Revitalizing urban neighborhoods by adopting green infrastructure: the case of Washington D.C. (English Translation)

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Abstract:
The concept of Green Infrastructure (GI), or using the natural processes of evapotranspiration and infiltration to manage stormwater runoff close to where rain falls is a popular concept among urbanists. In addition to providing the ecosystem services of flood management, GI realizes other goals of increasing urban livability, through mitigating urban heat island effect, providing community amenity, purifying air, and even reducing crime. At the same time, GI has been shown to be primarily driven by federal-level stormwater management regulations to make expensive improvements to aging infrastructure. GI is one way that cities may achieve this goal more efficiently. In this paper, I trace the history of stormwater infrastructure regulation and urban sustainability in the US, how this national context influenced local policy in Washington DC neighborhoods. In addition to the popular narrative that GI can spur neighborhood revitalization, I identify the market-driven urban processes that determine GI locations in already revitalizing neighborhoods. Using an overlay analysis of these factors—centrally-driven planning processes, distributed voluntary participation and distributed development patterns—I show how different neighborhoods throughout the District are likely to have different distributions of Green Infrastructure adoption rates, with areas experiencing high re-investment showing the highest levels of probable GI adoption.

Key words:
Green Stormwater Infrastructure, Infrastructure Regulation, Neighborhood Revitalization, Spatially Distributed Infrastructure

1. INTRODUCTION

In the US, many factors, including the decline of industrial manufacturing, increases in suburbanization and auto-centric development, and racial discrimination have left many inner cities depopulated and economically constrained. In light of this, a major goal of urbanists is how to provide amenity and economic development to attract residents back to urban cores to revitalize local economies. One commonly asserted belief is that improving urban livability through environmental improvements can be used to revitalize neighborhoods. In this paper, I explore an example of one case study in the US where GI is being aggressively planned and adopted, Washington DC. Through a close examination of both the history of the national regulations driving GI adoption in DC, the history of GI planning reception and implementation within the District, and the historical spatial patterns of adoption and the likely drivers of adoption, I explore under what circumstances GI can be a tool of revitalization, and under what circumstances, it is actually likely to depend on exogenous market forces that drive urban development and redevelopment.

Washington DC has promoted green stormwater infrastructure implementation as a revitalization strategy, restoring local ecology, easing the burden on conventional infrastructure systems, and creating community amenity. In this paper, I first provide a brief history of federal and local-level water quality control regulations and their relationship to GI implementation US. This history aids understanding of the implementation contexts of GI programs and policies in DC. Second I use the main “types” of GI planning that emerge from the historical timeline—targeted and opportunistic GI-- to characterize spatial patterns of GI within the district. Third, I analyze the social, environmental, and economic consequences of GI adoption in neighborhoods across the district. Lastly, I provide commentary on how lessons from DC’s implementation of GI may translate to China’s urban contexts.

2. MOTIVATIONS FOR GI PLANNING AND THE INCREASING IMPORTANCE OF THE NEIGHBORHOOD SCALE

Motivations for why US cities implement extensive GI plans cannot be understood without understanding the environmental regulation of sewage and drainage infrastructure. Today, 772 cities in the United States are still served by Combined Sewer Systems (CSS), now considered “legacy” infrastructures from the Industrial Revolution (US EPA 2004). Within these systems, domestic sewage and stormwater are collected within the same system, which, when it rains, overflow the mixture of stormwater and raw sewage into surrounding water bodies untreated. Although these systems were once considered the cutting edge technology, when they were first adopted during the late 1800s and early 1900s, they, no longer meets modern expectations for how urban stormwater infrastructure should function (Melosi 2000). Communities served by CSS are often older and located in the so-called “rust-belt” of the US. Development in many of these areas experienced rapid growth during the 19th and early 20th centuries, but since the transition of the US economy away from manufacturing, have suffered from population decline and economic stress (Birch and Wachter 2008; Schilling and Logan 2008). The regulation that governs surface water quality in the US, the Clean Water Act (CWA), currently targets the elimination of combined sewer overflow (CSO) events, through discharge permit regulations (US EPA 1995b). In addition, the CWA also regulates MS4 discharge points through the same permit system, although the goal is not to eliminate overflows, but to ensure that discharges meet water quality goals (US EPA 2012). Permitees for both CSS and MS4 systems are often public utilities or local governments.

Several key events occurred that passed on the federal-level water pollution policy to neighborhood-scale implementation and effects. First, the ruling in the legal case Montgomery Environmental Coalition v. Costle affirmed that CSO events were distinct from wastewater treatment plant discharges. This led to acknowledgement that managing CSO events would necessitate a different strategy than business-as-usual facility planning. Second, Congress passed a major amendment to the CWA, the “Water Quality Act of 1987, which created the “Nonpoint Source Management Program (Section 319 in the CWA). The amendment explicitly stated for the first time that wet-weather related discharges were required to obtain discharge permits for stormwater outfalls. This decision explicitly extended the classification of “point source” to include stormwater generated over vast areas discharged at discrete points, even when such sources were not at all related to sewage collection, conveyance, or storage. That a large area be held accountable to discharge at some point in space represented a conceptual challenge that would eventually become very relevant to the neighborhood-scale within cities.

Two years later, the EPA issued the National Combined Sewer Overflow Control Strategy in the Federal Register to provide clarification on this accountability (US EPA 1989). This document reaffirmed that CSO discharges *are* point source discharges independent of the POTW treatment facility, subject to discharge permit requirements that are mustbe brought into compliance with technology-based and water quality based requirements of the CWA. In 1994, the EPA expanded its focus and leadership on large area-generated water pollution by issuing the CSO Control Policy. The CSO Control Policy provided more technical detail for how large-area generated stormwater could be controlled and schedules for implementation (US EPA 1995a).The 1994 Policy additionally acknowledged the importance of diverse stakeholders within the contributing area as opposed to emphasis on a singular permitted entity, a development that was very important to identifying the importance of the neighborhood-scale in CSO-control strategy. After all, it would be these stakeholders who would bear the brunt of the cost to repair and remedy these legacy sewer systems, a cost that is estimated to be $63.6 (US EPA 2008). It was also at this time that the "sewershed," an area draining to a discrete point within the sewer pipe network became an important unit of analysis. Similar to a watershed-based approach for managing and restoring stream networks, concerns about the function of the pipe network drove these area-based delineations. Once delineated, neighborhood-based interventions and investments could be planned.

In 2004, the US EPA began recognizing best practices for managing stormwater runoff that controlled runoff near the source in addition to previous practices of managing stormwater at the "end of the pipe" (as was typically done through treatment works and storage chambers) (US EPA 2004). These source control measures included "green infrastructure" practices—bioswales, rain gardens, and pervious pavement—that captured rain close to where it fell, decreasing the loads on the existing infrastructure (US EPA 2004). It is a strategy that more and more cities in the US are employing to comply with federal environmental regulations for infrastructure while also improving the urban livability (Mandarano and Paulsen 2011). Compared to conventional drainage infrastructure, which is based on the efficient conveyance of stormwater runoff as quickly as possible away from development, GI attempts to restore the natural hydrological processes of infiltration, evapotranspiration and thus treat rain as a resource rather than a waste.

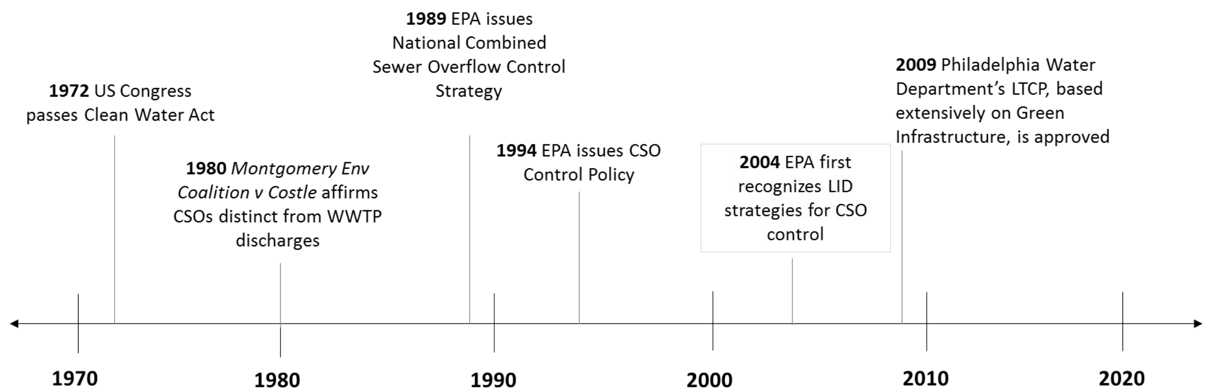
3.1 The sustainability paradigm becomes more commonly accepted

At the same time as more recognition was directed to the non-complying urban water infrastructure, the concept of the "triple bottom line" principals of sustainability were beginning to gain popularity among urbanists and environmentalists (Kidd 1992; Daniels 2009). These principals emphasized that the goals of environmental performance should be considered alongside economic and community development (Millennium Ecosystem Assessment 2005). The sustainability movement emphasized that development can and should be done in a way that recognizes the value that society derives from ecosystem services.

For wastewater and drainage infrastructure planning, this meant that the previous emphasis on durability and longevity of pipes, pumps and cisterns in the technical planning process, were now accompanies by broader goals of creating community amenity, revitalization of urban core neighborhoods. (Benedict and McMahon 2006).. A conventional gray infrastructure solution would have placed even more burden on depopulated urban cores, which would bear the brunt of the costs through increasing water, wastewater and stormwater fees.

By replacing large conventional infrastructure plans with GI, communities would benefit from the ecosystem services—recreation, air purification, heat island mitigation, even opportunities for urban gardening—that GI could provide. Improved urban livability would in turn increase property values, entice “creative class” young professionals into previously struggling neighborhoods, and encourage more redevelopment and investment (Florida 2002).

Figure 1 shows the timeline of events that increased the relevancy of the neighborhood-scale to stormwater management planning through GI. From the legal and regulatory definition of the problem, to assignment of accountability, to acceptance of large-surface area based strategies for prevention of CSO events, to the acknowledgement of sewersheds and the stakeholders within them as important aspects of analysis and planning, neighborhoods are now a critical component of the planning process for GI.



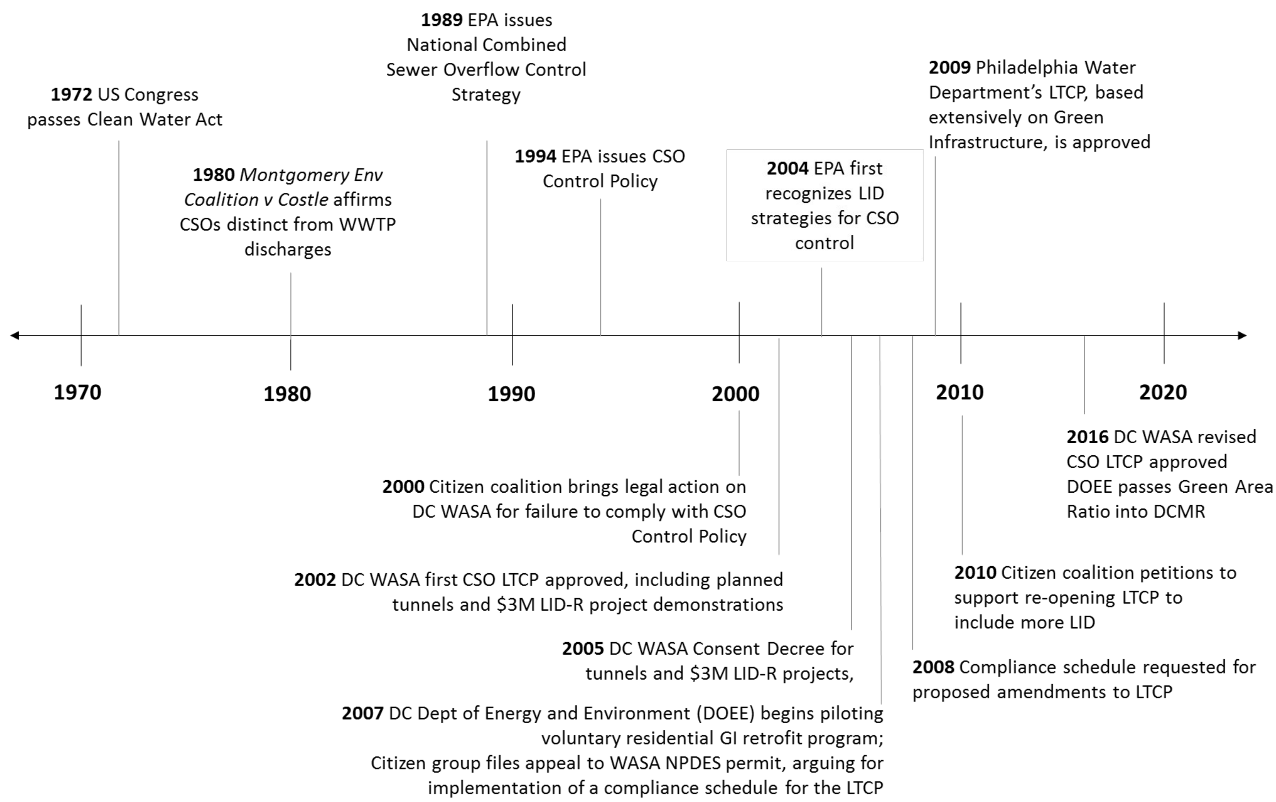


Figure 1. Timeline of National events relating to GI and CSO Long Term Control Plans in the US.

3.2 GI driven revitalization, or redevelopment driven GI implementation?

The narrative that GI could and should be used to revitalize urban neighborhoods is dominant in the urban planning sphere, however, GI has another relationship to revitalization that is less talked about. Unlike conventional infrastructure, which is centrally planned and usually located in the publicly-owned right-of-way (streets), GI is spatially distributed throughout the urban landscape, and relies on the widespread adoption of private property owners to be implemented on a large scale. Local stormwater managers cannot compel property owners to make changes to their properties such as removing impervious pavement and replacing it with stormwater BMPs such as bioswales and raingardens. The only way that stormwater regulations can be imposed on private property owners is through the construction permitting process. Subdivision and Land Development Ordinances (SALDOs) are one way that legally mandate that real estate developers comply with regulations to manage stormwater on-site through various BMPs. Such ordinances are typically triggered through the existing permitting process when some amount of land is disturbed through construction.

SALDOs are one of the most effective ways to plan for city-wide implementation of GI, however, they have a drawback. The process of land development in existing urban cores is not spatially uniform. Instead, the locations of where reconstruction, development and significant renovation occur within a city is driven by market value. This implies that if the majority of the GI implemented by a city is driven by redevelopment, that GI will be located in neighborhoods that are already otherwise experiencing revitalization. In turn, if neighborhoods that are already experiencing revitalization and the improvements in urban environmental amenities that accompany modern urbanism, this implies that any additional public subsidies towards building more GI on private property may in fact be funding projects that may have occurred otherwise due to market demand for these amenities. Market-driven GI implementation is also not redistributive, and would result in some neighborhoods continuing to be lack environmental amenities and the ecosystem services they provide.

Ideally, the role of a central planning agency should be to ensure that infrastructure serves all neighborhoods equally and that environmental resources and amenities are redistributed to the neighborhoods that most need them (Heckert and Rosan 2015; Wolch, Byrne, and Newell 2014; Krumholz 1982). This is especially true when we consider the existence of positive feedbacks that often occur in redevelopment processes (**Figure 2**). Market-driven development/redevelopment often encourages more investment. GI and vegetation in public areas has been shown to increase the perception of public safety, attract shoppers into stores, and increase property values (Branas et al. 2011; Garvin, Cannuscio, and Branas 2013; Bolitzer and Netusil 2000; Troy and Grove 2008; Wolf 2005). **Figure 2** also shows another positive feedback loop: that GI adoption, some completely funded by the central planning agency, others subsidized through voluntary adoption programs could also lead to more adoptions. This is because exposure to, knowledge of, and appreciation for GI projects spreads through proximity-based social networks (Lim 2017). This means that in areas where there are high concentrations of GI, residents are more likely to adopt GI in the future, potentially creating opportunities for more savings for the stormwater agency responsible for meeting the environmental regulations described above. Therefore GI and revitalization has both the potential to exhibit positive feedbacks that result in increased economic efficiency and increased inequality.

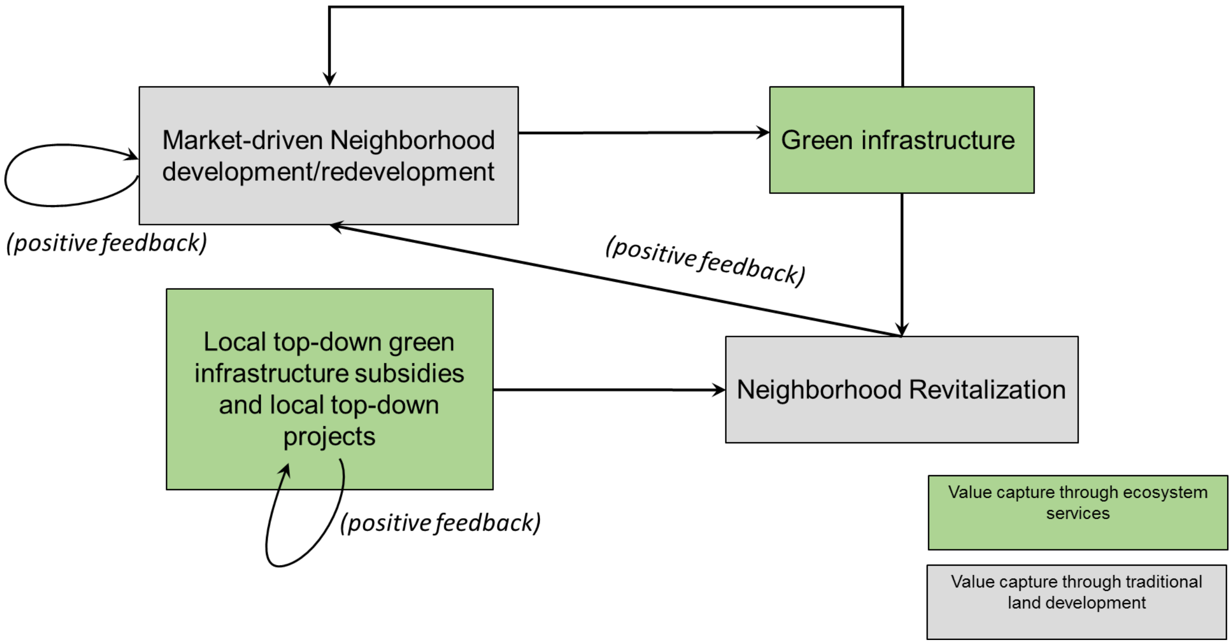


Figure 2. Potential relationships between neighborhood revitalization and GI implementation

4 WASHINGTON DC GI PLANNING AND IMPLEMENTATION

4.1 Policy history

The growth of GI programs in Washington DC (summarized in **Figure 3**) fits within the national context presented in the previous section, and is also reflective of the dynamics between neighborhood revitalization and GI adoption presented in **Figure 2**. DC is served in part by a CSS and in part by a municipal separated sewer system (MS4). (**Figure 4).** The District of Columbia Water and Sewer Authority (WASA) is the public utility responsible for water and wastewater services in the district, and therefore is the holder of the NPDES permit for the CSS that serves the city. The District's Department of Energy and Environment (DOEE, formerly known as the District Department of Environment, DDOE), is the holder of the NPDES permits for the MS4 portion of the city. Following federal-level guidance on CSO elimination in the mid-1990s, DC WASA drafted its CSO Long Term Control Plan (LTCP). The LTCP met the requirements CSO controls set forth by the CWA regulation by proposing to construct three massive stormwater conveyance and storage tunnels that would increase the capacity of the CSS (DC WASA 2002).

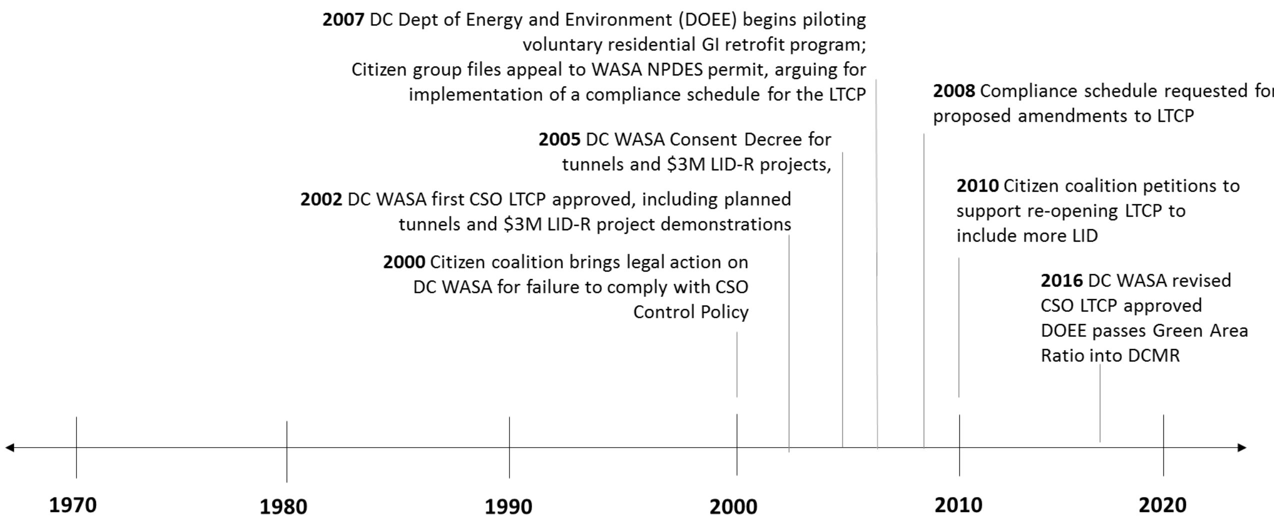


Figure 3. Key events and policies relating GI planning to urban neighborhoods in Washington DC

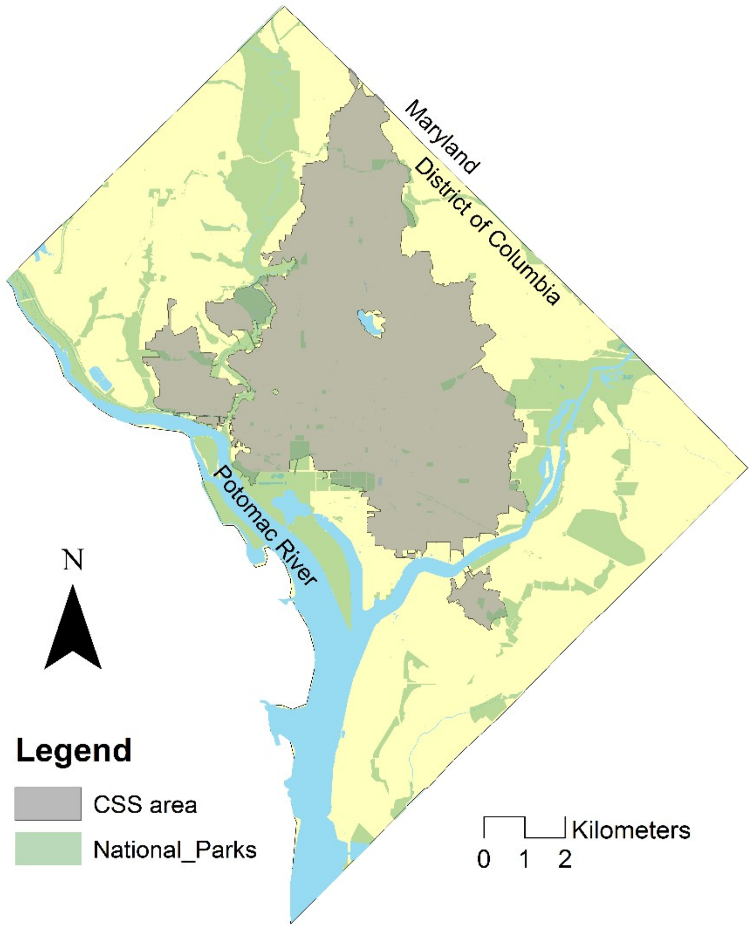


Figure 4. Combined Sewer System Area in Washington DC.

The official legal document binding DC WASA to the tunnel and GI infrastructure investments described in its 2002 LTCP is WASA's 2005 Consent Decree; however, this consent decree was spurred by the legal action of a coalition of environmental non-profit groups in 2000. Their actions, in turn were based on the assertion that WASA had not met the requirements of the CWA under the CSO Policy released by the EPA in 1994. Although for different reasons, both citizen environmental groups and WASA appealed the NPDES permit for the CSS system multiple times, in 2005 through 2007. Environmental groups sought to hold WASA responsible for the implementation of its plans, including, for the replacement of the proposed tunnel with LID-R (GI), without sacrificing interim water quality standards (DC WASA 2008). To WASA, in contrast, the plan without a clear compliance schedule represented the risk that it could be held "arbitrarily at risk of the Final Permit" while technologies were in the process of being implemented (DC WASA 2008).

Although not in explicitly listed as a rationale for consideration of an extended timeline for meeting interim water quality standards, the difficulty of implementing a widespread GI program in this timeframe was well-recognized. At the time of submission of the LTCP in 2002, even WASA acknowledged the existence of "LID-R" (Low Impact Development – Retrofit, which is distinguished from LID for greenfield development) facilities to control stormwater runoff. Three million dollars were allocated for LID-retrofits. These retrofits were seen as “system wide controls” that had “ancillary benefits” such as reducing cooling costs and increasing aesthetic value, however, the original LTCP also acknowledged the difficulty of WASA in incorporating such controls into its LTCP: “Since WASA does not control development or redevelopment in the District, WASA cannot mandate application of LID-R. WASA will, however, incorporate LID-R techniques into new construction or reconstruction on WASA facilities where applicable, and will act as an advocate for LID-R in the District” (DC WASA 2002; DC WASA 2005). This statement highlights the difficulty of WASA’s position as a public utility provider in delivering widespread GI practices in the District because of the dependence of GI on the development and management of private properties.

By 2010, national familiarity and experience with GI had already increased substantially. Instead of DC citizen action groups’ previous suspicion that GI might cause delayed implementation schedules, many of the same citizen groups began petitioning to re-open the LTCP to incorporate more GI (DC Water 2010). The groups Anacostia Riverkeeper, Anacostia Watershed Society, DC Environmental Network, Groundwork Anacostia River DC Inc., and Natural Resources Defense Council identified opportunities to collaborate with existing initiatives by the DOEE (then the DDOE, District Department of Environment) and the District Department of Transportation (DDOT) in order to streamline project construction and costs. The petitioners also identified opportunities to partner with other DC initiatives to promote revitalization and environmental quality, such as then-mayor Adrian Fenty’s Green DC Agenda.

By this point in time, a separate agency, the DOEE, had already begun to manage large, distributed GI programs in the district. Beginning in 2007, the DOEE began promoting subsidies for voluntary construction of GI on private properties through the RiverSmart programs (https://doee.dc.gov/service/get-riversmart). Through these programs, residents, small business, schools, and houses of worship are able to apply for evaluations and recommendations of simple stormwater management techniques suitable for their properties. Through diverse funding mechanisms that have included Fish and Wildlife grants and funding from the American Recovery and Reinvestment Act (2009 “stimulus” funding), the DOEE provides cost-effective installation of rain gardens, native landscaping, shade trees, rain barrels, and permeable pavement (Lim 2017).

While participants in the program are able to apply for ‘credits’ to their stormwater utility fees, most are not motivated by economic incentive. Instead, the RiverSmart programs are a means for residents to improve their properties and environment and participate in their communities. Through 2014, there have been a total of 3,737 RiverSmart Homes (the voluntary residential program) installations on 2,836 unique properties, or 2.5% of all residential properties in the District (Lim 2017). The RiverSmart Rooftops program has provided subsidies for 12 green roofs in the district. DOEE is also involved in ecological restoration of numerous streams and creeks within the District.

While DOEE’s mission includes broad ecological and social goals, DC Water, the water and sewer utility provider in the District is driven by a mission that makes very clear its emphasis on the operation of its permitted infrastructure and the flows (water, wastewater, and stormwater) within it. In 2015, DC Water successfully passed an amendment to its LTCP (DC Water 2015). The 2015 LTCP included the downsizing of two of the three originally planned tunnels, and aggressive GI plans (treating 30% of impervious surface areas with GI) in targeted sewersheds

(DC Water 2015) (**Figure 5**). The goal of the shift from gray to green infrastructure was to be able to provide taxpayers with experiential improvements to the city alongside the infrastructure upgrades that would have otherwise occurred completely hidden from public view in tunnels underground. As referenced in the 2010 petition by local environmental groups promoting collaborations between District agencies, DC Water's 2015 CSO LTCP indeed did reference leveraging the local expertise in the systems and procedures necessary to successfully delivering a distributed GI system (DC Water 2015).

Figure 5 shows a comparison of how the District's CSO LTCP measures changed between its original adoption in 2002 and its accepted amendment in 2015. Interestingly, despite citizen groups' original pushback against GI implementation for fears that the timeline to correct CSO events would be delayed, now citizen groups have an opposite concern. Neighborhoods in southeast and southwest Washington DC, which drain to the Anacostia River, will remain served by the large tunnel project originally planned in the 2002 CSO LTCP. The Anacostia River has borne the majority of water pollution in the District, and the planned tunnel is designed to be able to remove 98% of the river's pollution. However, local activists argue that neighborhoods will not benefit until the project is completed in 2022, when the new tunnel is scheduled to be completed. Unlike the GI target sewersheds, which will immediately begin to enjoy various ecosystem services benefits associated with GI—community amenity, heat island effect mitigation, air purification, in addition to stormwater management—the Anacostia River neighborhoods will have to wait until the entire project is completed. Many of the residents may never actually directly experience the benefits of the huge underground tunnel beneath their feet.

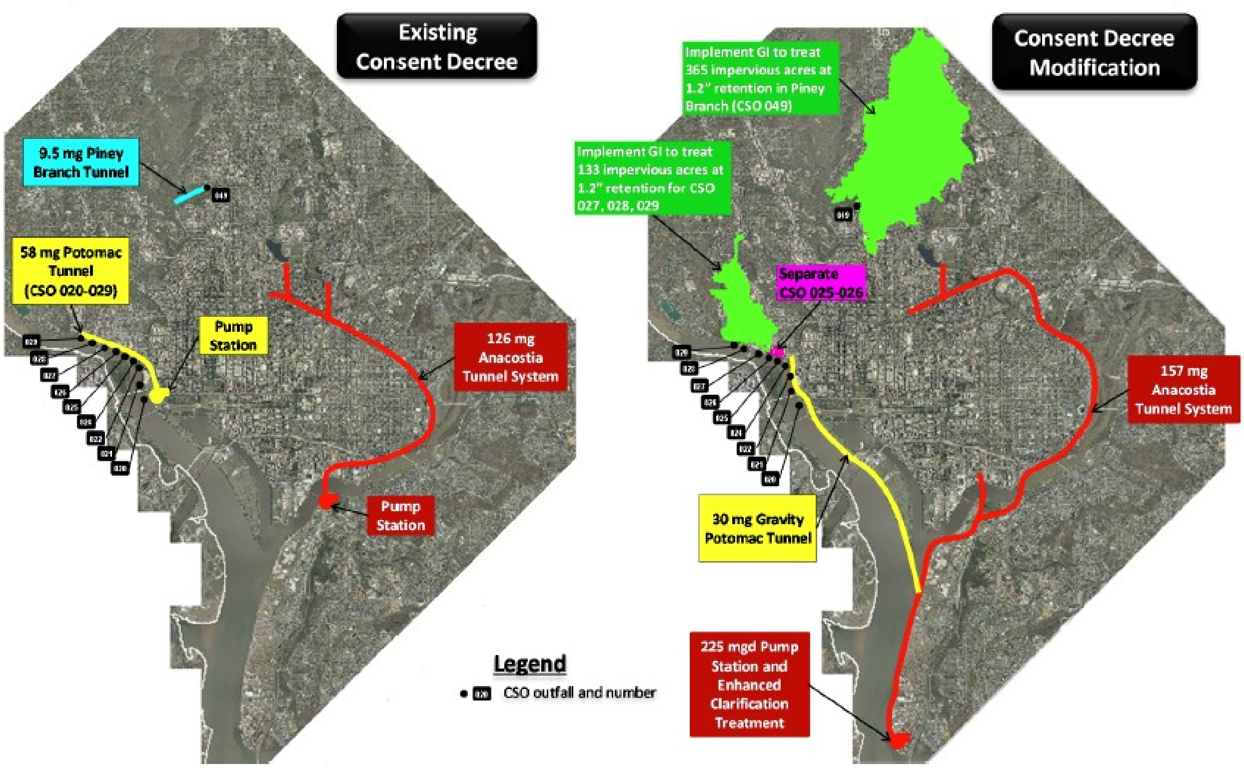


Figure 5 Comparison of original CSO LTCP (2002) and amended CSO LTCP (2016). Source: DC Water (2016)

Between both DC Water and the DOEE, there are only two 'required' GI construction programs. One is administered through the construction permitting process as an ordinance of the DC Municipal Regulations (DCMR). In 2013, the Stormwater Management Rule was passed to require that all construction projects disturbing 5000 sf of land or more or having a total project cost greater than or equal to 50% of the pre-project assessed value of the structure implement stormwater control measures to retain the first 1.2" of rainfall and maintain the peak discharge of the pre-development for a two-year storm and the peak discharge of the pre-project discharge for a 15-year storm. The second required GI program is also triggered through redevelopment. In 2016, the Green Area Ratio (GAR), which was passed into the DCMR adds additional landscape and vegetation quality standards into the District's zoning rules. While not explicitly stormwater-related, the GAR takes into account native vegetation and shade tree preservation in addition to just impervious surface-area based metrics (such as bulk lot coverages) previously part of zoning regulations. This regulation takes into account increasing scientific evidence that negative changes to the hydrologic cycle are not solely based on site imperviousness, but changes such as irrigation, decreased evapotranspiration resulting from vegetation change, and soil compacts that also accompany urbanization processes (Bhaskar et al. 2015; Lim 2016; Schwartz and Smith 2016).

Aside from these construction-dependent regulations (SALDOs), both agencies can only rely on encouraging private property owners to build GI on their properties or form strategic partnerships with other agencies to add GI an incremental cost to already-scheduled projects (for example a DDOT road paving project).

Table 1 summarizes the GI programs in DC, the responsible agency, and the implementation mechanism they rely on to increase GI within the District. In conclusion, because of the land surface-dependent nature of GI, GI program implementation, whether required or voluntary, are spatially opportunistic: they are usually passively dependent on where other choose to participate in the voluntary programs or where development or redevelopment are occurring within the District. In the following sections, we explore this landscape of implementation within the District.

Table 1. GI programs in DC, responsible agency, and implementation mechanism

GI-relevant programs	Responsible agency	Implementation mechanism	Relation to neighborhood
RiverSmart programs	DOEE	Voluntary subsidies for residents and property owners, DOEE-initiated, community outreach, outreach through service providers, partnerships agencies (eg: DDOT)	Knowledge about voluntary programs spreads through neighbors who have participated in the program
Ecological Restoration	DOEE	DOEE-identified projects and partnerships (eg: Park Service, universities, etc)	
Stormwater	District of	Required of new	Neighborhoods with high

management requirement	Columbia Municipal Regulations (DCMR); DOEE	construction and redevelopment projects > 5,000 sf	development/redevelopment rates will see higher GI construction rates
Stormwater Retention Credit Trading Program	DOEE	Voluntary participation where parcels can "trade" stormwater management volumes with other parcels in order to meet requirements	Neighborhoods with high real estate value may purchase trade with more distant neighborhoods to manage stormwater
Stormwater Retention Credit (SRC) Purchase Agreement Program	DOEE	Voluntary participation where parcels can opt to build GI facilities in exchange for credits	Neighborhoods with non-profits, faith-based organizations, government agencies, universities, or private enterprises may have higher GI construction rates
GI Certification Program	DC Water	Voluntary participation in training programs to better equip construction and maintenance GI workers in DC	Benefits neighborhoods with high development/re-development potential, building technical capacity in construction and maintenance of GI facilities; benefits neighborhood greening maintenance
DC Clean Rivers Project	DC Water	Tracking program unifying existing GI programs, especially those within targeted CSS sewersheds	No direct relevance to neighborhoods
Green Area Ratio	DOEE and DCMR	Required as part of zoning regulations, triggered by development	Benefits neighborhoods with high development/redevelopment potential by enforcing standards for landscaping and open space
Agency-identified GI construction projects	DC Water and DOEE	Partnerships formed between Agencies (for example with DDOT), or built on District land	Has potential to equalize development-initiated GI construction, and revitalize struggling neighborhoods, if agencies prioritize areas with environmental quality and greening needs

4.2 Neighborhood GI implementation

As can be seen in **Table 1**, the most processes by which GI might be adopted are either driven by redevelopment/new construction (in the case of required stormwater management regulations) or by voluntary participation in projects. The exception are agency-led collaborations for ecological restoration or GI construction projects on District-owned land. While DC Water to date has not yet overseen large-scale GI implementation, it is the holder of a legally binding NPDES permit that will make it accountable to meet a water quality compliance schedule. Therefore DC Water plans to continue to seek partnerships and means to efficiently track the distributed infrastructure practices that are already being implemented by other agencies and unify them onto one platform that will be able to “count” towards its permit requirements. The unified GI accounting system that DC Water has incorporated into its CSO LTCP does not merely account for practices implemented within the sewersheds that are of interest to it because of its CSO elimination obligations. Its proposed accounting system instead is meant to bring together distributed GI practices under a common infrastructure-asset management system that is also accountable to federal level environmental policy. This accounting system further legitimizes and values voluntary and neighborhood-based GI interventions by formally incorporating them into the asset management systems and regulatory framework of conventional infrastructure.

In particular, DC Water has identified two CSO outfalls where treatment of contributing impervious areas should reach 30% - 60%: the Potomac River sewersheds and the Rock Creek sewersheds The targeted sewersheds were once the sites of the planned tunnel interceptors. Some sub-sewersheds in the boundary are planned to achieve 60% of impervious surface cover treatment through GI, therefore many of the residential neighborhoods in these areas potentially have much to gain in community amenity through the targeting. The sewershed planning scale that DC Water is using for its LTCP is large enough to incorporate several neighborhoods, and these neighborhoods show diverse built-environment and socio-demographic characteristics across the district. **Figure 6** shows these sewersheds in relation to existing ecological restoration sites and to the median incomes of the census tracts (frequently used to define “neighborhoods” in the US) in DC. **Figure 7** shows a comparison of the breakdown of impervious surface types within the two target sewersheds.

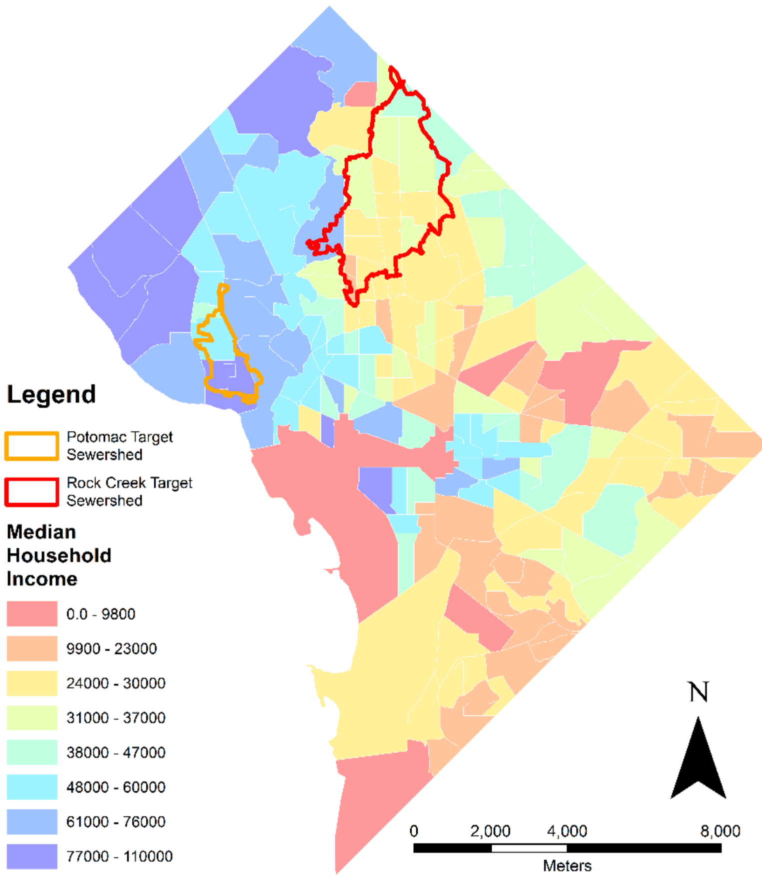


Figure 6 Targeted sewersheds in relation to median income in DC neighborhoods (census tracts). The targeted Potomac sewersheds are located in a wealthier area of the District while the Rock Creek sewershed includes some of the poorer census tracts within the District.

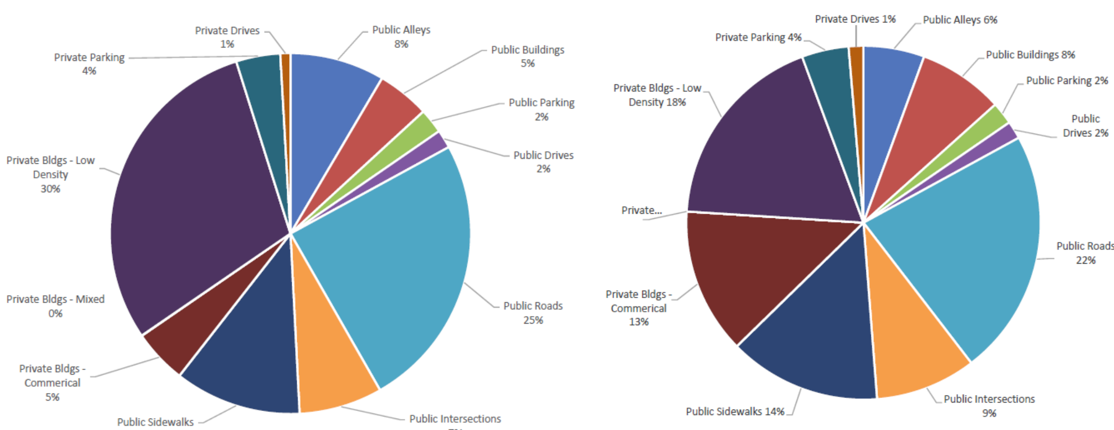


Figure 7 Breakdown of Impervious Land Use for Rock Creek (left) and Potomac (right) Sewersheds. Source: DC Water 2015. A greater percentage of imperviousness in the Potomac target sewershed is comprised of private commercial buildings, while a greater percentage of imperviousness in the Rock Creek target sewershed is comprised of low density private buildings. These built environment characteristics will have different implications for GI outreach

and implementation strategies within the sewersheds' neighborhoods, as well as for the types of GI-associated benefits that will be most relevant for the neighborhoods.

Ecological restoration sites, administered by the DOEE, have been sited near existing natural resources, such as urban streams and parks and are also not uniformly distributed in related to the District neighborhoods' the socio-economic or built environment conditions (**Figure 8**). **.**

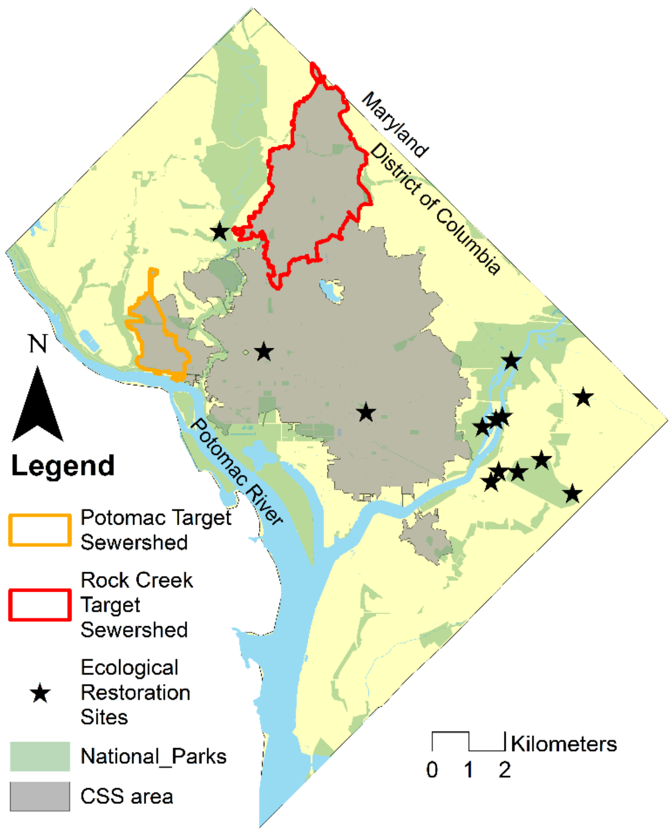


Figure 8. Areas target for GI implementation by DC Water and DOEE. DOEE ecological restoration sites are located near areas of existing natural resources. DC Water sewersheds targeted for GI retrofits are based on where additional capacity is needed in the conventional ("gray") infrastructure system.

5 MODELING SPATIAL DISTRIBUTION OF GI IN WASHINGTON DC

5.1 Determinants of Spatial distribution of GI types in DC

Above, I discussed the different dynamics that influence whether GI is redistributive or market-driven and the policies and programs in Washington DC that act as channels for these forces. In this section, I develop a map showing an example of the spatial clustering of GI across the District that could occur given urban processes that we observe, that are indicators of private and public investment across the city, both in real estate and in the natural environment. In this conceptual exercise, we develop density grids of various indicators of investment, then overlay them together in a final map showing how these indicators come together spatially. The grids were developed by constructing a 100 x 100 width x length fishnet across the boundary of the District. Densities and counts were calculated by intersecting the fishnet with various spatial datasets. Because property sizes are unevenly distributed in the District, each grid in the overlay analysis was normalized by the number of lots located within that grid, according to the District's records. Normalization by the total number of lots in the grid cell has the effect of representing a density. For variables such as the number of construction permits, or the number of property sales that occurred in 2016, normalization also has the appealing interpretation of probability. After normalization, the property sales layer represents the probability that a property within the cell will be sold during a given year. The input layers to the final overlay are shown in **Figure 9** and explained in detail below. The legends are shown on a low-to-high scale classified by quintile within the overall distribution.

Redevelopment and growth-triggered GI installation

Regulation

The DCMR requires that all construction projects that disturb over 5000 square feet of land surface area are required to meet stormwater control measures on site. To represent this driver of GI implemention, we have developed new building construction density maps for the District. Density maps represent the probability of construction across space.

Service-Provider initiated

One way that the voluntary program RiverSmart Homes conducts outreach to new residents is through service providers. DOEE and its partner NGOs conduct trainings for local landscaping companies in downspout disconnection, rain garden and bayscaping installation and shade tree planting. Projects initiated this way are directed through the RiverSmart Homes record-keeping system. Real estate agents showing properties for sale also promote the RiverSmart Homes subsidized GI program as a subsidized "landscape upgrade" that new homeowners can take advantage of. Density maps showing property sales represent probability that a property will enter a subsidized, voluntary GI program in this way. We anticipate that as more real estate agents learn of RiverSmart homes, more participants will learn of the program through the process of home sales.

Voluntary Participation

Through an analysis of six years of historical data from the RiverSmart Homes program, previous research has found that proximity to a past participant in the program, even after controlling for fixed spatial effects (such as two people of similar tastes and background being more likely to live in similar neighborhoods) (Lim 2017). Assuming that past patterns of voluntary participation will continue to have an effect on future participation, a density map of these past patterns provide the spatial distribution of past participants' effects on their neighbors.

Voluntary participation in the RiverSmart Roofs program has also shown evidence of spatial clustering. The literature has shown that property managers' willingness to install green roofs for environmental benefit is correlated with property value and competitiveness on the commercial real estate market. We represent the spatial distribution of competitive commercial buildings interested in environmental amenity creation using two layers: a density map of historical participation in the RiverSmart Roofs program, and a density map of EnergyStar rated buildings.

Institutions, including schools and houses of worship are the target participants of the RiverSmart Communities program. DOEE engages in active outreach and technical assistance with such institutions, therefore, we would only expect participant amongst these types of institutions to increase over time. We represent this potential opportunity with institutions using a density map of schools and houses of worship.

Public Right-of-Way

Potential spatial distribution of GI projects located in public (streets), referred to as the “Right-of-Way” (ROW), could depend on historical spatial patterns in two different ways. In the first type of spatial dependence, GI in the public ROW is indicative of future installation of GI in the public ROW. We would expect this assumption to hold if the selection of past ROW project locations were driven by capacity needs, construction feasibility, or similar replacement schedules for roads in similar neighborhoods. In the second type of spatial dependence, GI in the public ROW is build in neighborhoods that have not yet received projects. We would expect this assumption to hold if there was a step in the decision-making process to ensured that ROW projects were being evenly distributed across the district or if locations are driven by spatially uniform replacement rates of district pavement. Deliberate redistribution of public construction of GI might be the goal of the planning process that has environmental justice in mind, since communities will reap not only stormwater management, but many other benefits from proximate GI facilities (Heckert and Rosan 2015). In the overlay analysis shown here however, since GI planning has tended to be opportunistic, I consider the first scenario: that GI located in the public ROW is a positive indicator that more GI may be built there in the future.

Economic incentives

Researchers have long suggested that adoption of GI on private property should be motivated using economic incentives (Parikh et al. 2005; Thurston et al. 2008; Roy et al. 2008; Valderrama and Levine 2012). Stormwater fees based on the amount of impervious surface on a property (as a proxy for how much stormwater runoff is created by that property) could be offset with credits to the fee if the property owner is willing to reduce the amount of imperviousness of the site, or build GI to capture and treat the stormwater on the site (Parikh et al. 2005). Both DC Water and DOEE offer economic credits to property owners willing to treat stormwater on site. In addition, DOEE started a stormwater retention credit trading system that allows property owners to offer to treat volumes of stormwater on their properties for another property owner generating flows elsewhere. This opportunity was primarily to allow developers in the highly impervious, dense urban cores a chance to compensate another property owner located in an area of the city where it might be more economical to build GI facilities, instead of merely paying a “penalty” fee to DOEE.

Although both the SRC trading system and the stormwater fee credit programs have had limited participation to date—stormwater fee mitigation has not been cited as a major rationale for participation in the District’s voluntary programs—it is important to consider as possible policy lever in the future. These two economic incentive programs work towards somewhat different ends however. The stormwater fee credit programs might encourage properties with high levels of imperviousness (and are therefore paying higher stormwater fees) to mitigate stormwater on site. This would result in highly impervious areas adopting more GI. In contrast, highly impervious areas might choose to “trade” for stormwater credits where they can be built for cheaper, paying another land owner to manage stormwater offsite. We would expect this to result in more GI located in less dense, lower impervious areas of the District where it would be cheaper to construct GI. In our overlay, I consider the first case, of a property manager managing their own stormwater onsite, therefore implying that areas with higher imperviousness are more likely to implement than areas of lower imperviousness. This to some extent has been shown to be true empirically (Lim 2017).

5.2 Analysis of Spatial Drivers of GI Implementation

The final output shown in **Figure 10** applied equal weights to each of the layers included in the analysis. This implies that each of the determinants used as inputs all have equal influence on the outcome. This of course is a poor representation of reality. Perhaps the “real” driver of GI was simply the stormwater control measures required of new development/redevelopment. In this case, we would expect the spatial distribution of GI to be much more concentrated in the downtown area (near the center) and the stadium area (to the south), where the building permit data indicates the majority of such projects are located.

The weights applied to each input layer to this analysis can be adjusted to reflect different scenarios. A full scenario analysis is beyond the scope of this current research. Suffice it to say, depending on the vision and resources available to planners, a wide variation of outcomes could result from varying the weights on the input layers.

The results from this study (**Figure 10**) show that with no adjustment of layer weights, the spatial patterning of GI is predicted to occur in the downtown area, in the northeast and in the south Stadium area. Each of these areas have elevated scores in the building permit layer and the property sales layer. The underlying assumption to giving these two layers so much relative weight is that required stormwater regulations will be the spatial dynamic that drives GI implementation going forward. If, in contrast, we believe that word-of-mouth recommendations of the voluntary GI program between neighbors, then we could decide to apply additional weight on the RiverSmart Homes program participation rate layer.

Previous research has shown that homeownership rates in neighborhood are positively associated with voluntary adoption of subsidized GI on private property (Ando and Freitas 2011; Lim 2017). This means that even if information about voluntary subsidization programs, such as RiverSmart Homes does spread over time, participation rates may still lag in neighborhoods where many residents do not own their homes. The District may decide to acquire vacant land to build GI facilities on, or to invest more to build GI in the public ROW, on public school property, or on other District government property to make sure that these communities also receive the ancillary benefits of GI.

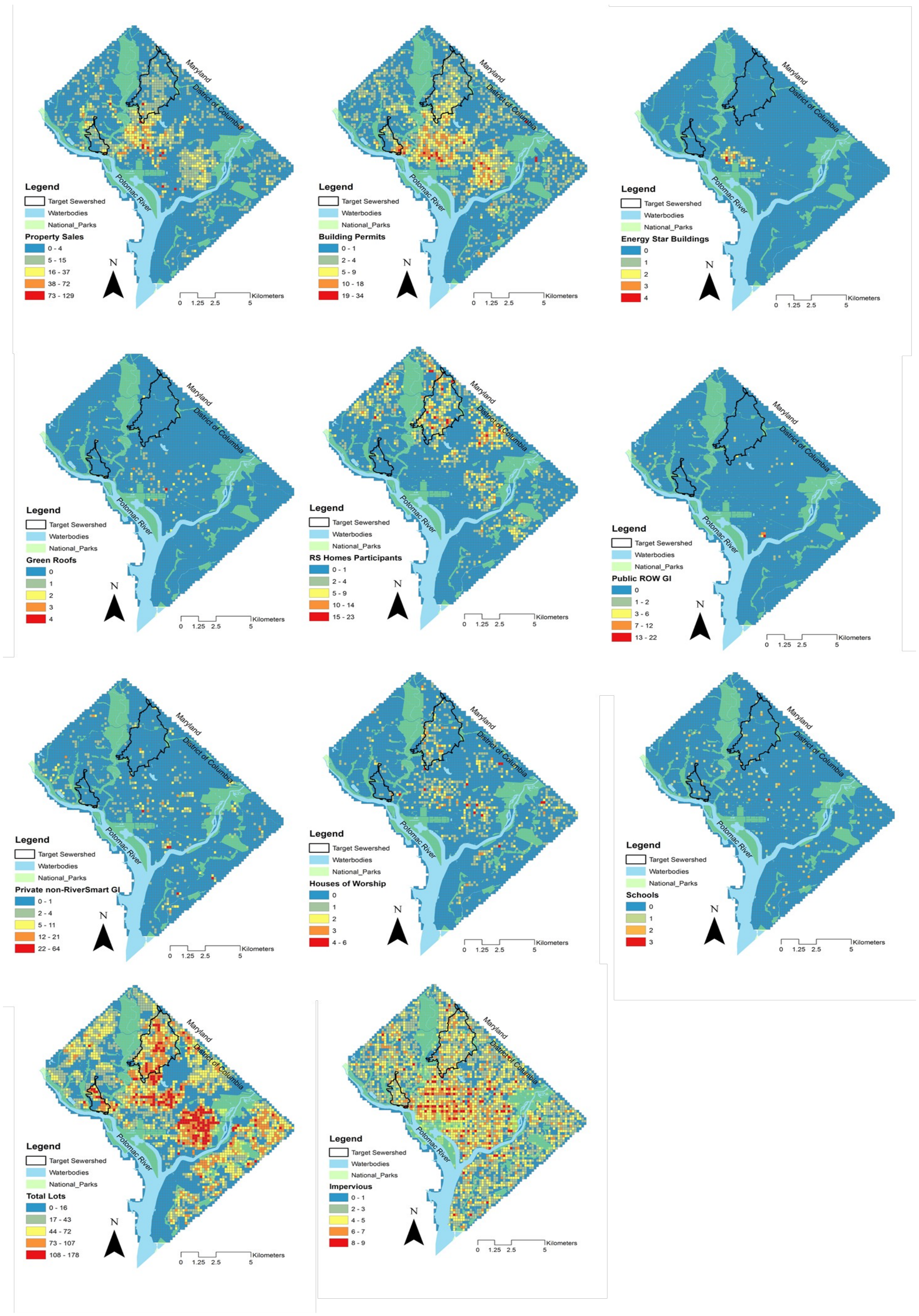


Figure 9. Input layers to overlay analysis

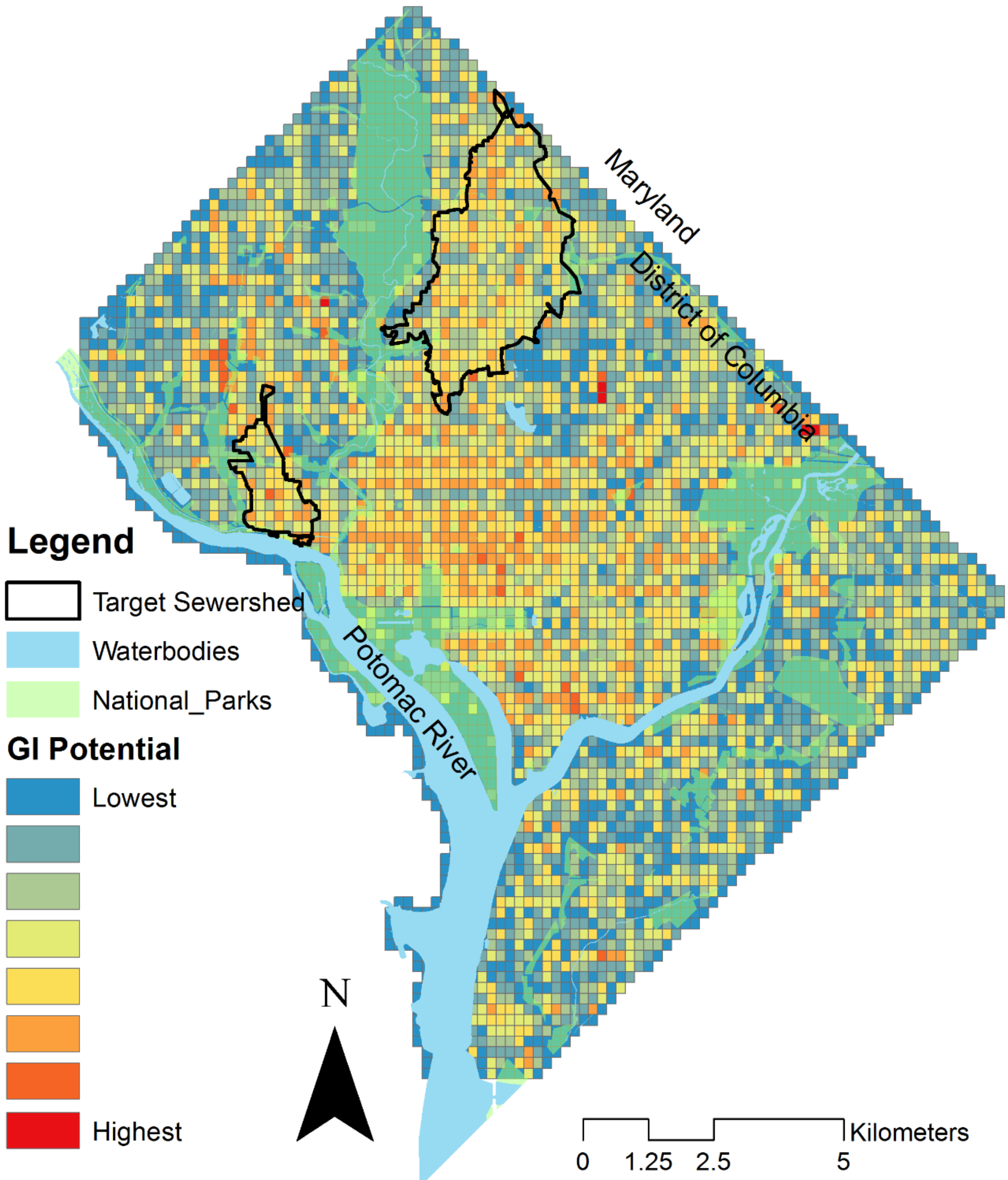


Figure 10 Result of final overlay analysis

6 DISCUSSION: IMPLICATIONS FOR NEIGHBORHOOD REVITALIZATION

The previous section outlined the primary ways GI is implemented in DC: SALDOs that are triggered by redevelopment, voluntary programs and centrally-planned projects. These policies are administered through two agencies with related goals, yet differing priorities. The DOEE is driven more by ecological and community building goals, while DC Water, the water/wastewater utility is driven more by its mandate to implement its CSO LTCP in an economically efficient way. The balance between these two agencies, their goals, and the processes of development/redevelopment and the spread of voluntary GI programs result in different areas of the district adopting GI through different channels.

GI implementation driven primarily by redevelopment and property sales might allow the district to reach its GI goals, especially since Washington DC is a hot real estate market with much competition for Class A Office and Federal office buildings that have incentives to implement green measures (Eichholtz, Kok, and Quigley 2010). However, this also means that other benefits that come alongside GI implementation: community amenity, air quality improvement, and heat island effect, for example, are also not equally distributed across the District. It is not coincidence that the poorer areas of the city, Southeast and areas of Northeast are predicted to have low levels of GI under the scenario where development drives GI adoption; these are areas that have suffered from decades of disinvestment, there are fewer property sales, and limited building. Some of this pattern can be seen from a simple comparison between **Figure 10** and **Figure 6** (Note: the census tract located in the middle of the District that displays as having very low median income in **Figure 6** is the location of the United States federal government buildings and has virtually no residents)**.** The observed spatial distribution illustrates the importance of planners taking a deliberate, non-opportunistic, and conscious approach to targeting projects for low-income or marginalized neighborhoods in order to balance market-driven GI adoption which tend to be more opportunistic.Only in this way can cities achieve an equitable outcome in terms of overall ecosystem services provided to residents by GI.

In these cases, it may also be necessary to set aside the notion that GI is “more economical” than conventional infrastructure. This notion comes from the savings that local utilities may be able to find by “aligning” the appropriate economic cost and incentives with the externalities of stormwater runoff production. Economic efficiency is theoretically achieved by allocating the cost of externality production to property owners, passing along some of the costs of construction, and the costs of operation and maintenance to the owners who are “generating” the most externality. In order to ensure that all communities can realize benefits from GI, there will be times when the city should deviate from true economic efficiency.

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