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Regulatory requirements and voluntary interventions create contrasting distributions of green stormwater infrastructure in Baltimore, Maryland

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HIGHLIGHTS

- Green stormwater infrastructure (GSI) in Baltimore was not installed systematically.
- About 60% of GSI was built for regulatory compliance and 40% was built voluntarily.
- Regulatory compliance and voluntary projects generated different types of GSI.
- Race and income have different relationships to regulatory vs voluntary GSI.
- More voluntary GSI is on public land in relatively disadvantaged areas.

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ABSTRACT

Green stormwater infrastructure (GSI) has been increasingly promoted as a strategy to augment gray infrastructure because it can reduce flooding, improve water quality, and provide additional social and ecological benefits. Government regulations in many places now require or encourage the use of GSI to mitigate impacts of development, while numerous funding opportunities incentivize installation of additional GSI features to enhance community and environmental benefits. The equity of GSI benefits may be affected by these different underlying motivations for GSI installation—mandatory compliance with regulations vs voluntary community improvement—which could create distinct patterns of GSI across the landscape. We examined this hypothesis in Baltimore, Maryland, USA, by comparing the city's database of GSI facilities that meet regulatory requirements ("regulatory GSI") to a dataset we compiled of GSI installed voluntarily by nonprofit organizations and community groups ("voluntary GSI"). We found that regulatory GSI included more facility types than voluntary GSI, which was dominated by microscale practices like rain gardens. The presence of regulatory GSI was negatively related to greater Black populations, while voluntary GSI was more likely to be found both in low-income areas with predominantly Black populations and in high-income areas with predominantly white populations. Voluntary GSI was much more commonly located on public land, and GSI on public land tended to be in more disadvantaged areas. These patterns of GSI distribution, which reflect different motivations and constraints in a fragmented implementation process, provide an opportunity for improving equitable access to GSI benefits through more systematic planning and management efforts.

1. Introduction

Green stormwater infrastructure (GSI) is widely promoted for its potential to provide multiple ecosystem services in urban landscapes. The use of vegetation, soils, and landscape features to mitigate the quality and quantity of urban stormwater runoff can, in theory, provide additional benefits to urban residents and wildlife, including heat reduction, habitat creation, and aesthetic value (Gonzalez-Meler,

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Cotner, Massey, Zellner, & Minor, 2013; US EPA, 2015). The equitable distribution of GSI across the urban landscape is thus an important concern. While some GSI is installed as part of systematic, citywide planning efforts that may take equity into consideration, a substantial amount is constructed without such formal coordination (Kuller, Bach, Ramirez-Lovering, & Deletic, 2018). Two circumstances that can lead to fragmented GSI implementation are regulations that require the use of GSI to mitigate the effects of development or redevelopment (Chini, Canning, Schreiber, Peschel, & Stillwell, 2017; McPhillips & Matsler, 2018) and the incentivization of GSI by philanthropic organizations and government granting programs promoting environmental and community improvement (Barclay & Klotz, 2019; Mandarano & Meenar, 2017; US EPA, 2015). In both cases, GSI is implemented by a variety of independent actors: GSI installed to satisfy regulatory requirements is built by developers or municipal agencies mitigating construction projects according to law, while GSI installed to achieve philanthropic aims is built by nonprofit organizations or community groups as part of their missions. These two different motivations for installing GSI may lead to distinct and uneven patterns of GSI across an urban landscape, with potential consequences for the distributional equity of GSI benefits.

Green stormwater infrastructure is a relatively recent addition to the urban landscape compared to other types of green infrastructure such as trees, parks, and green spaces, with the majority of GSI facilities in United States cities constructed since the 1990s (McPhillips & Matsler, 2018). Increasing recognition that impervious surfaces and engineered or "gray" stormwater infrastructure in urban areas can cause flooding and water quality issues, especially when existing infrastructure is aging and overburdened, has led many cities to turn to GSI as a stormwater solution (Golden & Hoghooghi, 2018; Green et al., 2021; Pennino, McDonald, & Jaffe, 2016). GSI prevents stormwater from flowing directly into storm drains, and often includes settling, soil infiltration, and plant uptake that can reduce the volume of stormwater and associated nutrient loads entering receiving water bodies (Gonzalez-Meler et al., 2013; Pennino et al., 2016). Regulations that require or encourage the use of GSI to mitigate the stormwater impacts of new construction or redevelopment projects are responsible for much of the recent increase in GSI in some cities (McPhillips & Matsler, 2018). Because these regulations are tied to construction, associated patterns of GSI installation are expected to follow trends in development or redevelopment (Mandarano & Meenar, 2017). GSI facilities associated with regulatory compliance are typically 1) designed as part of the construction permitting process, 2) based on a suite of acceptable GSI types, and 3) built to performance standards (US EPA, 2015). This process is designed to assure the functional quality of GSI, and aesthetic considerations may not be central to the project design (Fitzgerald & Laufer, 2017). When built as part of a private development, these GSI facilities may not be publicly visible, limiting any provision of aesthetic, recreational, or educational benefits for the general population.

In contrast to GSI that is built solely to satisfy regulatory requirements, GSI constructed with philanthropic support is often designed, built, and maintained with some level of community input and participation (Barclay & Klotz, 2019). Nonprofit groups that install GSI are concerned with a wide range of issues, including environmental protection, social cohesion, health and wellness, education, job creation and training, and neighborhood revitalization. These organizations may use GSI to bridge multiple objectives (Barclay & Klotz, 2019; Hager et al., 2013; Schifman et al., 2017). Given the numerous potential benefits of GSI, funding can come from a variety of disparate sources, including governmental, private, foundation, and other nonprofit entities, and even funding opportunities that are more targeted towards water quality protection typically embrace or encourage additional community goals (US EPA, 2015). Thus, because grants to install GSI provide opportunities for nonprofits to address multiple aspects of their missions, stormwater mitigation may not be the only determinant of GSI project locations, or even the primary determinant (Schifman et al., 2017). GSI placement is also guided by the geographical boundaries of the communities nonprofits serve, which may or may not match the boundaries of cities or other jurisdictions. In addition, many nonprofits depend on partnerships or agreements for access to land and resources. These relationships can determine the spaces available to install GSI and the priorities for its design, potentially affecting the public accessibility of projects and the type of GSI installed—for instance, attractive rain gardens may be favored over GSI types like stormwater ponds. Locations for GSI projects are further constrained by the availability of suitable spaces in dense urban areas (Green et al., 2021). While urban areas with high impervious cover often have the greatest need for stormwater runoff mitigation, they may also have scarce space available for GSI construction (Avila, Avila, & Sisa, 2016; Morsy, Goodall, Shatnawi, & Meadows, 2016).

Given these contrasting motivations and constraints for constructing GSI, the distributional patterns that emerge from voluntary, philanthropically driven GSI projects are likely to be different from those that emerge from GSI projects built for regulatory compliance. This study seeks to characterize these two different patterns of GSI installation in the City of Baltimore, Maryland, USA, and to explore implications for distributional equity. For simplicity, we refer to these two different types of GSI as "regulatory" and "voluntary" GSI, while acknowledging that regulations may provide an underlying motivation for voluntary GSI projects. Specifically, we ask: 1) What types of GSI have been installed for regulatory versus voluntary purposes in Baltimore? 2) How are the types and overall distributions of regulatory and voluntary GSI related to sociodemographic characteristics and the amount of impervious surface? 3) What proportions of regulatory and voluntary GSI are located on public land, and do projects on public land tend to occur in areas with different sociodemographic characteristics than those on private land? Working from city records and a variety of resources for GSI installed by nonprofits, we compiled a new GSI dataset to investigate these questions.

2. Methods

2.1. Study area and background

This study was conducted in the City of Baltimore, Maryland, which has a temperate climate and a population of 585,708 according to the 2020 Census. Baltimore's current population is approximately 62 % Black and 30 % white, with other racial identities comprising <10 % of the total population. Like most cities in the United States, Baltimore has a long history of racial inequality. Baltimore enacted a series of residential segregation ordinances between 1910 and 1913, followed by a slew of overtly racist housing and development policies that prevented Blacks from moving into white neighborhoods (Power, 1983), and these policies have contributed to the city's persistent "hypersegregated" status (Massey & Tannen, 2015). Continued disinvestment in Baltimore's primarily Black neighborhoods has sustained and exacerbated economic, health, and education disparities (Brown, 2021). Baltimore has also seen a dramatic reduction in its total population since the 1950s, leaving many vacant properties and sometimes resulting in the demolition of entire blocks of houses (Cohen, 2001).

Baltimore is located on the Chesapeake Bay, which has been severely impaired by excess nutrients and sediments (Boesch, Brinsfield, & Magnien, 2001). Unlike many older cities in the eastern United States, Baltimore's stormwater infrastructure is separate from its sanitary sewer system, and stormwater is not treated before it reaches receiving waters. To remain in compliance with federal regulations associated with the Clean Water Act's National Pollutant Discharge Elimination System (NPDES) program, Baltimore has operated under an NPDES Municipal Separate Storm Sewer System permit, or MS4 permit, since 1995. The MS4 permit, which is administered through the Maryland Department of the Environment, requires the city to develop and implement a plan to control the quality of its discharged stormwater, and GSI is one strategy that generates credits toward achieving the compliance targets. The

Baltimore City Department of Public Works (DPW) is the agency tasked with meeting these targets, and therefore is charged with tracking the GSI facilities that fulfill the requirements of the permit. In order to receive credit under the MS4 permit, GSI facilities must be of an approved type and, importantly, they must have engineered as-built certifications that show they were built to design specifications (Maryland Department of the Environment, Maryland Department of Agriculture, Maryland Department of Natural Resources, 2016).

Maryland state law has also played a large role in increasing the use of GSI to mitigate the stormwater impacts of development. The Maryland Stormwater Design Manual, released in 2000, established design standards for a variety of GSI facility types that could be used to satisfy stormwater management requirements (Maryland Department of the Environment, 2009), and in 2007, the Maryland Stormwater Management Act mandated the use of a certain set of these facility types—more modern, decentralized GSI features—to mitigate all new development, redevelopment, and retrofit projects to the maximum extent practicable (Maryland Department of the Environment, n.d.). GSI built to fulfill these state requirements also counts toward the city's MS4 permit requirements, regardless of whether it is publicly or privately built. In fact, in Baltimore City, nearly all the constructed GSI facilities reported for the MS4 permit have been constructed to comply with state mitigation requirements (N. Krause, personal communication, May 20, 2019). While the city has identified numerous locations to install GSI as part of its MS4 permit planning process (City of Baltimore, 2015), these projects had not been completed at the time of our data collection.

Concern over the impacts of urban runoff on water quality in the Chesapeake Bay has also stimulated many funding opportunities for constructing voluntary GSI in the city. The Chesapeake Bay Trust, for instance, is a nonprofit granting organization that provides millions of dollars each year to fund projects that contribute to protecting the environmental health of the Chesapeake Bay region, including many GSI installations (cbtrust.org). The Maryland Department of Natural Resources also provides grant funding for GSI projects through its Chesapeake and Atlantic Coastal Bays Trust Fund (dnr.maryland.gov/ccs/pages/funding/trust-fund.aspx), and the National Fish and Wildlife Foundation has provided support for GSI projects in Baltimore as well (https://www.nfwf.org). The City of Baltimore itself has funded nonprofit-led GSI installations through programs such as the Growing Green Initiative, which supported efforts to transform vacant lots into community amenities with GSI components (planning.baltimorecity.gov/programs-initiatives/growing-green-initiative). We found that some of these grant-funded voluntary GSI projects have been integrated into renovation projects like the redesign of a park or playground, but unlike regulatory projects, most are built to mitigate runoff from existing urban infrastructure rather than new development.

2.2. Data

2.2.1. GSI definition

We focused our analysis on visible GSI that could be mapped accurately within census and property boundaries. We thus limited our definition of GSI to spatially discrete installations with aboveground components, excluding projects such as street tree plantings and underground filters. The one partial exception was the inclusion of sand filters, which may or may not have an aboveground component; design information was not available, so we included all sand filters. Additionally, we excluded projects that involved only planting of vegetation without specific stormwater features, e.g., riparian buffer plantings and pollinator gardens. We also excluded stream restorations, as well as soil decompaction. These criteria are comparable to other studies of GSI in Baltimore (e.g., Baker, Brenneman, Chang, McPhillips, & Matsler, 2019), and all types of GSI included in the analysis can be found in Table 1.

Table 1
Total count of GSI facilities included in each GSI category and the number of block groups (*n*) containing GSI in each category used for analysis, for both regulatory and voluntary datasets. The facility types included in each category are also listed. Characteristics of block groups containing different types of GSI were only compared for GSI categories found in at least five block groups with full ACS data, so there is no *n* for uncommon categories; however, these uncommon types were included in the totals for all GSI.

		Regulatory		Voluntary	
GSI category[1]	GSI facility types[2]	count	*n*	count	*n*
All GSI	All types	419	124	293	103
Alternative surface	Green roof, permeable pavement	60	22	13	12
Dry structure	Extended dry detention structure, dry pond	120	60	0	
Land cover change	Impervious surface elimination	1		61	44
Microscale practices	Micro-bioretention, rain garden, rainwater harvesting, bio-swale, grass swale, stormwater planter, submerged gravel wetland	96	31	215	85
Nonstructural practices	Disconnection of rooftop/ non-rooftop runoff, sheetflow to conservation areas	4		1	
Nontraditional	Step-pool storm conveyance, other	5		2	
Open channel systems	Dry swale	6		0	
Stormwater filtering systems	Bioretention, perimeter/ sand filter	92	50	1	
Stormwater infiltration	Infiltration basin, infiltration trench	10		0	
Stormwater ponds	Extended wet detention structure, micropool extended detention pond, pocket pond, retention pond	25	10	0	

[1] Categories established by the Maryland Stormwater Design Manual.
[2] GSI types recognized by the Maryland Department of the Environment.

2.2.2. Regulatory GSI data

We acquired a spatial database of GSI projects from Baltimore City's DPW, which included all GSI from both private and public re-/development projects subject to the Maryland Stormwater Management Act. This database had been submitted to the Maryland Department of the Environment in December of 2018 as part of the requirements for Baltimore's MS4 permit reporting, and was the most up-to-date list of GSI facilities for the city. While the geodatabase contained both built and planned GSI, only facilities specifically marked as "constructed" in the geodatabase had fulfilled regulatory requirements, and these facilities are the focus of our analysis. The most recent permit year listed for a constructed project was 2016. The GSI types listed in the database were those recognized by the Maryland Department of the Environment, and for some parts of our analysis, we grouped these GSI types into categories established by the Maryland Stormwater Design Manual (Table 1). Multiple GSI facilities in the database were often part of the same project—for instance, one project mitigating the construction of a parking lot might contain several bioretention facilities and an area of permeable pavement—and we used the facility IDs to assign individual facilities to different projects.

2.2.3. Voluntary GSI data

We took a multi-pronged approach to compiling a dataset of facilities installed by nonprofits and community groups. We began by acquiring data and information on some GSI installed by nonprofits from Baltimore's Waterfront Partnership, as well as nonprofit partners and DPW staff. We then researched the organizations and programs listed above that funded GSI projects within Baltimore City and extracted information about funded GSI projects from their annual reports, public databases, and press releases. We subsequently reached out to the major nonprofit organizations that were the recipients or facilitators of these grants—Blue Water Baltimore, Civic Works, Interfaith Partners for the Chesapeake, and Parks & People Foundation—requesting any additional information that would help us identify, characterize, and map their GSI projects in the city. Each organization provided us with additional resources, ranging in format from grant reports to online maps. We merged project information from all data sources into one complete dataset, focusing on the most commonly reported characteristics: type and number of GSI facilities installed for each project, the location of facilities, and the year of installation. We then filled in missing information from online sources such as newspaper articles, reports, organizational blogs, and presentations. This process revealed additional projects, which we added to the dataset. We completed data collection in 2019.

To make the voluntary dataset comparable to the regulatory dataset, we assigned each facility to one of the GSI types recognized by the Maryland Department of the Environment (see Table 1). However, because the terms "bioretention," "microbioretention," and "rain garden" were often used interchangeably, we did not differentiate these facility types and included them all in the "microscale practices" category, as these facilities were too small to meet the state's criteria for bioretention. We also verified the exact latitude and longitude of each facility using imagery from Google Streetview and Google Earth when possible. Because we knew from our communications with nonprofits that some of their projects were going through the city's permitting process, we then checked the location of each nonprofit project against those in the city's MS4 database to avoid redundancies. Finally, we again reached out to nonprofit organizations and Baltimore's DPW to see whether they would be willing to review and verify the compiled dataset for accuracy. We received feedback from DPW, Parks & People Foundation, and Blue Water Baltimore and incorporated all new information they provided. These data are now publicly available (Solins, Phillips de Lucas, Cadenasso, & Grove, 2021).

2.2.4. Sociodemographic characteristics and property ownership

To describe sociodemographic characteristics across the city of Baltimore, we used American Community Survey (ACS) five-year estimates for the years 2012–2017 at the census block group level. Block groups are contiguous statistical areas that contain 600–3,000 people (census.gov). The 2017 five-year estimates were chosen to match available property and impervious surface data, and because 2017 is the year by which the vast majority of GSI projects in our datasets had been completed. The variables we considered were race (the percent of the population identifying as Black), median household income, percent

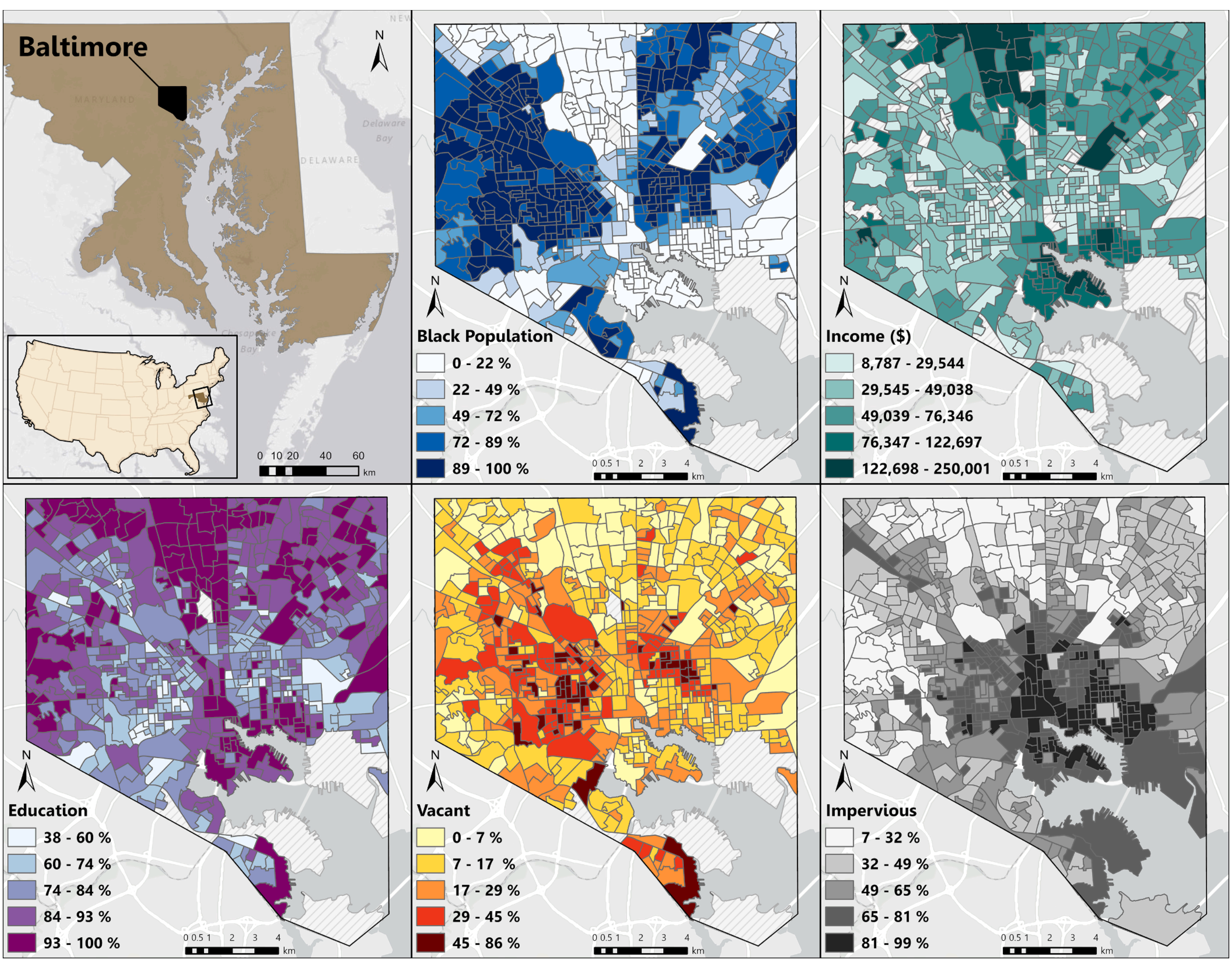

Fig. 1. For census block groups in the city of Baltimore, Maryland, the distributions of variables that were included in statistical analyses. Income refers to median household income, and the distribution for education is the percent of the population over 25 years of age with a high school degree. Data were classified based on the Jenks Natural Breaks algorithm.

vacant properties, and educational attainment (the percent of the population over 25 years of age with a high school degree or higher), which have been linked to other environmental justice concerns in Baltimore (Boone et al., 2009; 2014; Grove et al., 2018). Of the 653 total block groups in Baltimore City, ten were estimated by the ACS to contain <30 households and lacked data for some variables, so we removed them from analysis. All retained block groups included more than 80 households. An additional 45 block groups were missing income data, and thus could not be used for models or tests including income. Distributions of the variables across the city are shown in Fig. 1.

To determine whether GSI was located on private or public land, we used parcel ownership data from the City of Baltimore's Real Property dataset, updated in July 2017. This dataset was the most current available at the time of analysis. Any parcel with a city or state public agency or office listed as the owner was considered public, as was the public right of way. We were unable to determine private or public land ownership for one regulatory facility and five voluntary facilities.

2.2.5. *Impervious cover*

We determined the percent impervious cover in each census block group using a high-resolution land cover dataset for Baltimore that was generated using object-based image analysis techniques by the University of Vermont's Spatial Analysis Laboratory. Primary sources for the dataset were 2015 color infrared aerial imagery from the National Agriculture Imagery Program and LiDAR flown in 2014. Land cover types were classified with a minimum mapping unit of eight square meters. Our calculation of percent impervious cover (Fig. 1) included any land classified as buildings, roads and railroads, or other impervious surfaces.

2.3. *Analysis*

All statistical analyses were carried out using R version 4.0.0 (R Core Team. (2021), 2021). Only 216 of Baltimore's 653 block groups contained any constructed GSI from either dataset, so we considered the presence of GSI in a block group as the primary outcome variable for analyses. The total numbers of block groups containing GSI used for different analyses are shown in Table 1. Given that our data did not meet the assumptions for parametric *t*-tests or ANOVA, we used nonparametric tests. We compared the characteristics of block groups that contained regulatory vs voluntary GSI using Wilcoxon rank sum tests. Within the regulatory and voluntary GSI datasets, we compared the characteristics of block groups that contained different categories of GSI types using nonparametric Kruskal-Wallis tests. GSI types that occurred in fewer than five block groups with full ACS data were excluded from this analysis (Table 1), but were included in all other analyses. When significant differences ($p < 0.05$) were detected with Kruskal-Wallis tests, we tested for pairwise differences among groups using Nemenyi posthoc tests (Pohlert, 2021).

For both the regulatory and voluntary datasets, we used generalized linear models to establish whether the presence of GSI in a block group was related to sociodemographic variables and impervious cover. Models also included the land area of the block groups as a predictor to account for the greater likelihood of GSI being present in larger block groups. In addition, we tested for an interaction between race and income to see whether the relationship between race and the presence of GSI depended on income levels. Non-significant interactions were removed from final models to prevent them from masking the main effects of the variables. Predictor variables were transformed as necessary to achieve more normal distributions. Spearman correlations between predictor variables were all $<|0.65|$ (Table S1), and we checked that the variance inflation factor was <2 for all model variables not included in an interaction. We conducted model diagnostics using simulated standardized residuals from the "DHARMa" package (Hartig, 2020), including tests for dispersion, uniformity, and outliers. We then tested these simulated residuals for spatial autocorrelation based on a global Moran's I statistic, using queen contiguity-based, row-standardized weights. We used Monte-Carlo simulations ($n = 999$) to determine significance with the "moran.mc" function of the "spdep" package (Bivand & Wong, 2018), and ensured $p > 0.1$.

To examine differences related to public vs private land ownership, we separated projects located on public and private land and assigned each project the sociodemographic and impervious cover characteristics of the block group in which it was located. We compared these block group characteristics between projects on public vs private land for both regulatory and voluntary GSI projects using Wilcoxon rank sum tests. Four projects included GSI facilities in two different block groups, and for these projects we used weighted mean values of characteristics based on the number of facilities in each block group.

3. Results

The regulatory dataset included a total of 419 constructed GSI facilities across 243 projects. We identified 293 voluntary GSI facilities that had been constructed across 156 projects; of these 293 facilities, there were eleven we were not able to locate with enough precision to include in analyses. Locations of regulatory and voluntary GSI across Baltimore are shown in Fig. 2. There was no overlap of projects between the voluntary GSI dataset and constructed GSI in the regulatory database. The oldest facilities in the regulatory dataset were built in 1985, but about 60 % of the facilities had been completed since 2010. The vast majority of voluntary projects—all but nine—were built after 2010, with about two-thirds completed between the years 2014 and 2017. Only 13 voluntary projects were completed after 2017.

Regulatory GSI was relatively evenly distributed among several different categories of GSI, whereas nearly 75 % of all voluntary facilities were microscale practices (Fig. 3). In addition, more than 85 % of

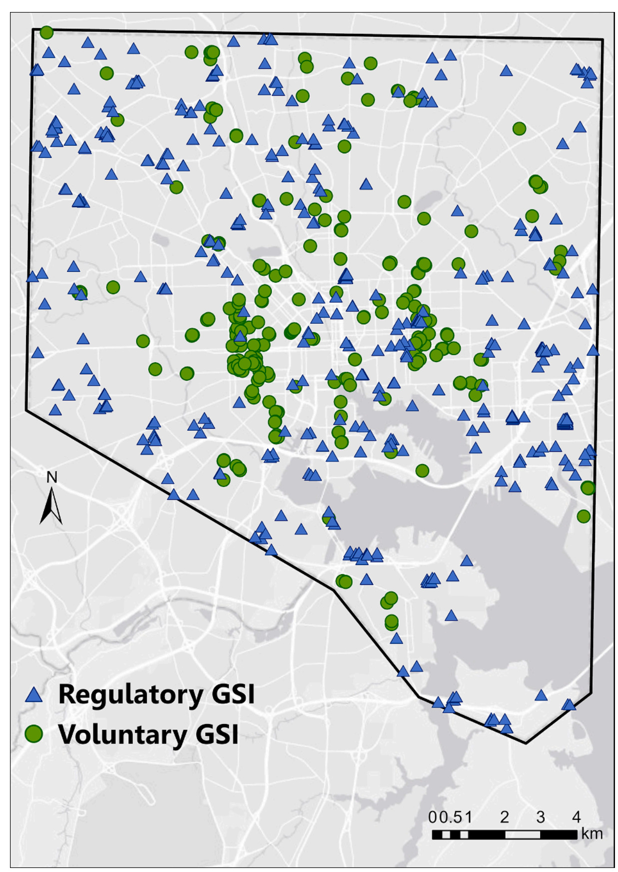

Fig. 2. Distributions of regulatory and voluntary GSI across the city of Baltimore.

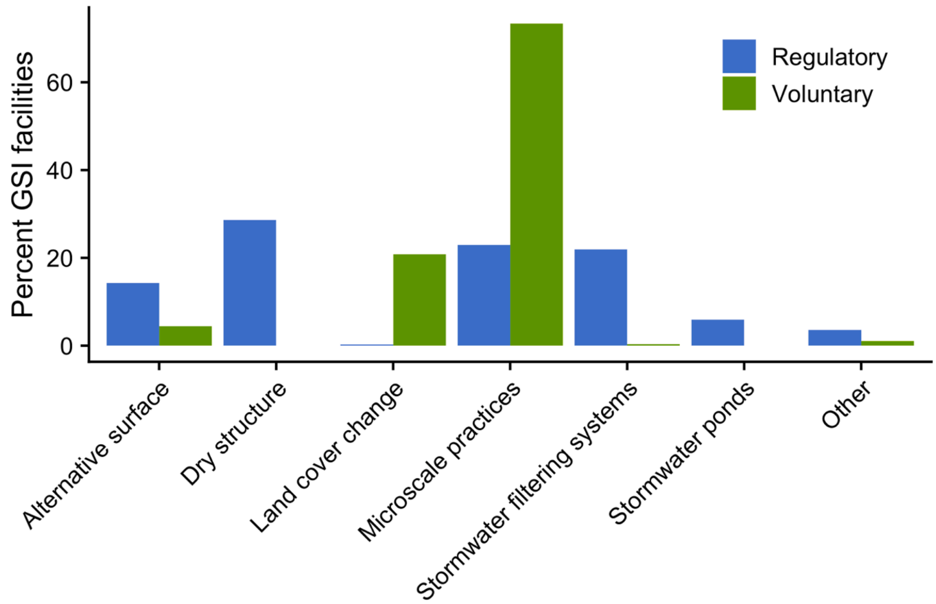

Fig. 3. The percent of regulatory and voluntary GSI facilities in different categories established by the Maryland Stormwater Design Manual.

the 215 voluntary microscale facilities were rain gardens, micro-bioretention, or stormwater planters, with swales and rainwater harvesting each including only 15 facilities. While there were more voluntary facilities in the microscale practices and land cover change categories, there were more regulatory facilities for all other GSI categories.

Voluntary GSI tended to be located in block groups with greater vacancy ($p < 0.001$) and impervious cover ($p = 0.003$) than regulatory GSI (Fig. 4). However, there were no strong or consistent patterns differentiating the characteristics of block groups containing different categories of GSI. For voluntary GSI, there were no significant differences. For regulatory GSI, dry structures and stormwater filtering systems tended to be located in areas with slightly higher income than stormwater ponds ($p = 0.06$ and $p = 0.07$, respectively), while alternative surfaces tended to be located in areas with greater impervious surface cover than dry structures and microscale practices ($p < 0.001$ and $p = 0.005$, respectively; Figure S1).

Generalized linear models showed that the presence of regulatory GSI was negatively related to both the Black population and median household income of a block group, whereas it was positively related to impervious cover and area (Table 2). There was no significant interaction between race and income for regulatory GSI ($p > 0.1$), but for voluntary GSI, the effect of race was influenced by income level. At very low income levels, the probability of a block group containing GSI became somewhat greater with an increasing Black population, whereas at very high income levels, the probability of a block group containing GSI decreased substantially with an increasing Black population (Fig. 5). The presence of voluntary GSI was also positively related to vacancy, impervious cover, and block group area (Table 2).

A much greater percentage of voluntary GSI was located on public land. We found that 71 % of voluntary projects were located on public land (including 67 % of facilities), but only 13 % of regulatory projects were located on public land (including 17 % of facilities). For both regulatory and voluntary GSI, projects located on public land tended to be found in block groups with greater Black populations, lower incomes, lower educational attainment, and greater vacancy, although the differences in income and education were not significantly different for regulatory facilities (Fig. 6). Impervious cover did not differ substantially between projects on public vs private land for either regulatory GSI ($p = 0.34$) or voluntary GSI ($p = 0.20$).

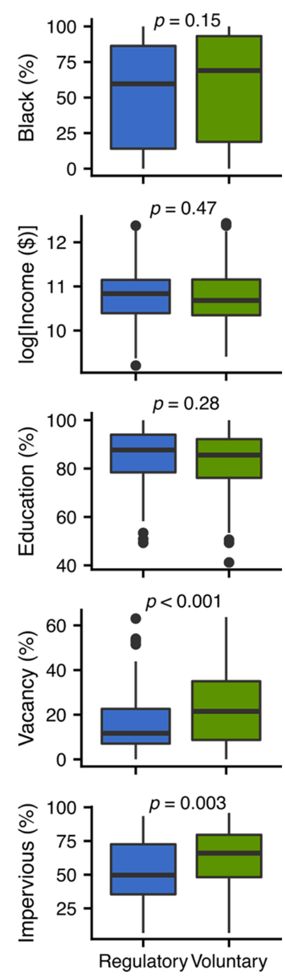

Fig. 4. Comparison of characteristics for block groups containing regulatory GSI vs those containing voluntary GSI. *P*-values were derived from Wilcoxon rank sum tests.

Table 2
Results of generalized linear models predicting the presence of GSI in a block group for both regulatory and voluntary GSI. Area refers to the size of the block group.

	Regulatory GSI				Voluntary GSI			
	Estimate		S.E.	*p*-value	Estimate		S.E.	*p*-value
Race (% Black)	−0.35	*	0.15	0.02	−0.09		0.17	0.60
Median household income (log $)	−0.48	**	0.17	0.005	0.006		0.17	0.97
Vacancy (%)	−0.14		0.14	0.30	0.37	**	0.14	0.009
High school education (%)	0.26		0.16	0.11	−0.03		0.14	0.84
Impervious cover (%)	0.45	**	0.16	0.004	0.35	*	0.15	0.02
Area (log km^2)	1.36	***	0.16	<0.001	0.48	***	0.14	<0.001
Race*income					−0.32	**	0.11	0.006
Intercept	−1.7	***	0.13	<0.001	−1.87	***	0.15	<0.001

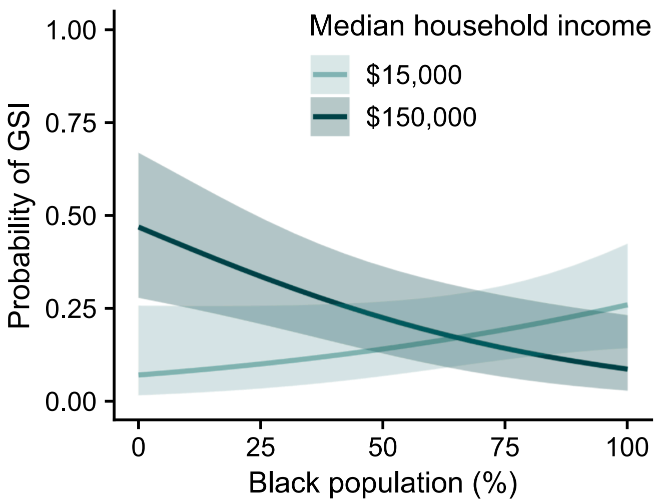

Fig. 5. The interaction between race and income in predicting the presence of voluntary GSI in a block group.

4. Discussion

Our analyses reveal contrasting patterns for GSI projects in Baltimore that were installed voluntarily versus those installed for regulatory compliance. In the following discussion, we explore possible origins of the major differences between regulatory and voluntary GSI in Baltimore and consider how the outcomes relate to issues of equity.

4.1. Different types of GSI are installed for regulatory and voluntary projects

Our finding that regulatory GSI was more evenly distributed among different types of facilities than voluntary GSI likely stems from a few factors. First, regulatory GSI is installed with the specific aim of mitigating the impacts of construction on stormwater quality, meaning that facilities are designed to meet whatever conditions exist for a given planned development (Maryland Department of the Environment, 2009), and space for GSI can be incorporated into designs from the beginning. In cases where a substantial amount of impervious area needs to be treated, larger facilities like detention structures and stormwater ponds can make sense, and were particularly promoted in past decades (McPhillips & Matsler, 2018). On the other hand, voluntary GSI is typically constructed on a smaller scale, within constraints of limited space, funding, and technical capacity or expertise, and also with more community input or outreach. Smaller voluntary projects also avoid permitting requirements. These considerations tend to favor more compact GSI types that can be promoted as beautification efforts, such as rain gardens or stormwater planters, helping to explain the predominance of microscale practices in the voluntary GSI dataset. In addition, regulatory GSI has been installed over a longer time period, and some of the types of facilities that were common in the past—e.g., detention basins—have fallen out of favor (McPhillips & Matsler, 2018).

The voluntary GSI dataset also included a substantial number of projects in which impervious surfaces were removed and replaced with vegetation, while this practice was nearly non-existent in the regulatory dataset. While it may be unusual for development projects associated with regulatory GSI to reduce impervious cover, nonprofits have seized opportunities to remove unnecessary and often degraded paved surfaces in schoolyards and neighborhood parks, replacing them with turf and other vegetation to improve recreational and educational opportunities, as well as water infiltration (Buckley, Boone, & Morgan Grove, 2017; Hager et al., 2013).

4.2. Regulatory and voluntary GSI show different relationships to block group characteristics

Both regulatory and voluntary GSI were found in block groups with a wide range of characteristics (Fig. 4). However, there was a striking difference in the levels of vacancy between block groups with regulatory and voluntary GSI—the median percent of vacant properties for block groups with voluntary GSI was nearly double that of block groups with regulatory GSI. Similarly, while vacancy was a strong positive predictor for the presence of voluntary GSI in a block group, it was not a significant predictor for regulatory GSI. This difference likely reflects the fact that high levels of vacancy in Baltimore tend to be associated with disinvestment (Baltimore Department of Planning & Office of Sustainability, 2015) and weak real estate markets (Kromer, 2002). While areas with high vacancy rates may not be attractive for private development projects that would require the use of GSI for stormwater mitigation, some nonprofits in Baltimore, including Civic Works and Parks & People Foundation, specifically work to bring GSI to underserved neighborhoods. In addition, although the ACS vacancy metric in our analysis is based on vacant housing units, the removal of vacant buildings is a priority in Baltimore, and resulting vacant lots provide opportune spaces for installing GSI (Baltimore Department of Planning & Office of Sustainability, 2015). Indeed, at least ten of the voluntary GSI projects in our dataset were completed in vacant lots (Solins et al., 2021). In other cities that have experienced population declines, including Detroit, Michigan, and Cleveland, Ohio, vacant properties have also been considered opportunities for installing GSI (Albro, 2019; Kim, 2018; Lichten, Nassauer, Dewar, Sampson, & Webster, 2017). Our findings stand in contrast to trends in Philadelphia, though, where regulatory GSI was positively linked to vacancy due to development opportunities in vacant parcels; however, this private development of vacant land was still concentrated near Philadelphia's central business district, and not in areas with greater Black and Hispanic populations and higher levels of poverty (Mandarano & Meenar, 2017). The economic value of vacant land can determine whether it is attractive for development or remains available for the construction of voluntary GSI (Chaffin et al., 2016).

Models for both regulatory and voluntary GSI in Baltimore showed that the presence of GSI was significantly related to race and income; however, the nature of these relationships in the two models differed substantially. Regulatory GSI was less commonly present in block groups

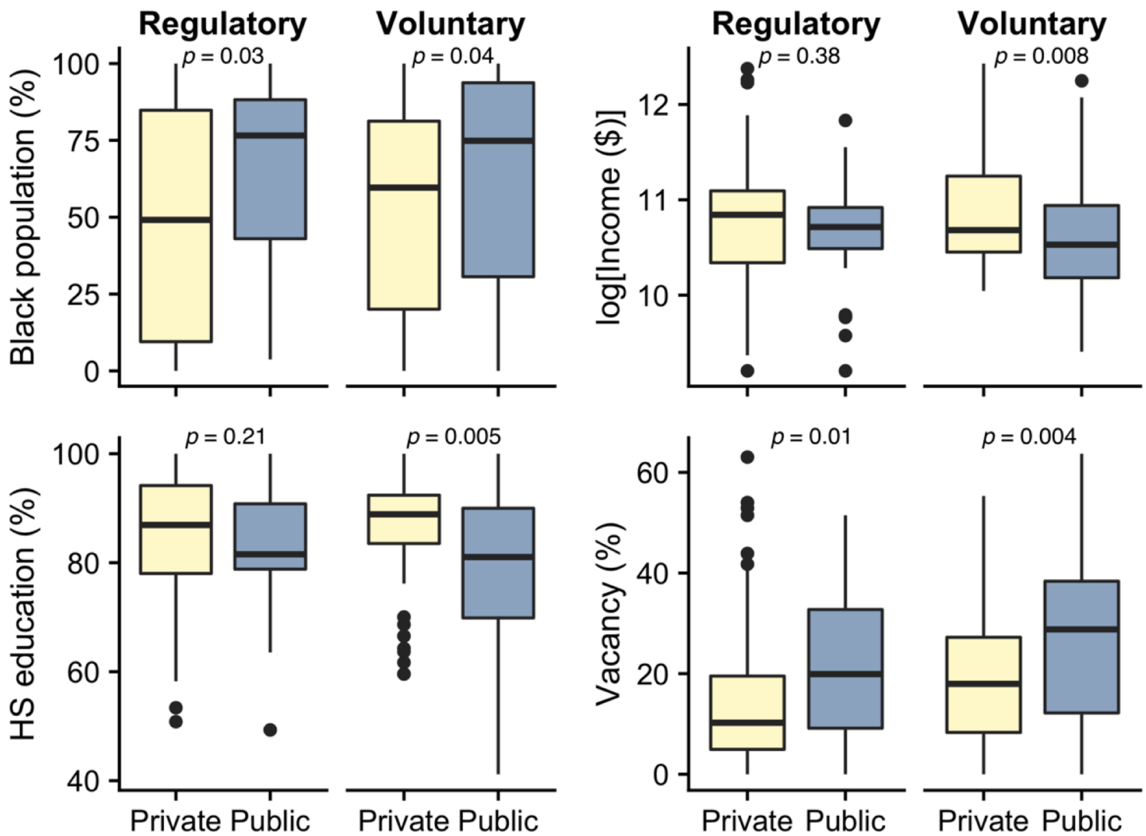

Fig. 6. Comparison of the sociodemographic characteristics for GSI projects found on public and private land for both regulatory and voluntary datasets. *P*-values were derived from Wilcoxon rank sum tests.

with predominantly Black populations, even when accounting for income. Unexpectedly, regulatory GSI also showed a negative relationship to income, meaning that regulatory GSI was actually more common in lower-income block groups regardless of race. These relationships suggest that the lower incidence of regulatory GSI in predominantly Black areas is not due to income disparities, and may represent a relative lack of development and re-development activity in Black communities. This finding contrasts with the results of the analysis conducted by Baker et al. (2019), which identified no relationship between regulatory GSI in Baltimore and race or income. The discrepancy is likely due to different statistical methodology, as their use of geographically weighted regression is better suited to exploring spatial nonstationarity than identifying overall trends (Matthews & Yang, 2012).

For voluntary GSI, we found that the relationship between GSI presence and race depended on income. This interaction showed that block groups were more likely to contain voluntary GSI when their populations were either wealthy and white or poor and Black, a dichotomy that reflects two facets of nonprofit and community engagement with GSI. Some nonprofits and funding opportunities in Baltimore specifically aim to bring GSI to underserved neighborhoods. However, another role nonprofits play is to assist or partner with interested parties, such as schools or religious organizations, in applying for grants to install voluntary GSI projects. In Baltimore, it is more common for institutions in wealthy, white areas to have properties with enough land available to seek these opportunities (M. Cameron, personal communication, April 12, 2022). While these patterns may be widely relevant in areas where nonprofit activities drive the location of voluntary GSI, voluntary GSI installation can also be driven by municipal incentive programs like stormwater fee credits (Malinowski, Schwarz, & Wu, 2020), which may lead to different distributions.

The importance of specific nonprofit activities in structuring the distribution of voluntary GSI in Baltimore is illustrated by an early GSI project spearheaded by a partnership between the nonprofit group Parks & People Foundation and Baltimore's DPW. This project aimed to assess the capacity of GSI to both revitalize a dense urban community and address its stormwater runoff issues. To allow evaluation of impacts to stormwater, all GSI interventions were concentrated within a portion of a small watershed known as Watershed 263 (WS263), which encompasses 376 ha in a predominantly Black area of the city with high levels of vacancy (Hager et al., 2013). The WS263 project accounts for 65 facilities across 34 of the voluntary GSI projects in our dataset, which is more than 20 % of all voluntary GSI we identified in Baltimore. Rerunning our generalized linear model for voluntary GSI without the WS263 projects did not substantially change the interaction we found between race and income, but the presence of voluntary GSI was no longer positively associated with vacancy without these facilities (analysis not shown). This change highlights the strong influence of this one campaign on voluntary GSI distribution.

In the future, the Baltimore DPW's increased efforts to install GSI are also likely to influence distributional patterns. These city-led projects would form a distinct category of GSI from the voluntary and regulatory GSI considered in this analysis: they are being planned specifically to meet MS4 permit requirements, yet their locations are flexible (i.e., not tied to construction) and planned citywide, providing the opportunity to address equity issues (M. Cameron, personal communication, April 12, 2022). This growing dataset will provide an interesting comparison for future research.

While we expected that different types of GSI might be associated with different block group characteristics, we found few substantial or significant differences at the level of aggregation we were able to analyze (Figure S1). The relatively uniform distribution of GSI types across block group characteristics suggests that neither regulatory nor voluntary GSI patterns demonstrate differential allocation of particular types of GSI to different populations. As more GSI is built in the city, it may become feasible to investigate the distributions of more specific types of facilities (e.g., green roofs vs permeable pavement within the alternative surface category), which could reveal different patterns.

4.3. Voluntary GSI is more common on public land

We found a striking difference in the proportion of GSI built on public land between the regulatory and voluntary datasets, with voluntary GSI projects more than five times as likely to be located on public land. This disparity reflects the different constraints on the placement of voluntary and regulatory GSI. Whereas locations for regulatory GSI are determined by re-/development activities, voluntary GSI must be installed in locations where space is available to accommodate the installation and the landowner is supportive. In Baltimore, many such locations for voluntary GSI are on land owned by the city—public parks and school grounds, city-owned vacant lots, and curb bump-outs into roadways—and may involve non-profits securing agreements or cooperation from city agencies (Hager et al., 2013). On the other hand, our data show that voluntary GSI projects located on private land in Baltimore are typically the result of a private entity such as a religious institution or private school applying for funding to install GSI on their property, often in partnership with one or more non-profits with GSI expertise (Solins et al., 2021). This distinction could help to explain why voluntary GSI on private land in Baltimore tends to be found in more affluent and well-educated areas, where community members are more likely to have the resources and land availability to apply for these grants.

In contrast, regulatory GSI is more common on private land because more development requiring stormwater mitigation has been completed by private entities. Regulatory GSI is typically only built on public land when a city agency undertakes a project large enough to require stormwater mitigation. Compared to regulatory GSI on private lands, regulatory GSI on public land is located in areas with greater Black populations and higher rates of vacancy, suggesting that the city is investing in the type of development activities that require stormwater mitigation in Black and disadvantaged neighborhoods proportionally more than private entities are.

The tendency for GSI on public land to be located in more disadvantaged areas than GSI on private land appears promising in terms of promoting equitable access to GSI. The vast majority of the facilities on public land are voluntary, though, which is associated with both benefits and limitations. In Baltimore, voluntary GSI projects tend to be planned, constructed, and maintained with more community involvement than regulatory GSI, so they may be better designed to meet community needs and preferences (Barclay & Klotz, 2019; Schifman et al., 2017). However, voluntary GSI in Baltimore has not historically been required to meet the same standards for design and maintenance as regulatory facilities, which must undergo inspection every-three years (N. Krause, personal communication, May 20, 2019), potentially affecting both its initial efficacy and its longevity. Many voluntary GSI projects in Baltimore have also been constructed with the understanding that neighbors, landowners, or community groups will maintain them in perpetuity, as grants typically do not provide funding for maintenance (Phillips de Lucas, 2020). This type of unpaid labor has been shown to be disproportionately carried out by Black women in Detroit (Riedman, 2021), and if interested community members move on, facilities can fall into disrepair because community maintenance agreements lack binding enforcement mechanisms (Phillips de Lucas, 2020).

4.4. Is GSI always an amenity?

The issues raised above force us to reexamine whether GSI should be universally regarded as an amenity, and whether understanding the spatial distribution of GSI facilities in and of itself is sufficient to support arguments about distributional equity. The many benefits that GSI can provide are frequently enumerated in its favor (e.g., US EPA, 2015), yet not every GSI facility provides all of these benefits (Matsler, Meerow, Mell, & Pavao-Zuckerman, 2021). The particular design of any given GSI facility is variable, and there is also a strong tendency for different types of GSI to have different associated suites of common benefits, as well as limitations (Taguchi et al., 2020). For instance, types of GSI that can be designed as gardens have more claim on landscape beautification than GSI types like permeable pavement, rainwater catchment, or dry ponds, yet may abate less stormwater if they are small.

It follows that the distribution of different facility types is also important in determining stormwater mitigation benefits. While it is unknown whether the current GSI distribution in Baltimore is having a meaningful positive impact on water quality, the relatively small number of regulatory facilities in Baltimore is not sufficient to meet the city's MS4 permit requirements. Instead, requirements have largely been satisfied by increased street sweeping and other forms of trash and debris abatement (City of Baltimore, 2015). The ways in which such alternatives to GSI influence the distributional equity of environmental benefits is an important topic of future investigation.

The benefits provided by GSI also depend on its accessibility, and thus the vastly greater incidence of regulatory GSI on private land may limit its impact on the wider community. While some benefits of GSI, such as the retention of stormwater pollutants, can be regarded as community benefits regardless of public access to the facilities, other benefits like aesthetic improvement are limited to those who can see or access the facility. GSI on private property can be publicly visible when placed in front of commercial businesses or along property edges, but other regulatory facilities are sited within private housing or corporate complexes, or on industrial land, and are completely inaccessible to the public.

Whether a community views any given GSI project as an amenity may depend not only on its accessibility and the benefits it is designed to provide, but also how well those benefits are maintained over time (Venkataramanan et al., 2020). GSI projects commonly degrade without proper maintenance, potentially becoming eyesores and ceasing to provide stormwater functions (Klein, 2016; Taguchi et al., 2020). Even where GSI is regarded as an amenity, it may have the perverse effect of stimulating gentrification (Anguelovski et al., 2019; Walker, 2021; Wolch, Byrne, & Newell, 2014), which has a long history of displacing Black populations in Baltimore (Brown, 2021). Thus, while understanding the spatial patterns of GSI locations is an important step in identifying equity concerns, future work that assesses the condition, size, design, function, and community perception of GSI projects in Baltimore will be necessary to deepen our understanding of how GSI benefits and detriments are distributed across the landscape.

5. Conclusion

Flooding and extreme heat, which are already major concerns in Baltimore, are projected to become worse with climate change, and often disproportionately affect disadvantaged neighborhoods (Cassie, 2019; Huang, Zhou, & Cadenasso, 2011). Because GSI is intended to address these issues, understanding its current distribution and the factors that influence its placement is an important step in evaluating whether its associated benefits are likely to be located in the areas that need them most. Our research promisingly suggests that both regulatory and voluntary GSI in Baltimore occur more frequently in areas with greater impervious cover. However, only voluntary GSI was commonly found in public spaces and in neighborhoods with high rates of vacancy. This discrepancy reflects the contrasting motivations for constructing GSI: market-based redevelopment patterns driving regulatory GSI locations vs mission-based community work driving voluntary GSI locations. While the voluntary GSI in underserved neighborhoods may be providing benefits for local communities, the total numbers are low, the common types of facilities are small, and their maintenance is uncertain. A more systematic approach to planning and managing GSI, in which it is given the same level of attention and resources as other types of municipal infrastructure, would be necessary for it to effectively address environmental and social issues at a citywide scale.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104607.

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