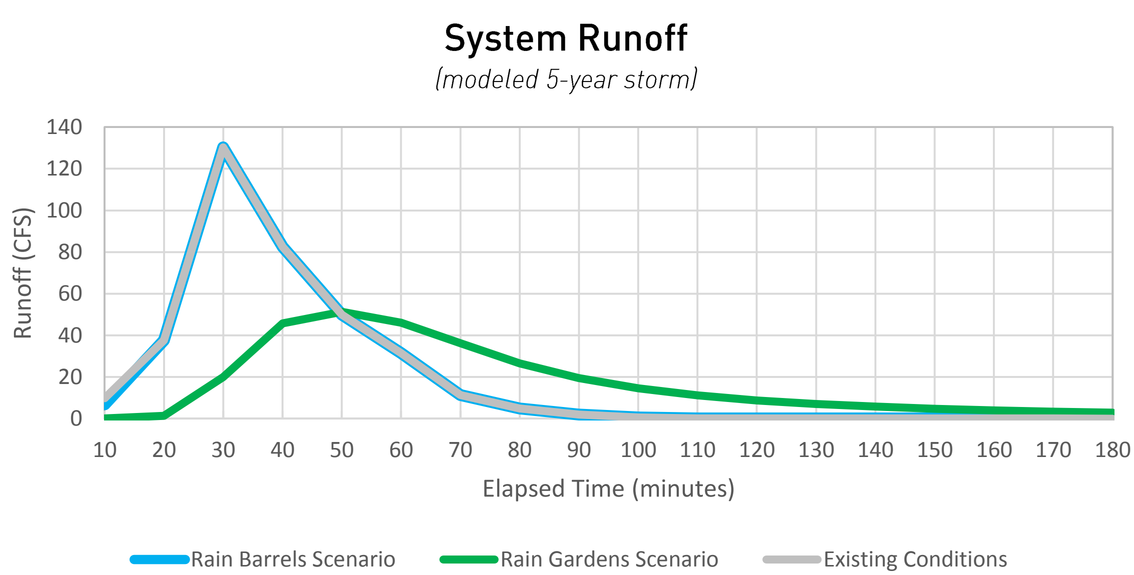


Figure 13 System Runoff for Existing Conditions, Rain Barrel, and Rain Garden Scenarios (5-Year Storm)

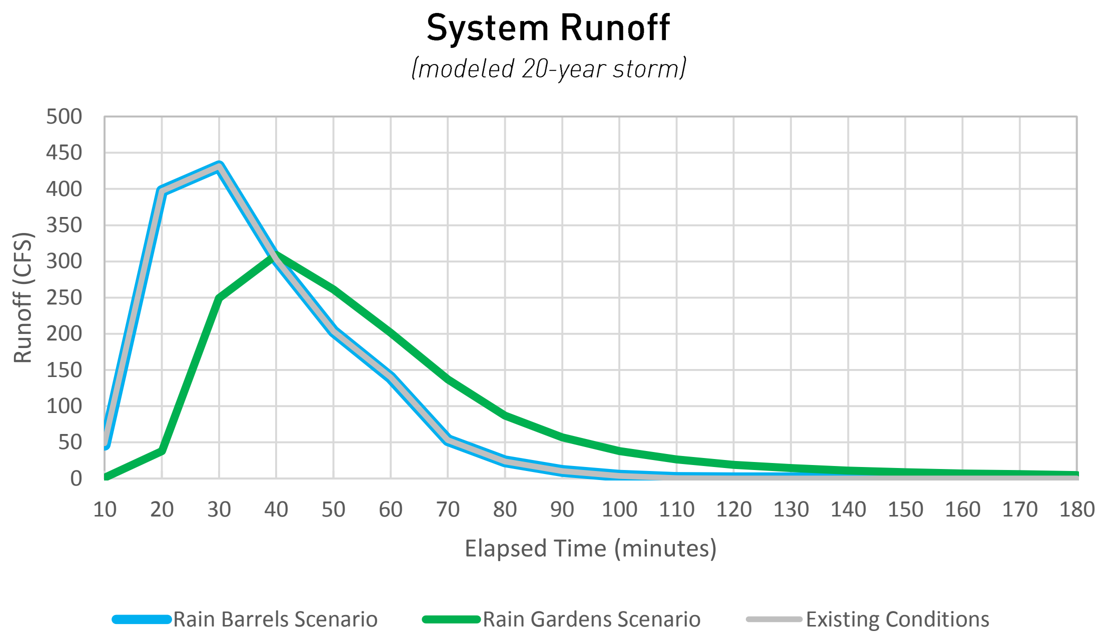


Figure 14 System Runoff for Existing Conditions, Rain Garden Scenario, and Rain Barrel Scenario (20-year Storm)

Due to the unavailability of detailed topographical information and channel cross sections, the model is not sufficiently developed to provide an estimate of peak flows at this time. Because an estimate of peak flows is central to the calculation of flood depths, it is impossible to accurately assess the potential reduction in flood depths due to the implementation of rain gardens and rain barrels. This is the topic of additional research and modeling, beyond the scope of the current study.

Community Capacity to Implement a Rain Garden/Rain Barrel Program

The participation of numerous individual properties across the contributing watershed is essential to any decentralized approach to stormwater management. This is especially important in areas such as Los Platanitos where any available public space has been encroached upon by private homes, leaving very little in the way of public open space. None of the potential runoff or flood reductions modeled above are feasible without community buy-in and participation, so the qualitative portion of my research was devoted to evaluating the community's capacity to construct, monitor, and maintain a system of rain gardens and rain barrels.

Existing civil society groups within Los Platanitos are already highly motivated to address flooding, and would likely be interested in pursuing any reasonable flood mitigation proposal. There are two primary organizations, both of which are dedicated to preventing solid waste from entering the channel. During rain events, this solid waste accumulates at choke-points along the principal channel and exacerbates flooding problems. The Fundación Los Platanitos (FUMPLA) is following the Fundazurza model for community-based solid waste management and recycling, with the objective of generating income from recyclables that would otherwise accumulate in the channel. Mujeres Unidas, the other active group, is attempting to reduce the amount of organic waste in the channel while also generating income through a vermicomposting project. Though both of these groups are still in the early phases of developing their organizational capacities and have yet to generate significant income from their projects, they have demonstrated that they are capable of implementing long-term projects (Sletto ed., 2014). Furthermore, both groups have established working relationships with other civil society organizations, the municipality, and local and international educational institutions. Tapping FUMPLA or Mujeres Unidas to run the potential rain garden/rain barrel program enables the program to leverage the group's existing connections, trust, and experience to recruit participants.

While the participation of trusted civil society groups would be a great advantage, stormwater controls would most likely be maintained by individual homeowners. If more well-off residents in higher elevations are not motivated to help lower-income residents who live adjacent to the channel, they will not participate altogether or their controls will not be adequately maintained. Based on my interviews with homeowners in higher-income neighborhoods within the watershed, however, it appears that most residents would be willing to install a stormwater control on their property if it would alleviate channel flooding. Ten out of the eleven community members interviewed stated that they would consider installing a rain garden if they received some sort of support (rain barrels were not included in the prompt). When asked whether they thought a monetary incentive or technical support would be better, the majority of respondents strongly preferred a scenario in which the materials and technical support were provided to participants. Reasons for this preference varied: respondents noted that monetary incentives had a tendency to be misused (J. Garcia, personal communication, August 2014), and expressed their unfamiliarity with the construction techniques (A. Gómez, personal communication, August 2014). Others expressed more altruistic reasons, such as: "It is a problem that is affecting the community--if there is a problem and each person takes a small part of the problem, we can solve the problem…it is not a question of negotiating a price." These positive responses and the rejection of the use of monetary incentives suggests that the rate of rain garden adopters in Los Platanitos could potentially surpass that of the EPA's "citizen-based stormwater management" study (Shuster et al., 2013; Green et al., 2012).

Although individuals were willing to help their neighbors, the concept of a rain garden was wholly unfamiliar to all of the respondents. Any potential program would need to include a training element to teach interested community-members how to construct and maintain a rain garden, and the proper way to use a rain barrel for stormwater purposes. Fortunately, many individuals in Los Platanitos work or have worked in construction, and many have demonstrated skill in "insurgent architecture" in past collaborations with UT students. Also referred to as "guerilla architecture," insurgent architecture is defined as "small-scale interventions in the social and urban landscape. . . intended as an immediate and inexpensive way of satisfying the needs of a specific group''(Corser and Gore 2009, p. 32). Insurgent architecture projects such as the vermicomposting sites constructed in 2012 and 2014 are assembled on-site from easily obtainable materials with little prior design, with frequent course corrections and on-the-spot discussion of possible configurations (see Figure 15). Once taught the basics of rain garden construction and maintenance, these individuals could easily carry out construction activities using an insurgent architecture approach. It is important to note that these individuals would need to be compensated fairly for their time. In the words of Elias Brito Reynoso, a community-member highly-skilled in construction, "It could be an honorary position, but here no one does anything for free" (Personal communication, August 2014).

Assuming the level of participation seen in the EPA's "citizen-based stormwater management" study, a SWMM model of the addition of 230 moderately sized (70 ft^3) rain gardens throughout the three watersheds shows a 19% reduction in flood volumes for the 5-year storm; and the addition of nearly 300 rain barrels brings the total reduction to 20%. To reach this predicted reduction, however, residents who do not experience flooding must volunteer to dedicate portion of their patio to a stormwater control. Furthermore, existing community capacities must be utilized to gain the community's trust, ensure that the rain gardens are constructed correctly, and that both rain gardens and rain barrels remain functional. While both prerequisites have been met in this case, an influx of some money will be necessary to implement such a project. Whereas the interview respondents did not believe monetary compensation was appropriate for homeowners that decide to adopt a control, some costs are associated with the materials, labor, and training of local skilled construction workers. These costs beg the question, are these costs worth a 20% reduction in flood volumes for a small-storm?

Figure 15 Residents of Los Platanitos building a vermicomposting site in March 2014. Photograph by Kelly Strickler

CHAPTER SIX: Conclusions

This study investigated the feasibility and potential benefits of implementing a network of decentralized green stormwater infrastructure controls in the subwatersheds of three channelized creeks that contribute to flooding in Los Platanitos, an informal settlement in Santo Domingo Norte, Dominican Republic. The project sought to answer two related questions: 1) What are potential resources to be leveraged or barriers to the implementation of an incentive- or community-based stormwater infrastructure provision model? 2) Given the predominant urban form, soil characteristics, rainfall patterns, capacity of current stormwater infrastructure, and percent impervious cover within the channels' subwatersheds, what are the runoff and storage implications of the construction of these controls? Through a mixed-methods research design, a Stormwater Management Model (SWMM) was developed to estimate the potential runoff and storage impacts of the construction of a network of rain gardens and rain barrels throughout the contributing subwatersheds.

Assuming the level of participation seen in the EPA's "citizen-based stormwater management" study (Green et al., 2012; Mayer et al., 2012; Shuster et al., 2013), the addition of 230 moderately sized (70 ft3) rain gardens throughout the three watersheds shows a 19% reduction in flood volumes for the 5-year storm; and the addition of nearly 300 rain barrels brings the total reduction to 20%. These findings beg the question—is a 20% combined reduction in flood volumes for a 5-year storm worth the monetary, human, and social capital needed to achieve it? Even if such a project could attract economic support from a non-governmental organization or the *Ayuntamiento*, most homes are still going to flood during the 5-year storm, and the intervention will have little to no effect on larger storms. As planners in a position of trust, is it ethical to advocate for a community to spend its limited resources on such a small return? While the utilization of social and human capital does not carry economic costs, they are finite resources—and there are many other pressing needs.

Moreover, could it be counterproductive to make half-measures towards flood mitigation given the retreat of the state under neoliberal governance? This study has demonstrated that to truly protect the residents adjacent to the channel from flooding due to extreme weather events, a combination of grey and green infrastructure is needed. While a decentralized approach can work concurrently with a centralized system, and a community-based approach aimed at decreasing flood frequency in the short-term does not preclude the potential implementation of larger-scale grey infrastructure, the municipality may see a community-based service provision as justification for not addressing the problem. More generally, does providing community-based services in the absence of state-provided services only serve to reinforce and enable the neoliberal shift from government to governance, leaving service provision to the voluntary sector (Chantada, 2014)?

On the other hand, there are multiple other benefits of green stormwater infrastructure that are not captured in simple terms of flood volume reduction. While upgrades to the conventional grey infrastructure must be implemented by the local government, rain gardens and rain barrels can be employed almost immediately for immediate results. The enhancement of storage and infiltration capacity in the channels' watersheds will also impact flood frequency—some smaller storms will not cause flooding at all. Those living along the channel will be exposed to highly contaminated water with less frequency; children may be healthier and miss less school; and adults may miss less work due to illness. Rain gardens that are vegetated with suitable plants will also beautify the urban environment, contribute to a reduction in urban heat island effect, and buffer a highly vulnerable population from the potential social, psychological, and physical hazards of living in a precarious living situation (Kuo & Sullivan, 2001).

Do these relatively small ancillary benefits to green stormwater infrastructure outweigh the risk of the potentially large opportunity costs of a) spending valuable human and social capital and/or b) inadvertently endorsing a rollback of municipal provision of stormwater infrastructure? Perhaps. Could the risk of enabling the rollback of services be mitigated through partnerships with the local government, whereby nongovernmental organizations (NGOs) and/or residents contribute manpower and resources in return for local government intervening more than what they would otherwise? Again, perhaps—without a more thorough investigation, it is impossible to make recommendation with any degree of confidence. Ultimately, the decision does not lie with planners, of course. It lies with the individuals and civil society organizations of the communities of Los Platanitos, Los Trinitarios, and Santa Cruz. Our obligation as planners is to provide complete information and open a space for dialogue. To that end, I propose the following recommendations.

Recommendations

This report recommends that the communities of Los Platanitos, Los Trinitarios, and Santa Cruz adopt an approach to stormwater management that combines green infrastructure with more traditional solutions. As the modeling results demonstrate, green stormwater infrastructure alone cannot protect the most vulnerable residents from larger storm events. By enabling a reduction in design parameters, the implementation of green stormwater controls can, however, reduce the costs associated with upgrading the grey system. In the City of Austin Brentwood Study, a combination of green stormwater infrastructure and targeted traditional infrastructure improvements completely eliminated structural flooding for moderate storms, and significantly reduced the number of structures subject to flooding in somewhat larger storms. While these traditional infrastructure upgrades added approximately one million dollars to the projected costs, these costs were still significantly lower than the traditional infrastructure scenario (City of Austin, 2014). The necessary expansions to the grey infrastructure system will require coordination with the *Ayuntamiento* and significant funds expenditures. Unfortunately, the lack of sufficient resources in the *Ayuntamiento* for such a project is exactly one of the obstacles that a green infrastructure approach was intended to circumvent.

While large-scale upgrades to the grey infrastructure system require inputs from the *Ayuntamiento*, in the short term, the community can take several immediate actions. Sletto ed. (2008) identified improvements to La Piscina as the lowest cost project to provide direct flooding relief to the community. Currently large deposits of solid waste are blocking the culvert under the highway into the Parque Mirador Norte. Cleanup and/or expansion of La Piscina and the culvert would increase the channel's conveyance capacity for a relatively low cost, and could be done with little disturbance to residents. In the short term, the community could begin putting together a participatory budgeting proposal for such an upgrade. Because these improvements are highly targeted and could be performed with limited funds, it would be a good participatory budgeting candidate.

Another immediate action that can be taken is the establishment of a test/demonstration area within the community to introduce green infrastructure concepts and teach a few local technicians how to construct rain barrels and rain gardens properly. This demonstration site could be located on a tract of land that was recently awarded to the community by the *Ayuntamiento.* This initial training by an experienced engineer is very important, for the failure or mismanagement of the first few controls could negatively influence the community's opinion of the entire paradigm. Any demonstration project would also need to carefully manage expectations, clearly explaining that green infrastructure alone will not solve flood problems, but it can possibly help with smaller storms if enough controls are implemented throughout the entire watershed. The demonstration site should be jointly led by both FUMPLA and Mujeres Unidas. While FUMPLA has more connections to homeowners in the upland areas of the subwatersheds, Mujeres Unidas manages a source of compost that could serve to enhance the attractiveness and functionality of potential rain gardens. Mujeres Unidas also has cultivated a relationship with the National Botanical Garden, which provides free or low-cost plants to community groups. The Botanical Garden could potentially advise the project on suitable plant assemblages for the wet/dry conditions of rain gardens.

More long-term solutions will all require cooperation with the *Ayuntamiento* because they require regulation of development practices or the expenditure of significant monetary capital. Many of these solutions are currently infeasible given the current technical, regulatory, and financial capacity of the *Ayuntamiento*, and any potential expenditures in these areas should be weighed against the costs of infrastructure upgrades. From a regulatory standpoint, the *Ayuntamiento* should ensure that all new (formal) development does not exacerbate downstream flooding. Currently, most apartments and housing complexes are designed to drain to the nearest natural channel, regardless of downstream flooding problems. This attention to downstream effects should especially include the nearby mattress factory, which has been filling in the northwest channel's lagoon and continuing to exacerbate the problem. The *Ayuntamiento* should also establish a system to prevent further informal encroachment into flood risk areas, perhaps by setting up desired, but nonresidential uses in currently unused lots adjacent to the channel. Los Platanitos lacks access to many basic services, so these lots could serve as mobile healthcare stations (or whatever service is needed). Los Platanitos also must have access to reliable solid waste collection to reduce the accumulation of trash in the channel, which exacerbates flooding. Such a solid waste solution could follow Fundsazurza's community partnership model, or be provided by the *Ayuntamiento*.

If all these long-term solutions were successfully carried out, the required infrastructure upgrades might be minimal. As mentioned previously, La Piscina and its associated culvert should be cleaned, dredged, and protected from further alterations. If at all possible, the *Ayuntamiento* should also deepen the current channel, especially in those areas where it is only 15 cm deep. In order to reduce contamination by illegal sewer connections, the *Ayuntamiento* should also provide a separate sanitary sewer. Alternatively, composting toilets that can dispose of waste without contaminating the channel could be provided at a lower cost than installing a separated sewer system. It is possible that an international NGO such as SOIL (Sustainable Organic Integrated Livelihoods) could be recruited to help install and educate the community about composting toilets. SOIL is an NGO operating in Haiti that promotes the use of ecological sanitation, a process by which human waste is converted into valuable compost (SOIL, 2015).

The model developed to estimate the stormwater impacts of rain garden and rain barrel implementation in Los Platanitos, Los Trinitarios, and Santa Cruz is still rather coarse—additional data is needed to develop more precise estimates of the potential flood impacts due to green stormwater infrastructure. Follow-up research should calibrate the SWMM model with real runoff and rain gauge data, and incorporate more detailed topographical information to estimate peak flows, flood depths, and potential reduction in flood depths. Follow-up research should also include an assessment of the feasibility and potential impacts of other controls such as infiltration trenches, green roofs, and larger-scale rainwater cisterns.

Conclusions

Theoretically, in the absence of large investments of physical capital to construct large-scale grey infrastructure, a decentralized green stormwater infrastructure approach is well-suited to an informal context in that it can be implemented by citizens themselves. Individual controls can be constructed incrementally as time, space, and materials allow. With low costs relative to conventional grey infrastructure (Thurston et al., 2003; ECONorthwest, 2007; USEPA, 2007; Brewer and Fisher, 2004), human and social capital are among the few requirements to construct and ensure the continuing functionality of a large number of individual small-scale stormwater controls. In informal communities, human and social capital is often the only form of capital readily available—as a result, these communities often have robust networks of formal and informal social ties that can be leveraged for a community-based, decentralized stormwater management system. In Los Platanitos, local civil society organizations and programs, highly skilled individuals and their connections, and opportunities to collaborate with the University of Texas are all sources of human and social capital that, if utilized for a bottom-up stormwater management paradigm, can partially substitute for the current lack of technological and physical capitals of grey infrastructure.

The EPA's "citizen-based stormwater management" study also demonstrated that community engagement and the activation of social capital may actually enhance the effectiveness of a stormwater control program. In additional to measuring the effectiveness of the green stormwater infrastructure in increasing the storage and infiltration capacity of the watersheds, the researchers also employed a statistical analysis of the spatial distribution of successful bids to illustrate the significant role of social capital in forming clusters of participating properties. Homeowners within a five property radius from successful bidders were more likely to be successful bidders themselves (Schuster et al., 2013), indicating that as participants shared their positive experiences with their neighbors, neighbors may have become more willing to enroll themselves (Green et al., 2012). According to Shuster et al. (2013), these findings indicate that "investing in strategies that grant responsibility and power to individuals may increase the economic benefits of financial investments in small to medium sized physical projects by inducing collective action and strengthening social cohesion" (p. 8). In communities with strong social cohesion such as Los Platanitos, this transmission through social ties could potentially lead to a higher rate of stormwater control adoption than in Shuster's original study (23% and 30% for rain gardens and rain barrels, respectively).

While the current study has demonstrated that green stormwater infrastructure alone is only capable of reducing flood volumes for small, 5-year storms in the informal settlement of Los Platanitos, even small flood reductions can have a significant effect on quality of life and health of vulnerable communities. Furthermore, many of the model parameters were generated under assumptions taken from studies conducted in the US. In contexts where increased engagement of social capital is necessary to compensate for a lack of government-provided services, this study suggest that a similar incentive- or community-based program could see a higher rate of green stormwater infrastructure adoption and success than in US applications. Regardless of specific green infrastructure adoption rates, however, a combination of green and grey infrastructure approaches to stormwater management is still needed to protect vulnerable residents from very large storms.

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