Green Infrastructure and Stormwater Management: Opportunities and Challenges

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KEYWORDS

Green infrastructure; green infrastructure finance; water quality management; stormwater management

ABBREVIATIONS

American Society of Landscape Architects (ASLA)
Combined Sewer Overflows (CSO)
Green Infrastructure (GI)
Green Infrastructure Finance (GIF)
Metropolitan Water Reclamation District (MWRD) of Greater Chicago
New York City (NYC) Department of Environmental Protection (DEP)
Social, Ecological, Technological Systems (SETS)
Total Maximum Daily Loads (TMDLs)

ABSTRACT

The magnitude of unwanted water discharges in and around urban areas often approaches unmanageable levels, and includes many different phenomena: combined sewer overflows, fluvial flooding (e.g. the 1993 Midwest Floods), pluvial flooding (precipitation exceeds drainage, exceedance of soil capacity to hold water), and failed man-made structures such as releases from channelized streams and storage structures. A common theme is performance, e.g., capacity exceedance. Green infrastructure (GI) innovations aim to expand urban storm water management capacity and improve water quality, and case data analyses (for Los Angeles, Chicago and New York City) are presented illustrating this. Analytical approaches and models abound addressing GI interventions, and persistent model structure and data gaps arise. Social, ecological and technological systems ("SETS") are combined to evaluate GI as an innovation. Combining technological and ecological conditions addresses where green infrastructure increases structural/technological or ecological capacity to retard water movement, providing mutually reinforcing technological and ecological water management strategies. Incorporating social dimensions into ecological/technological dimensions are evaluated in terms of institutional support, e.g., finance and regulation, and social behavior that can provide for transitions to GI for effective adaptation to water- related aspects of extreme weather and climate. Acknowledgements: National Science Foundation Cooperative Agreement 1444755, Urban Resilience to Extremes Sustainability Research Network and other support.

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1 INTRODUCTION

The conventional development of cities is associated with radical alteration of natural hydrologic processes. As cities develop, densify and, in many cases, sprawl, large areas of land are converted to impervious cover, natural stream channels are culverted into sewers, and the natural topography is frequently regraded (Booth, 1991). In the megacities of the United States (US), storm sewers, tunnels, and vaults and similar 'gray' infrastructure have been the primary approach for conveying and storing stormwater – either separately or in combination with sewage flows - during precipitation events. These cities have also relied on wastewater treatment plants to restore water quality before it is released to receiving waters. However, these gray infrastructure systems are vulnerable to intense rainfall events, resulting in water quality impacts and contributing to multiple types of flooding. As a result, green infrastructure (GI), which provides supplemental stormwater management capacity while providing nature-based social and ecological co-benefits, are increasingly being deployed in US megacities. In this paper, we present case studies of the novel design of green infrastructure systems to support resilience to rain events that would overwhelm the capacity of conventionally designed infrastructure.

The management of urban stormwater has rapidly evolved over the past few decades, and the associated terminology has become increasingly diverse (Fletcher et al., 2015). In this study, we use the definition of GI provided in a memorandum drafted by the US Environmental Protection Agency (US EPA, 2007), where GI is defined as that which:

'Facilitates or mimics natural processes that also recharge groundwater, preserve baseflows, moderate temperature impacts and protect hydrologic and hydraulic stability'

In this memorandum, the US EPA first encouraged the use of GI to meet the regulatory requirements of the US Clean Water Act, the primary law that regulates the discharge of pollutants into waters of the United States. Through facilitation of the infiltration of stormwater into soils, the detention of stormwater in topographic depressions and the evapotranspiration of water from soil stores over long time scales, GI can reduce the volume of stormwater that must be conveyed and treated by gray infrastructure during precipitation events. Through broad implementation of GI, overflows and backups of combined sewers can be prevented or mitigated, resulting in the improved quality of urban receiving waters.

In the United States, the US EPA plays a limited role in flood risk mitigation. At the national scale, large scale infrastructure projects related to navigable waters are designed and managed by the US Army Corps of Engineers. Other federal agencies such as the Federal Emergency Management Agency and the National Oceanic and Atmospheric Administration play the primary role in flood management and resilience planning. The use of GI to support the management of flooding has only recently been considered by these federal agencies (Atkins/EPA, 2015). At the local scale, regional agencies and municipalities play an important role in the development and implementation of flood management plans.

While GI can potentially play a major role in flood management, the extent to which flood mitigation is incorporated in the design of GI varies across US cities (McPhillips et al., 2020; Rosenzweig et al., 2019). In the consideration of the flood management benefits of GI, it is important to be mindful of the multiple types of precipitation-driven flooding that can impact urban areas:

- **Fluvial flooding** occurs when water levels in rivers and streams exceed bankfull stage, inundating surrounding land areas.
- **Pluvial flooding** occurs when precipitation rates exceed the combined drainage capacity of soil infiltration and storm sewer systems, resulting in ponding and overland flow.

- **Sewer backup flooding** may co-occur with pluvial flooding and results from the back-up of water from surcharging sewers.
- **Groundwater flooding** occurs when the water table rises above the level of the land surface.
- **Lakeshore flooding** occurs when the water level in lakes and ponds rises to levels that result in the societally or ecologically impactful inundation of land.

These mechanisms of flooding can occur in combination during a precipitation event and can be exacerbated by co-occurring coastal flooding (NASEM, 2019). GI flood mitigation performance will vary by type of flooding, design of individual GI projects, and the extent of GI implementation within a catchment area.

In this study, we evaluate the implementation of GIs and their potential to provide water quality and flooding benefits through consideration of the social, ecological, and technological dimensions of their planning (McPhearson et al., 2016). The social dimension (S) is represented primarily by finance and institutions. The ecological dimension (E) is primarily reflected in varying physiographic and climatological settings of case study cities and early projections for future climate change. The technological dimension is reflected in the GI technologies and their interface with conventional stormwater infrastructure.

2 METHODS

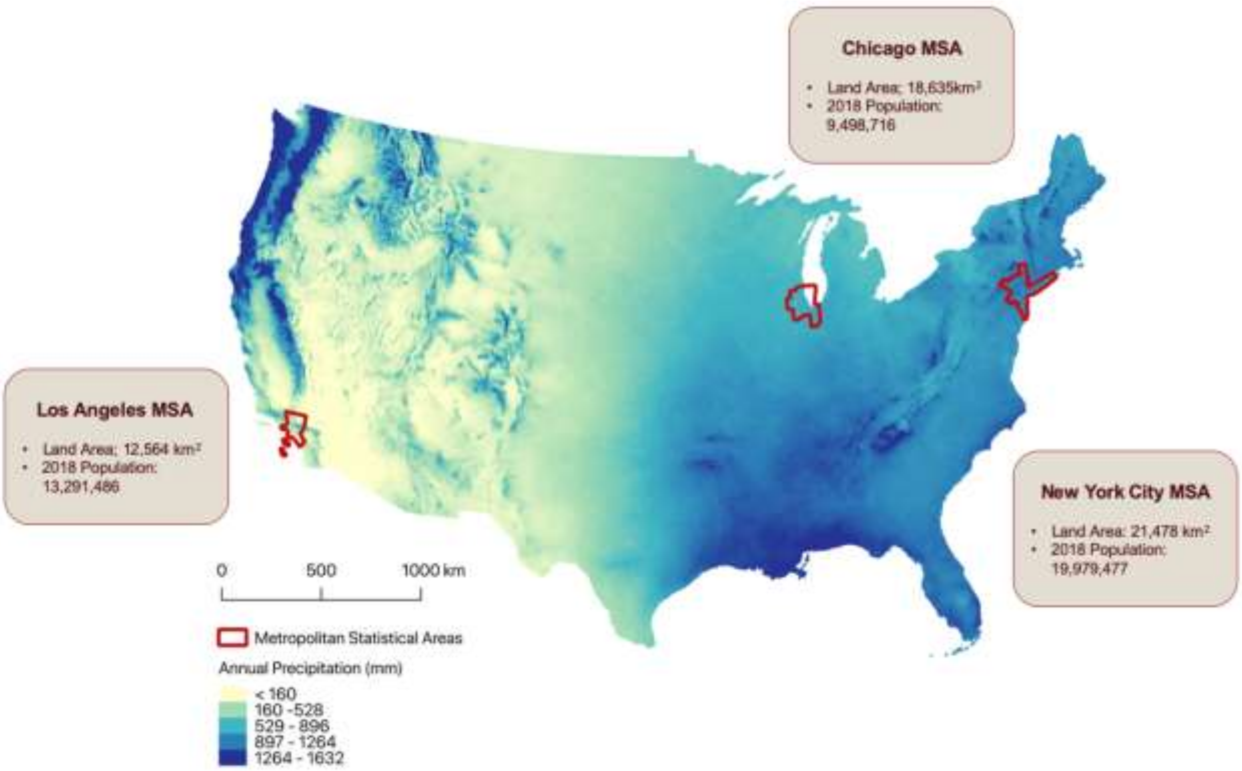

Figure 1: Three US Case Study Cities. Data sources: PRISM Climate Group, 2004, US Census 2019.

Case studies were developed for the three most populous US cities: Chicago, Illinois; Los Angeles, California and New York City, New York (Figure 1). Both Los Angeles and New York City are megacities, with regional populations exceeding 10 million. Chicago is an emerging megacity with a regional population of 9.5 million (Zhao et al., 2017). The three case study cities were selected based on their status as megacities or emerging megacities. These cities are located in different regions of the US and have diverse topography and climate. Case studies were developed through a review of McPhillips et al., 2020).

Another source of case and analytical data particularly for the GI finance section was the American Society of Landscape Architects (ASLA) used by Zimmerman, Brenner and Llopis Abella (2019). The ASLA data represents a convenience sample (non-random) drawn by ASLA from its members. The case areas were surveyed over several years from about 2011-2015. The total size of the ASLA convenience sample was about 400. Finance and GI data were coded from ASLA case writeups by Zimmerman, Brenner and Llopis Abella (2019).

3 RESULTS

3.1 Case Studies

3.1.1 Case Study of Los Angeles

Los Angeles is located on the Pacific Coast of the United States. Its sprawling metropolitan region includes the adjacent cities of Long Beach, Anaheim, and various suburbs in Orange County. The downtown core of the city is located on a coastal plain, bounded to the north by the Santa Monica Mountains and the east by the San Gabriel Mountains (USGS, 1971). Its complex topography results in diverse microclimates within the city's metropolitan area. The windward side of the San Gabriel Mountain Range is subtropical while the leeward side is arid. Most precipitation occurs during the winter and rainless periods of several months during the summer are common. Interannual rainfall is highly variable and can be significantly impacted by regional scale oscillations such as El Niño (Orsi, 2004).

As a result of its climate and topography, Los Angeles is susceptible to ultrahazardous flooding, with the potential for rapid-onset high velocity flood flows that convey large fluxes of sediment and debris (Sanders and Grant, 2020). The region experienced numerous impactful fluvial flooding events during the 19th and 20th centuries (Orsi et al., 2004). Since the 1940s, flooding in the region has been managed collaboratively by regional and federal authorities, and focused around the use of gray infrastructure such as concrete-lined open channels to convey rivers flow and large centralized dams (City of Los Angeles, 2018).

Flood management responsibilities in Los Angeles are determined by event magnitude. While regional and national authorities are responsible for the management of moderate flood events (associated with a 10 –100 year return interval), the city is responsible for mitigation efforts for more frequently occurring events. Historically, the city also relied on gray infrastructure to manage flooding in Los Angeles' highly urbanized coastal plain. This includes a storm sewer system sized to carry flows associated with a 10-year return interval design storm, supplemented by a complex system of pumps and culverts. The road network is designed to convey the balance of the 25-year frequency design storm without resulting in damage to property (City of Los Angeles, 1986).

Some GI elements have always been incorporated into Los Angeles' flood management systems. For example, many of the large-scale dams are associated with spreading basins, which allow for the infiltration of stored water to recharge groundwater aquifers. However, most existing GI projects were constructed for water quality improvement and, in many cases, to meet the regulatory requirements of the US Clean Water Act.

Stormwater in Los Angeles is conveyed through a drainage system that is separate from sewage flows, but still an important source of nonpoint pollution to the city's receiving waters. As a result, the city's stormwater system is regulated under the Clean Water Act's Municipal Separate Storm Sewer System (MS4) and requires a permit to operate. This permit requires control of stormwater discharge to the sewer system to the maximum extent possible and incorporates Total Maximum Daily Loads (TMDLs), which set a water body-specific threshold on the maximum amount of a particular pollutant associated with water quality degradation. Twenty two receiving water bodies in the city of Los Angeles are subject to TMDLs and their regulated pollutants include trash, metals, and bacteria.

Los Angeles' MS4 permit allows for flexibility in the development of a plan to meet permit requirements. GI plays an integral role in Los Angeles' stormwater management planning. These include small-scale GI projects distributed throughout the city, which utilize technology such as green roofs, bioswales, and bioretention gardens. Like New York City, Los Angeles considers unvegetated infrastructure that mimics natural processes to be GI. Examples of small-scale projects include the use of porous pavement to facilitate stormwater infiltration and site scale detention projects that mimic natural depression storage. Large-scale GI projects include flow-through wetlands for stormwater treatment and the diversion of low-flow stormwater into parks and green spaces to facilitate aquifer replenishment. These large-scale GI serve as a supplement for regional-scale gray infrastructure such as concrete channels, pumping plants, reservoirs and dams. (City of Los Angeles, 2018).

The performance of Los Angeles' stormwater GI is still under evaluation. The City has estimated that with full implementation of its existing watershed management plans, an annual average of 29,000 million gallons of stormwater would be prevented from entering the storm sewer system (City of Los Angeles, 2018). Los Angeles is also planning for greatly expanded deployment of GI over the next 2 decades. The city's current water resource management planning utilizes an integrated strategy that considers all aspects of the water cycle in the development and prioritization of projects (Water IRP 1999). Under this paradigm, stormwater management projects are planned using a '3-legged stool approach', where potential benefits for water quality improvement, water supply augmentation, and flood risk management are all considered, and projects that provide benefits for all 3 issues are prioritized. The total estimated capital costs for planned stormwater management is $5.6 billion, with 90 percent allocated to regional and distributed GI. The planned GI will also result in increased operations and maintenance obligations as projects are constructed (City of Los Angeles, 2018).

3.1.2 Case Study of Chicago

Chicago is located on a relatively flat glacial plain along the western shore of Lake Michigan. The city has a humid, continental climate and receives moderate precipitation distributed evenly throughout the year. The city is underlain by relatively shallow groundwater and the Chicago River and its tributaries converge in the downtown core of the city (Duncker and Johnson, 2015).

Chicago's water management history is dominated by large-scale gray infrastructure projects. The city's sewer system was initially constructed in the mid-1800s and involved extensive regrading of the city to facilitate gravity-driven flow. In the late-1800s, the natural streams and tributaries of the Chicago River were channelized along with manmade canals to create the Chicago Area Waterway System (CAWS) a highly engineered network of surface channels, locks, and pumps that allow for the control of water levels and flow. Since 1896, this system has been used to reverse the flow of the Chicago River so that it drains water from Lake Michigan rather than draining into it, in order to protect the water quality of the lake from urban nonpoint source pollution and sewage loading (Hill, 2019). The CAWS is operated by the Metropolitan Water Reclamation District (MWRD) of Greater Chicago, a regional water authority and the US Army Corps of Engineers. Flood losses in Chicago have been estimated by Ajax and Montgomery (2020, p. 1) as costing between 2004 and 2014 about $1.8 billion, combining grants, loans, and insurance.

Chicago is vulnerable to cloudbursts and other heavy rainstorms due to its flat topography and shallow groundwater (Chagnon and Westcott, 2002). Since 1972, the city has been constructing a network of deep rock tunnels and surface reservoirs (known as the Tunnel and Reservoir Plan, or TARP) to convey and store sewage and stormwater during heavy rain events, when the capacity of the wastewater treatment plants is exceeded. When the capacity of the TARP infrastructure is also exceeded a mixture of sewage and stormwater will overflow through Combined Sewer Outfalls (CSO) into the city's receiving waterways. During heavy rain events, the combined sewage and sanitary flows can also back up into basement properties (City of Chicago, 2014). During the heaviest rain events, the CAWS is operated to allow the system's waterways to discharge into Lake Michigan. These flow reversals prevent potentially catastrophic fluvial flooding but result in significant water quality impacts for the lake (Sinha, 2013; Zhu et al., 2013).

Like MS4s, discharges through CSOs are regulated by the US Clean Water Act. The MWRD of Greater Chicago has arranged a consent decree with the US EPA to reduce CSOs, which relies primarily on the buildout of TARP. However, under the consent decree, the MWRD is also required to implement a GI Program, with an anticipated cost of $25-50 million. Under the consent decree, the city must prioritize GI projects that reduce basement backups and other flooding, are permanent, create amenities for local residents and improve socio-economic conditions in needy communities. TARP is scheduled for completion in 2029, but even when completed will not have the capacity to completely prevent basement flooding during the most intense rain events (City of Chicago, 2014).

In addition to the GI that must be implemented in accordance with the MWRD consent decree, the City of Chicago (2014) has developed its own Green Stormwater Infrastructure Strategy (City of Chicago, 2014). This municipal plan builds on existing programs in Chicago to plant trees along 'Green Streets' and construct green roofs and vegetated, pervious 'Green Alleys.' The initial 5-year plan was budgeted at $50 million with a goal to reduce runoff by $250 million gallons annually (City of Chicago, 2014).

3.1.3 Case Study of New York City

New York City is located on the US Atlantic Coast and is the core of a metropolitan region that spans multiple US states. The city itself is physiographically diverse: The Bronx, its northernmost borough, is located on the US mainland and drains the piedmont along the eastern shore of the Hudson River. Manhattan and Staten Island are geologically diverse islands along and adjacent to the Atlantic

Fall Line. The easternmost boroughs are located on the western end of Long Island and overlie glacial outwash sediments.

The hydrology of New York City has been radically altered through the course of its development and nearly all of the city's natural stream channels were culverted into sewers by the mid-1900s. Many of the city's coastal communities were built on reclaimed wetlands, particularly in the easternmost boroughs (Walsh and LaFleur, 1991). The city experiences frequent pluvial flooding during cloudburst events (Depietri and McPhearson, 2018; Rosenzweig et al., 2018).

In older areas of New York City, the sewer system is combined. In communities developed since the mid-1900s, stormwater and sewage are conveyed separately. The NYC GI Plan was developed primarily as an alternative strategy for the City to control CSOs, as mandated by the US Clean Water Act. In 2005, the NYCDEP agreed to a consent order for the mitigation of CSOs under the Clean Water Act (Rosenzweig and Fekete, 2018). Under this consent order, New York City's GI Program was developed as a cost-beneficial alternative to traditional tanks and tunnels, and demonstrates the adaptability and the potential for GI to evolve to complex and changing conditions.

The NYC GI Program required a new governance approach that forged partnerships and intergovernmental agreements to fund the implementation of GI on city-owned property, as well as a new grant program that created a new mechanism for the transfer of funds to private property owners. GI implementation is largely funded by the NYC Department of Environmental Protection (DEP), which operates the City's drinking water and wastewater infrastructure and manages stormwater drainage and water quality objectives.

GI technology has evolved quickly to adapt to the urban and natural environment of the city, including plant species selection that can potentially weather conditions such as runoff laden with road salt and sub-surface conditions including high groundwater and bedrock. The capacity of GI installations has also been tested and, in some cases, expanded to handle larger runoff volumes. NYC's Performance Metrics Report submitted to the Department of Environmental Conservation in 2016 showed that the City can achieve 507 million gallons per year of CSO reductions with the 2015 target, primarily from GI assets. DEP is ultimately working toward a reduction of 1.67 billion gallons per year by 2030 through GI implementation (NYC DEP, 2019). The NYC GI 2019 Annual Report showed that 10,032 GI assets had been constructed, or were in construction. In total, 1,230 "greened acres" were implemented from 2010-2019. According to the report, a "greened acre" is another way of saying "equivalent impervious acre" and represents a volume of runoff managed by a GI practice. Taking that volume and spreading it out evenly at a 1" depth over an impervious area represents a "greened acre."

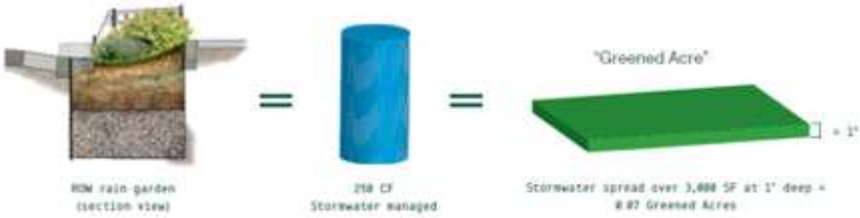

Figure 2: Performance metric approach under the NYC GI Plan (NYC DEP, 2019: 55)

As an extension of the GI Plan, New York City is currently working with the City of Copenhagen to develop pilot projects based on adaptations to its current GI approach from Copenhagen's cloudburst resilience strategies (Rosenzweig et al., 2019). Leveraging a governmental relationship with the NYC Housing Authority (NYCHA), DEP is piloting a "cloudburst" project (inspired by its partnership with Copenhagen) featuring a series of interconnected dry ponds that flow to a sunken basketball court that will utilize below- and above-ground detention. The basketball court is in part modeled on Rotterdam's "Water Square." NYCHA and DEP conducted extensive community engagement to incorporate local resident input into the design and amenities associated with the project.

3.2 The Social-Ecological-Technological Systems Perspective (SETS)

3.2.1 Social Dimensions of GI Implementation

In all 3 case study cities, federal governance and oversight of Clean Water Act mandates (often by state or regional jurisdiction) helped spur GI development as cities conceived innovative responses to regulations. Los Angeles' GI Program was developed under consent decree to reduce nonpoint source pollution from its separate storm sewer system. The MWRD of Greater Chicago and New York City both developed GI Plans under consent decree to reduce CSOs. Beyond fulfilling regulatory requirements, both Chicago and New York City have also developed municipal plans for additional GI projects that address local flooding concerns and provide community amenities.

Financing GI is part of the general area of proactive actions to save future costs associated with natural hazards. The National Institute of Building Sciences (NIBS) (2019, p. 2) has been estimating the worth of investing initially in mitigation to avoid future costs of natural hazards (also expressed as benefit-cost ratios), and found in 2005 a 4:1 benefit (a $1 investment yields $4 in benefit) for building above code, improving infrastructure, and building retrofits; 6:1 in 2018 associated with federal grants for mitigation; and 11:1 in 2019 for model codes. NIBS (2019) also applies the approach specifically to riverine flooding and those benefit to cost ratios range from 5:1 for actions that are above codes to 8:1 for the retrofit of lifeline infrastructures.

GI finance is generally a non-mandatory water management mechanism used for purposes other than water management as well such as energy conservation. Despite the non-mandatory element, many incentives are built into the acquisition of finance that emphasize GI. A number of references now exist in infrastructure financing legislation encouraging GI finance. The finance of GI reflects how social institutions are charged with responding to or undertaking responsibilities voluntarily for technological and ecological water management issues. The financing of GI has emerged in a variety of forms given the considerable diversity of the GI product and the magnitude and type of costs. Zimmerman, Brenner and Llopis Abella (2019) analyzed a convenience, non-random set of 444 cases from the American Society of Landscape Architects (ASLA). They identified about a half dozen general financing tools spanning public and private sources: "Grants, Loans, Bonds, User Fees, Tax Exemptions, Donations, and Developer Support" (Zimmerman, Brenner and Llopis Abella 2019, Table 1). These general categories, however, break down into dozens of very specific programs (Zimmerman, Brenner and Llopis Abella 2019, Appendix A). What emerged from the study was that in spite of the large number of financing choices, only a few sources are used and public funding sources were more popular than private ones. In the ASLA set, only a small relationship existed between size and cost of project and the number of financing tools used (Zimmerman, Brenner and Llopis Abella, 2019, p. 10).

Cost or valuation are fundamental contributors to the choice and use of financing mechanisms. Cost of GI however is tricky since like other forms of infrastructure it depends on whether one is referring to capital costs or operating and maintenance costs and the timeline of the facilities or life cycle analysis (US EPA 2017), and these cost estimates typically vary by type of GI (NOAA, 2015). US DHS FEMA (2013, p. 5) for example in its benefit cost analysis has estimated “Annual Estimated Monetary Benefits per Acre per Year for acquisition-demolition or acquisition-relocation projects” of green open space at $7,853, which NIBS (2019, p. 353) incorporated into its estimates.

However, the application of GI in US megacities has displayed a considerable variety in terms of the technologies used and the types of developments to which the developments have applied, i.e., streets, parks, and housing. Similarly, the types of finance mechanisms vary, primarily emphasizing public funding at all levels of government and occasionally private funding in terms of donations.

3.2.2 Ecological Dimensions of GI Implementation

The ecological setting of all 3 cities plays an important role in their localized flood risk and primary water quality issues, as well as the type of GI that can potentially be used to mitigate flooding. In Los Angeles, the city’s topography allows for the generation of high velocity flows and the transport of large volumes of eroded, sediment-borne pollutants (Sanders and Grant, 2020). In Chicago, the city’s flat terrain and associated high water tables is a key contributor to its vulnerability to pluvial flooding and sewer overflow flooding into basements (Duncker and Johnson, 2015). New York City, which contains areas of relatively high relief along with extensive areas of coastal plains and wetlands, is vulnerable to multiple mechanisms of flooding (Depietri and McPhearson, 2018).

Groundwater plays an important role in the way that GI is integrated into broader water management. In Los Angeles, infiltration to recharge groundwater aquifers is a high priority in the design of all GI projects (City of Los Angeles, 2018). In contrast, in many areas of New York City, existing high water tables can limit the utilization of infiltration-based GI (Rosenzweig and Fekete, 2018)

3.2.3 Technological Dimensions of GI Implementation

The GI programs of all 3 cities involve the use of a variety of types of small-scale GI technologies, including bioswales, rain (bioretention) gardens, green roofs and pervious pavement. In Los Angeles, GI elements are incorporated into large scale gray infrastructure projects and include spreading basins that facilitate the recharge of groundwater aquifers, along with the diversion of stormwater into large-scale constructed wetlands that provide a variety of ecosystem services along with the retention of stormwater.

It remains difficult to estimate the benefits of these systems for flood mitigation as the benefits do not fully accrue until these systems are fully built out and operating (Fischbach et al., 2020). Furthermore, most of the implemented GI in all 3 cities rely primarily on infiltration to manage stormwater, and may not provide the detention capacity needed to mitigate flooding during cloudbursts. In other parts of the world where the Clean Water Act is not the driver, GI has taken on different forms (Mell, 2016).

4 Conclusions

The use of GI has been proliferating throughout the US and internationally, primarily as a stormwater management mechanism. The financing of these projects and sources of financing remains very diverse and often inconsistent, in part due to the various programs under which the projects fall and the benefits derived. The cases and literature reviewed here indicate the use of GI in selected megacities and the performance in light of water quantity and quality goals. GI has established a strong presence nationwide, based in the innovation of cities to find novel solutions to persistent environmental issues, and the flexibility of regulators to recognize GI as a complementary element to traditional gray infrastructure. GI implementation has spurred cities to form important partnerships between different levels of government, develop innovative financing mechanisms and incentives, and to adapt GI to the specific conditions present in each city.

Leveraging these innovations, cities can expand GI to help meet multiple objectives, provided that regulations and governance are adapted to enable new applications. GI demonstrates that significant volumes of stormwater can be managed through infiltration and detention, and, collectively, experiences throughout the country indicate this approach shows promise in achieving water management goals in light of persistent threats from flooding. Moreover, the integration of multiple domains is critical to their success, namely social, ecological, and technological systems (SETS). The social dimension (S) is represented here primarily by finance and institutions. The ecological dimension (E) is reflected in the relationship to natural environments. The technological dimension (T) is reflected in the GI technologies and their interface with conventional stormwater infrastructure. As the number of these cases increases it is important to codify them as lessons learned to benefit other areas experiencing similar threats.

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