Mapping Predicted Areas of Common Maintenance Impacts to Green Stormwater Infrastructure in Philadelphia, Pennsylvania

Kate Homet[1]; Peleg Kremer, Ph.D.[2]; Virginia Smith, Ph.D., A.M.ASCE[3]; Richard Ampomah, Ph.D.[4]; and Stephen M. Strader, Ph.D.[5]

Abstract: Green stormwater infrastructure (GSI) has become a popular alternative to gray infrastructure design by decreasing stormwater pollution and providing a multitude of social, environmental, and economic benefits to communities. Although there has been an increase in the implementation of GSI within the planning and development of communities, little is known about the spatial distribution of maintenance impacts to GSI systems. To address this knowledge gap, a GSI maintenance needs index (MNI) was created for Philadelphia, Pennsylvania using a combination of variables that have been shown to potentially negatively affect the lifespan of GSI, such as litter, leaf litter, and sediment buildup. Philadelphia was used as a case study for creating this index because recently, GSI has been prioritized in the planning and development of projects throughout the city. Our findings suggest that these GSI impact variables are spatially diverse. This newly created GSI MNI is beneficial for decision makers involved in the planning stages of GSI implementation. This, in turn, will allow planners and municipalities to implement siting based on GSI type and local environment and apply targeted maintenance programs to ultimately improve the performance and extend the lifespan of local GSI systems. **DOI: 10.1061/JSWBAY.0000986.** © *2022 American Society of Civil Engineers.*

Introduction

Green stormwater infrastructure (GSI) is also commonly referred to as stormwater management practices (SMP), or best management practices (BMP); these are only a few of the terms that can be thrown around during conversation about adaptation infrastructure. This can become quite confusing to many professionals that have to address these different types within their jargon (Fletcher et al. 2015), so within this study, the term green stormwater infrastructure will be defined as "a network of decentralized stormwater management practices, such as green roofs, trees, rain gardens and permeable pavement, that can capture and infiltrate rain where it falls, thus reducing stormwater runoff and improving the health of surrounding waterways" (Foster et al. 2011; Fletcher et al. 2015). Green stormwater infrastructure has been progressively utilized by municipalities as communities react and adapt to increased stormwater and water quality issues associated with urbanization (Debbage et al. 2017). GSI uses natural processes to intercept stormwater, infiltrate a portion of it into the ground, evaporate some of it into the air, and reduce the fraction of it released back into the sewer system (PennFuture 2019). While traditional gray stormwater infrastructure has produced successful results and continues to be implemented by many urban planners and municipalities, these entities are also starting to recognize the need for change when it comes to flood control within urban environments and meeting federal storm water regulations (Dietz 2007; Zimmer et al. 2007). With the implementation of GSI projects, communities have seen cobenefits including runoff retention, cooler surfaces, increased vegetation performance, pollutant accumulation, an increase of pollinators (Jones et al. 2015), reduced combined sewer overflows (CSO) releases, improved downstream water quality, and a reduction in energy consuming practices (e.g., air conditioning being used to cool a housing structure) (Landauer et al. 2019).

In many places around the world, precipitation frequency and intensity is increasing due to climate change, resulting in an increase in flood risk (van der Wiel et al. 2017). Simultaneously, urbanization and impervious surface cover in metropolitan regions is escalating over time (Bierwagen et al. 2010). Many municipalities in the US have turned to GSI as an effective and efficient manner for meeting federal stormwater regulations (EPA 2021; Jones et al. 2015; Hung et al. 2020; Philadelphia Water Department 2011). However, as these systems become more prevalent, their maintenance has become an increasingly critical topic to ensure GSI performance and sustainability (Wadzuk et al. 2021).

[1]Graduate Student, Dept. of Geography and the Environment, Villanova Univ., 800 E. Lancaster Ave., Villanova, PA 19085 (corresponding author). ORCID: https://orcid.org/0000-0001-5706-8143. Email: khomet@villanova.edu

[2]Assistant Professor, Dept. of Geography and the Environment, Villanova Univ., 800 E. Lancaster Ave., Mendel Hall G61-C, Villanova, PA 19085. ORCID: https://orcid.org/0000-0001-6844-5557. Email: peleg.kremer@villanova.edu

[3]Assistant Professor, Dept. of Civil and Environmental Engineering, Villanova Univ., 800 E. Lancaster Ave., Villanova, PA 19085. ORCID: https://orcid.org/0000-0002-5640-8692. Email: virginia.smith@villanova.edu

[4]Doctoral Student, Dept. of Civil and Environmental Engineering, Villanova Univ., 800 E. Lancaster Ave., Villanova, PA 19085. Email: rampomah@villanova.edu

[5]Assistant Professor, Dept. of Geography and the Environment, Villanova Univ., 800 E. Lancaster Ave., Mendel Hall G61-B, Villanova, PA 19085. ORCID: https://orcid.org/0000-0002-6472-3182. Email: stephen.strader@villanova.edu

Note. This manuscript was submitted on August 19, 2021; approved on January 22, 2022; published online on April 28, 2022. Discussion period open until September 28, 2022; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Sustainable Water in the Built Environment***, © ASCE, ISSN 2379-6111.

Several different factors can lead to GSI underperformance, including sediment clogging, high inflows, and mulch accumulation (Holt 2021). More importantly, the usefulness and critical implementation of GSI maintenance has only recently begun to be addressed within literature. Due to the relatively new nature of GSI, the dynamics and requirements of maintenance are not fully realized (Wadzuk et al. 2021). Research has illustrated that the efficiency and longevity of GSI can be directly linked to GSI maintenance and care as well as the siting of the infrastructure (Golden and Hoghooghi 2018). Without regular upkeep, GSI sites, and the associated inlets, could have issues like clogging, weakened vegetation and invasive species, debris buildup, or even structural damage (DelGrosso et al. 2019; Reynolds et al. 2020). This research aims to address this growing issue of unanticipated maintenance impacts that can be addressed in the planning stages of GSI to prepare and budget for routine maintenance of a city's green stormwater infrastructure. The continued maintenance and quantitative monitoring of GSI performance status is not often employed due to budget and resource constraints (Wadzuk et al. 2021; Stormwater BMP Maintenance TC 2019). Studies have also started to examine the importance of routine GSI maintenance by observing common issues such as litter, sediment, and algae accumulation (Taguchi et al. 2020).

The clogging of trash is one of the more visible impacts that can affect GSI performance. While filters can keep most waste out, the accumulation of litter can diminish the effectiveness of the infrastructure and the benefits it can produce (McLaughlin and Cheng 2012). Routine maintenance is still required to prevent material buildup and prolong infrastructure lifespan, but this can also lead to higher costs and budgeting issues (Taguchi et al. 2020).

Within cities, sediment can build up in many different areas and often stems from a variety of places. Landcover development associated with urbanization results in sediment buildup (Wolman 1967). In the urban landscape, a primary sediment producer are construction sites in locations with high geographic relief that causes sediment and waste accumulation within GSI systems (Backhaus and Fryd 2013; Russell et al. 2019). A prominent study looking at urban landscapes with stormwater infrastructure (Backhaus and Fryd 2013) comes from northern Europe, where practices differ from the US. However, other studies have shown that even with control measures in place, construction activities can generate large amounts of sediment (Brown and Hunt 2010; DelGrosso et al. 2019). For many municipalities, the cost of removing sediment and other built-up debris from areas in GSI can become costly and lead to increased maintenance budgets (Hunt et al. 2005; Water Environment Research Foundation 2008; Wadzuk et al. 2021).

The seasonal falling of leaves (i.e., leaf litter) can also create buildup and clogging in GSI systems if not addressed in a timely manner. In urban streams in particular, leaf litter research has shown estimated nutrient releases of chemicals such as nitrogen and phosphorous when built up in urban water bodies (Duan et al. 2014). Although the decomposition of urban leaf litter can be complicated to predict in such varying environments (Sun and Zhao 2016), the stage of buildup before decomposition is detrimental to GSI efficiency because it can clog inlets and block the capture and filtration of stormwater runoff. If not swept properly, buildup on streets may lead to clogging and nutrient-loading in GSI and traditional storm drains (Taguchi et al. 2020).

Understanding the maintenance needs for GSI is a critical step in the planning stage of any implementation. These can influence cost, effectiveness, durability, and the local communities that host GSI. The frequency and intensity with which municipalities plan to perform routine maintenance is a key factor for ensuring effective and long-lasting GSI (DelGrosso et al. 2019). Literature on the maintenance and management of GSI has steadily increased within the last few years (Water Environment Research Foundation 2008; Chow et al. 2014; Reynolds et al. 2020). This has given planners some idea of maintenance expectations but has largely left out methods for predicting where impacts are most likely to impede GSI and where the community may be affected by both GSI and GSI maintenance. The planning of GSI needs a robust assessment of maintenance issues and their potential impact on the social, economic, and physical cost associated with upkeep.

Variables Affecting GSI Maintenance

Common GSI maintenance impacts seen by municipalities utilizing GSI include articles that can build up or conglomerate such as sediment, trash, or vegetative debris (Hunt et al. 2005; Seattle Public Utilities 2009). Frequent maintenance is needed in Philadelphia for controlling the growth of weeds and for pruning the healthy vegetation considered a part of the GSI. Other impacts that require what the Philadelphia Water Department (PWD) calls *reactive maintenance* include compacted soils in GSI such as tree pits, formation of sinkholes, or erosion after storm events (Philadelphia Water Department 2016). Routine maintenance is necessary to keep these systems safe and functioning efficiently during stormwater events, which is why some of the more common maintenance impacts like sediment, trash, and leaf litter buildup need to be better understood to stay on top of maintenance.

Litter

Philadelphia has long experienced issues relating to waste collection and management. Pennsylvania Department of Transportation (PennDOT) describes litter as trash put in the wrong place and an expensive problem that is harmful to communities (Esposito 2020; Pennsylvania DOT 2021). The accumulation of litter is not just an environmental problem, but it is also directly related to the health and safety of the local community (Jaramillo 2020). To better understand the spatial distribution of this waste issue, the City of Philadelphia Streets Department created a litter index in 2007. This index was recently reconfigured in 2018 (City of Philadelphia: Zero Waste and Litter Cabinet 2019) with help from various city departments and many staff trained in survey and data collection. The survey data rated litter conditions found in streets, vacant lots, public school sites, parks and recreational sites, green stormwater infrastructure, transit stations, and many other public rights of way. Each public property or asset of the city was given a rating from 1 (being little to no litter) to 4 (being litter that requires heavy machinery to remove). Within this data set, the city also combined these 1–4 ratings into a weighted mean litter index for each block within the city.

Leaf Litter

It is critical to understand where leaf litter is first dropping to have a better sense of where it can be accumulating in local GSI. Maintenance of GSI can be heavily impacted by vegetation and foliage. The removal of leaves and other vegetative buildup is an important part of maintaining a well-functioning GSI site. In particular, the surface buildup of trash, sediment, and vegetative debris plays a large part in regular local GSI maintenance (Philadelphia Water Department 2014). Leaf litter can be considered advantageous to local ecosystems because it breaks down and releases nutrients into soil (Gosz et al. 1973; Mctiernan et al. 1997), but it also is hazardous to the quality of local waterways and to the functionality of GSI. Leaf litter can hinder infiltration and block curb cut inlets, reducing system efficiency (Bean et al. 2019). Leaf litter and its impact on GSI is likely further exacerbated by the implementation of GSI tree trenches in areas that lack tree canopy (Philadelphia Water Department 2016). The processes leveraged by different types of GSI can also make them vulnerable to different stressors, which is why this study aims to identify these impact trends. To map areas of possible heavy leaf litter buildup, seasonal satellite imagery and the normalized difference vegetation index (NDVI) were used to understand where foliage is falling throughout the city of Philadelphia (Pettorelli 2014).

Precipitation Trends

When GSI become impaired due to issues such as clogging, negative consequences can occur, especially during precipitation events. Insufficient maintenance can cause failures such as a reduction in runoff capture and filtration leading to pooling of water and localized flooding, as well as possible damage to GSI systems (Erickson et al. 2013; DelGrosso et al. 2019). Climate change research indicates that precipitation trends will change as global temperatures rise. For example, in the mid-Atlantic region of the United States, precipitation is expected to both increase and become more extreme because of increased CO_2 levels in the atmosphere (Rush et al. 2021).

Like many cities, Philadelphia has seen renewed population and urban development growth within the last decade, which has led to over 1.5 million residents and a high population density consisting of approximately 29,267 residents per square kilometer (US Census Bureau 2019). Due to increasing urban development, the city has reached approximately 51.3% of total impervious surface in 2018 (University of Vermont Spatial Analysis Laboratory 2018), which increases the chances of polluted stormwater runoff occurring during precipitation events.

The increased precipitation records from the recent past and the prediction of continued increasing precipitation volumes have led to a greater frequency of flooding and stormwater events in Philadelphia (Malter et al. 2017). As more intense precipitation develops within this region, it is probable to expect greater impacts to stormwater control and filtration.

Philadelphia GSI Planning

To address this issue and meet federal water quality regulations, the PWD has been prioritizing GSI implementation throughout the city with the 2011 plan *Green City, Clean Waters*. The primary goal of this project is to comply with an EPA mandate within the Clean Waters Act. The city aims to reduce polluted stormwater from discharging into the surface water system by 85% by the year 2035 (Philadelphia Water Department 2011). In 2018, the city had already created nearly 1,100 greened acres (i.e., an acre of once impervious surface that was transformed to capture the first inch of stormwater runoff through green technology) (Stutz 2018) and continues to implement their green stormwater infrastructure plan.

This study aims to better understand the question of how GSI maintenance impacts are spatially distributed across Philadelphia, Pennsylvania. This research presents a platform for a multifaceted maintenance framework, which is required to address issues of GSI efficiency, cobenefits, and economic sustainability (Wadzuk et al. 2021). While the city has become well-equipped to tackle stormwater retention and GSI, the PWD could benefit from more in-depth GSI planning and maintenance analysis. Advancements in data collection now allows for smart system analysis that could help PWD increase GSI system efficiency and effectiveness while reducing costs.

Understanding the spread of potential impacts is one of many steps that will help to approach an equitable methodology for planning and siting GSI in urban environments. In this study, the spatial distribution of environmental factors such as litter, leaf litter, and sediment yields will be evaluated as they are known to impact the quality of GSI performance. This study will also create a GSI maintence needs index (MNI) to locate areas of high maintenance impact in Philadelphia, which could lead to a need for planning changes such as different GSI designs or increased maintenance inspections.

Materials and Methods

GSI Maintenance

The introduction of the mapping of maintenance issues allows for identifying the types of infrastructure to utilize in a neighborhood for longevity and efficiency purposes. To accomplish mapping these impacts, social data, such as gentrification trends and local litter surveys, were integrated with high-resolution 3×3-m pixel satellite imagery and the revised universal soil loss equation (RUSLE) to map three major impacts to GSI across Philadelphia (Fig. 1).

Litter Index

The litter index provided by the city represents a great database for local litter estimates (OpenDataPhilly 2018). It was acquired as a shapefile based on hundred blocks (neighborhoods) throughout the city. It was then converted to a raster within ESRI's ArcGISPro platform under version 2.8. The raster was set to a resolution of 3×3 m to match that of the leaf litter data. This index, along with all the maintenance impact indices, was rescaled from 0 to 1. For the litter index, this represents litter severity from 0 to 1.

Leaf Litter Index

To develop an estimate of the distribution of leaf litter in the city, the NDVI (Pettorelli 2014; Tillack et al. 2014) and a fine-scale (3×3 m resolution) landcover were used to determine healthy vegetation change of tree canopy pixels between leaf-on (July 2019) and leaf-off (January 2020) season. These two dates represented the seasonal change of leaves and a calculation of percent change in NDVI values offers an estimation of where trees in Philadelphia lost the most leaves.

Satellite imagery of the city of Philadelphia on July 15, 2019 and January 21, 2020 were acquired from Planet Labs, which utilizes their PlanetScope instrument that collects data from over 180 satellites at a 3×3-m resolution with four bands (Planet Team 2017). These dates were utilized to represent an amount of full canopy cover and/or vegetation in midsummer against a representation of little to no canopy cover and/or vegetation midwinter. It is critical to understand where leaf litter is first dropping to have a better sense of where it can be accumulating in local GSI. Previous work has shown higher leaf litter nutrient leaching in urban and residential areas during the fall, with the lowest rates in summertime (Duan et al. 2014). These dates were also picked for their clarity and lack of cloud cover in the imagery that could block out parts of the surface.

NDVI values were calculated with the standard range of values from -1 to 1 representing no vegetation/unhealthy vegetation (-1) up to healthy vegetation (1) (Pettorelli 2014). NDVI is commonly used to estimate the health and density of vegetation, or the proportional coverage of vegetation. In recent studies, it has been utilized in understanding annual peak vegetation and land surface

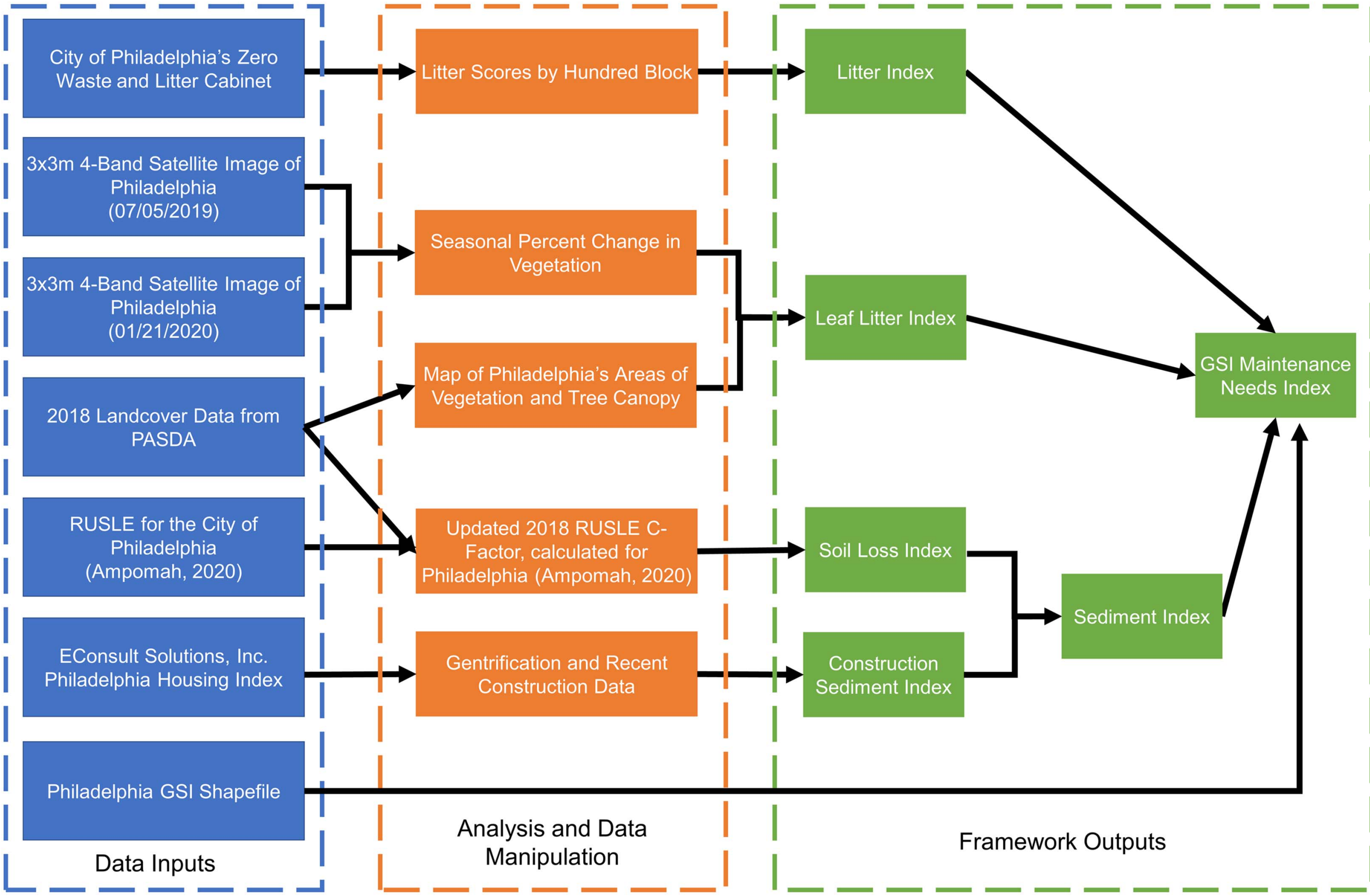


Fig. 1. Data sources utilized for mapping each component of GSI maintenance impacts. Where PASDA stands for the Pennsylvania Spatial Data Access where the University of Vermont Spatial Analysis Lab data was acquired and RUSLE stands for revised universal soil loss equation, used in creating the soil loss index.

emissivity for research on seasonal temperature changes in urban spaces (Neeti et al. 2011; Elmes et al. 2017). In this study, NDVI was used for the purpose of estimating seasonal tree canopy loss as a proxy for leaf litter. Landcover data for Philadelphia in 2018 (University of Vermont Spatial Analysis Lab 2018) was used to extract all NDVI values associated with tree canopy.

A raster calculator tool was used to calculate the percent difference in NDVI between summer and winter for all tree pixels and is given as follows:

$$\frac{(\text{January NDVI}-\text{July NDVI})}{|(\text{July NDVI})|} \tag{1}$$

The resulting calculation displayed a range of percent change from approximately 0 to −0.98 with a negative value representing loss of healthy vegetation (i.e., the fallen leaves).

Sediment Index

Clogging and buildup from sediment in catchments and different drain systems is another common maintenance impact that is addressed by the city's water department (Philadelphia Water Department 2014). To better assess where sediment is building up the most within the city, two different sediment data sets were combined. One included potential sediment accumulation from recent construction and gentrified areas of Philadelphia while the second data set estimated soil loss in tons/acre/year using the RUSLE for the county of Philadelphia.

The Philadelphia housing index (EConsult Solutions 2020) was used as a proxy for estimating the potential severity of sediment buildup from construction due to gentrifying areas. Gentrification is the change of neighborhoods from low to high value that can cause displacement of businesses and original residents (CDC 2009). The index data and metadata for understanding gentrification trends were acquired from EConsult Solutions (2020). It includes a compilation of Philadelphia housing trend data from 2001 up to 2020 with weekly updates for each major neighborhood within the city. This index represents how sales prices of houses within neighborhoods have changed over time. This index is adjusted for different housing and building traits such as "square footage, lot size, age, age squared and cubed, the presence of a tax abatement and its age, distance to the central business district, fireplaces, garages, central air, stories, building material, whether it's on the corner, and some technical markers in the deed record" (EConsult Solutions 2020).

To estimate the sediment buildup from construction for Philadelphia, the 2019 data was utilized because it was the most recent and completed data on housing price trends and potential gentrification in Philadelphia neighborhoods. Monthly housing index values per neighborhood were cross tabulated to calculate average annual index values for each neighborhood in 2019 and joined to the Philadelphia housing index shapefile.

Soil loss was calculated by modifying an application for the RUSLE method for the city of Philadelphia (Ampomah 2020).

Due to the complex dynamics of urban systems, urban sediments remain largely undefined in quality or quantity. However, although RUSLE is widely used for agricultural modeling, it has effectively been applied for modeling urban sediment generation (Odhiambo et al. 2021; Zhou et al. 2021; Patowary and Sarma 2018; Wachal et al. 2009).Within this model, the RUSLE resulted in an estimate of soil loss that is not 100% accurate but is an estimate relative to the land use in the Philadelphia region.

For calculating the RUSLE, five factors are used as inputs

$$A = R \times K \times LS \times C \times P \tag{2}$$

where A = soil loss; R = runoff erosivity; K = soil erodibility; LS = slope length and steepness; C = cover management; and P = support practice. Eq. (2) solves for soil loss (A), by combining the runoff erosivity (R), soil erodibility (K), slope length and slope steepness (LS), cover management (C), and the support practice (P). Following Ampomah (2020), the factors of S and L were combined, as shown by Kim and Maidment (2014) for efficiency and assumed a P-factor of 1 due to the urbanized setting of Philadelphia, therefore rendering it unnecessary for calculation in this study.

The R-factor was calculated with the equation

$$R = 1.24P^{1.36} \tag{3}$$

where R = runoff erosivity in hundreds of foot-ton-inches per acre per hour; and P = mean annual precipitation in inches for Philadelphia. The mean annual precipitation was estimated to be around 111.76 cm (44 in.) for the city, which is a value that was utilized by previous RUSLE work by Ampomah (2020) and stemmed from a long-term meteorological measurement between the years 1950 and 2000 (USGS 2011). This yielded an R-factor of approximately 213.10 hundreds of foot-ton-inches per acre per hour. The K-factor was obtained from the United States Department of Agriculture's (USDA) web soil survey (Soil Survey Staff, Natural Resources Conservation Service, USDA 2020) as a shapefile that was converted to a raster layer in ESRI's ArcGIS Pro software using version 2.8. All GIS analyses were performed on this platform.

The LS-factor is a unitless factor that is computed based on the unit stream power erosion and deposition (USPED) method through calculations within GIS software. The C-factor was modified (Ampomah 2020) and updated to fit the latest 2018 Pennsylvania spatial data access (PASDA) landcover data set (University of Vermont Spatial Analysis Laboratory 2018). The updated landcover was assigned different values for each landcover category based on recommendations by Yoo et al. (2014), see Table 1.

Due to the highly urban setting of Philadelphia, the P-factor was set as 1 assuming that there was minimal erosion control being implemented in the study area.

Table 1. Updated 2018 landcover subclassifications from PASDA and their adjoining C-factors

2018 PASDA landcover classification	C-factor
1. Tree canopy	0.0001
2. Grass/shrub	0.0380
3. Bare earth	0.7000
4. Water	0.0000
5. Buildings	0.0000
6. Roads	0.0001
7. Other paved surfaces	0.0001

Using Eq. (2), the updated factors were calculated within a raster calculator tool and results displayed an estimation of soil loss for the city of Philadelphia per pixel of landcover with a majority in the range of 0–14 t per acre per year. Once rescaled, the soil loss and construction sediment data were utilized [Eq. (4)] to create an overall sediment severity estimate

$$Overall\,Sediment = \frac{(Soil\,Loss + Construction\,Sediment)}{2} \tag{4}$$

Finally, the GSI MNI was created in ArcGIS Pro version 2.8 by taking the average of the three common maintenance impact indices: litter, leaf litter, and sediment buildup [Eq. (5)]

$$Maintenance = \frac{(Litter + Leaf\,Litter + Sediment)}{3} \tag{5}$$

Taking the average of the three indices gave an equal weight to each index so as not to favor one impact more heavily than the other. The resulting index revealed estimated average common maintenance impacts around the city of Philadelphia.

GSI MNI and Current GSI Locations

To assess the spatial distribution of maintenance vulnerabilities in current GSI locations, the GSI MNI values were extracted for all GSI locations (Philadelphia Water Department 2016). The mean maintenance value per GSI type [basins, bioinfiltration/bioretention, porous pavements, and/or water quality (WQ) treatment devices] were also calculated. Blue roofs, green roofs, and cisterns were excluded from this comparison as they receive significantly less impact from litter, leaf litter, and sediment buildup. Cisterns particularly were excluded as they already include sediment filtration traps and are not influenced the same by elements like leaf coverage. An optimized hotspot analysis was performed on values of the GSI MNI extracted to current GSI locations. This analysis reveals which GSI locations in the city show spatial clusters of similar index ratings. For example, a hotspot reflects neighborhoods that are home to GSI that expect to experience higher maintenance impacts. The opposite is true for cold spots in this analysis, revealing clusters of GSI that are in areas of estimated low maintenance impact.

Finally, further analysis was used to determine how specific types of GSI that are already in place are being impacted by potential maintenance issues across the city. This analysis was performed as an initial step to understanding a relationship between where GSI are placed and what type, and how that is affected by the spatial distribution of high and low severity maintenance impacts. GSI types were identified within shapefiles provided by the PWD and were analyzed with zonal statistics and then compared using a nonparametric Kruskal Wallis analysis and Tukey's honestly significant difference test. This analysis tested whether any of the current GSI types were subjected to maintenance requirements based on the local environment.

Results and Discussion

GSI MNI: Litter

The results of the rescaled litter index are displayed in Fig. 2(a). The darker areas represent a majority of high litter accumulation, mostly found within neighborhoods closest to downtown Philadelphia. High accumulation also appears clumped in areas

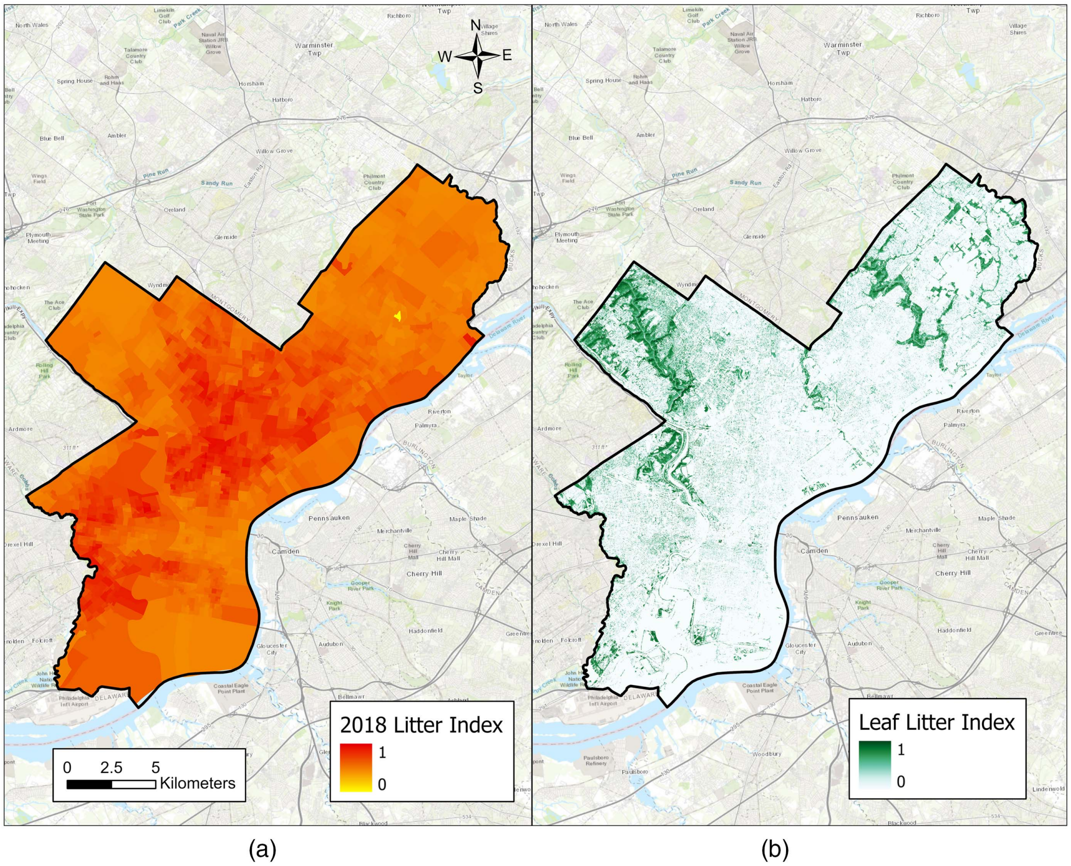


Fig. 2. (a) Neighborhood ratings from the city of Philadelphia's litter index rescaled from 0 to 1; and (b) leaf litter index showing results of the seasonal percent change in tree vegetation representing leaf litter buildup from late 2019 and early 2020. [Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, and the GIS User Community.]

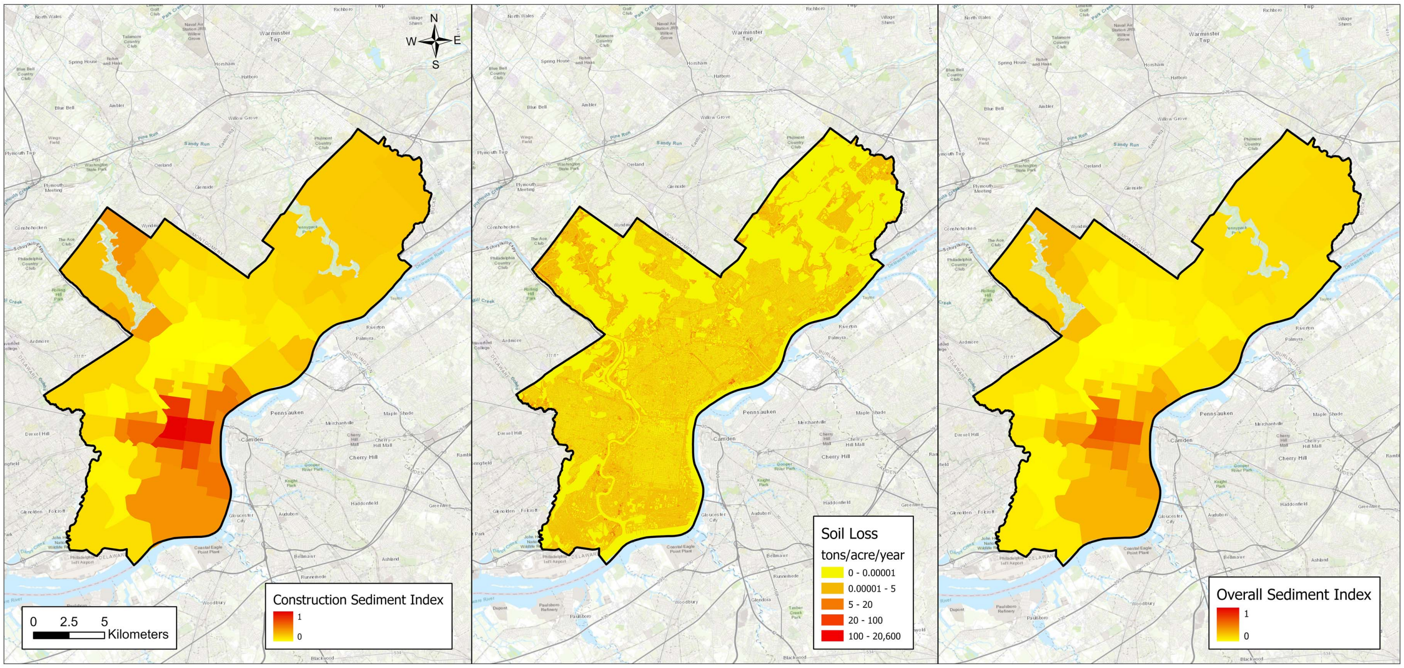
of the southern and eastern blocks of the city. These agglomerations make sense due to higher population densities and packed infrastructure within downtown areas, leading to greater people on the streets and a higher likelihood of waste accumulation. The spatial distribution of litter appears like that of overall sediment accumulation due to the high severity in central Philadelphia and surrounding neighborhoods. Although the estimated sediment loads are not as severe across the city as the litter appears to be, it is important to note that the central hotspot appears to overlap with both maintenance issues.

GSI MNI: Leaf Litter

This index provided a range of values that signified the severity of vegetation change or leaf loss from tree canopy, with heavy leaf loss displayed as darker areas in Fig. 2(b). The areas showing some of the highest concentrations of leaf litter included neighborhoods surrounding Wissahickon Valley Park in northwest Philadelphia. Along with Wissahickon Valley Park, Pennypack Park in northeast Philadelphia and Fairmount Park in northwest Philadelphia also showed the widest ranges of leaf litter values going from little to no loss (between 0 and 0.506), to major leaf loss (>0.773). Most areas with higher values were found to contain heavy tree canopy cover such as parks and protected environments. This would indicate that seasonal vegetation change would be heaviest in areas that might lose seasonal canopy cover. Otherwise, results indicating high leaf litter appear to be scattered throughout Philadelphia and areas of low leaf litter seem to appear in smaller concentrations throughout the city. This indicates that buildup will be highest in these park areas, but decomposition of leaf litter could be more rapid in stormwater infrastructure itself than in nearby natural spaces (Hobbie et al. 2014). Looking at where current GSI are sited, while most are around central Philadelphia there are still numerous installations surrounding the various parks in the northeast and northwest neighborhoods. This could indicate a need for more intensive and frequent maintenance at these sites, something that public park and recreation agencies have requested greater funding for (National Recreation and Parks Association 2019).

GSI MNI: Sediment

The averaged calculation from both the construction sediment and soil loss estimates created a sediment index that shows some spatial trends. Fig. 3(c) highlights the averaged sediment losses throughout the city landscape, displaying the largest losses as darker areas, with minimal to no sediment loss represented by lighter areas. The areas with the highest estimated sediment concentrations appear to be Center City and its surrounding neighborhoods. The next highest concentrations are found just outside these neighborhoods as well as in south Philadelphia and some neighborhoods of northwest Philadelphia. This is an example of neighborhoods that could potentially utilize GSI that is infiltration-focused to best mitigate



(a) (b) (c)

Fig. 3. (a) Construction sediment index resulting from the 2019 Philadelphia Housing Index per neighborhood rescaled from 0 to 1, with 1 representing greatest rates of gentrification. These areas also act as a proxy for recent construction and likely sediment buildup; (b) resulting soil loss estimates in tons/acre/year from the RUSLE method for Philadelphia; and (c) averaged result of the construction sediment and soil loss data sets. [Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, and the GIS User Community.]

impacts such as total suspended solids (Beganskas et al. 2021). In contrast, siting GSI with sediment infiltration systems within areas of high sediment loads could also be inefficient or even harmful if routine maintenance is not performed. Future decisions on choosing GSI type for areas of high sediment will need to address not only a GSI's filtration system and how to minimize clogging, but also capture the local sediment material and reduce the burden on maintenance (Smith et al. 2021). The lowest concentrations of sediment appear to conglomerate in the northwest and southwest parts of the city. This study recognizes that the impact of soil loss is not an accurate assessment due to the agricultural-based RUSLE method, which leaves the overall sediment impact to be driven substantially by the proxy for construction sediment due to gentrification trends.

Overall Maintenance

The compilation of variables averaged within the index provided an uneven spatial distribution of potential maintenance impacts for GSI throughout Philadelphia (Fig. 4). While areas like Center City displayed more uniform distribution of higher maintenance impacts, outlying neighborhoods and parks displayed a mix of impact ratings. These ratings ranged from 0 to 1, with the highest impacted neighborhoods seeing values approaching or equal to 1. This index also had an average rating of approximately 0.366 [standard deviation (SD) ± 0.103]. This mix appears to have a correlation with the leaf litter ratings that saw diversity among the outskirts of the city and around major parks. This index was created through equal weighting of each impact index, which is a method studied in past green stormwater infrastructure planning research (Mandarano and Meenar 2017; Meerow 2020; Evans 2021). In the future, these types of maintenance models could be weighted differently based on specific study areas, seasonal aspects, stakeholder weighting, or other influences on GSI maintenance (Heckert and Rosan 2016; Meerow 2020).

Maintenance Ratings per GSI Type

The results of the optimized hotspot analysis revealed that most hotspot clusters of high index values existed almost completely in central Philadelphia and surrounding neighborhoods, with a less visible amount of consistent high vulnerability spread across the city [Fig. 5(a)]. These clusters are likely exacerbated by the heavy litter and sediment ratings estimated for these neighborhoods, which indicates a significant maintenance impact for all GSI in this area. The overall maintenance results [Fig. 5(b)] reveal that many existing GSI (both public and private) are already in these central neighborhoods, some of which are in the process of gentrifying or are areas that are heavily littered. This could indicate potential issues for not just maintenance, but also budgeting for GSI in these neighborhoods. With a large amount of existing GSI in central Philadelphia, the continued scheduled maintenance of these infrastructures need a long-term budget to keep them efficiently functioning. For GSI placed in more heavily impacted neighborhoods, a larger budget may be necessary to keep up with more frequent maintenance to maintain performance.

The use of zonal statistics revealed the average GSI MNI ratings for each current GSI throughout the city. A boxplot displays those statistics for four of the seven different GSI types used by the city. The types excluded in this comparison included blue roofs, green

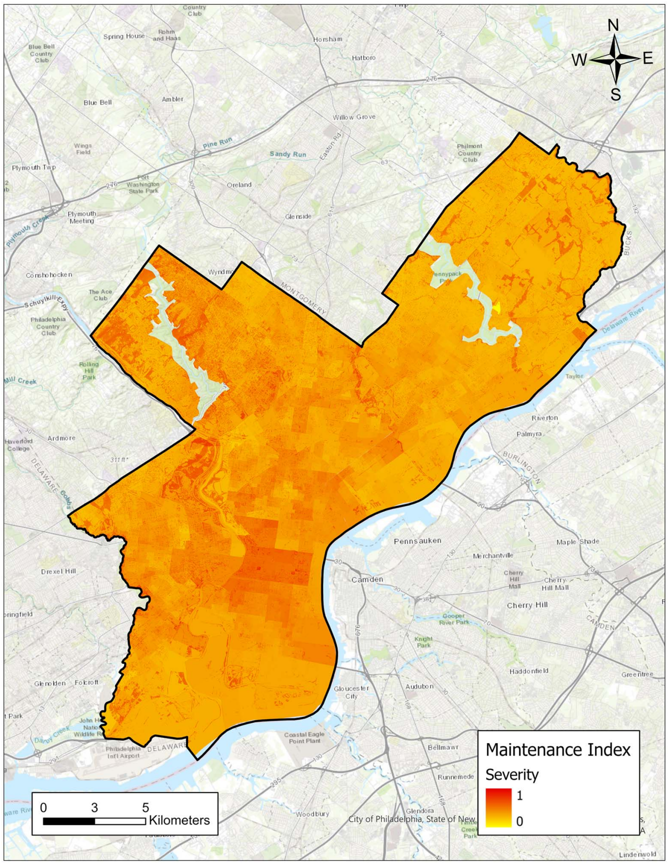


Fig. 4. Overall GSI maintenance needs index created by averaging the litter, leaf litter, and sediment indices together. [Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, and the GIS User Community.]

roofs, and cisterns. This comparison of the remaining four GSI types revealed that all GSI types had an average GSI MNI rating less than 0.4, indicating no severe maintenance impact differences based on type (Fig. 6). The GSI MNI ratings for basins and bioinfiltration/bioretention infrastructure revealed a few outliers with ratings greater than 0.6, indicating potentially severe sites for maintenance impacts.

A pairwise comparison was performed using Tukey's honestly significant difference test on the four different GSI types to understand how each existing GSI type was impacted by common maintenance issues. This analysis was used to understand if there existed any GSI types that tended to be sited in areas of particularly high or low maintenance impacts compared to other types. A pairwise comparison analyzed the mean maintenance ratings for each GSI type and revealed which types had a significant difference in their mean maintenance rating. There was at least one GSI type that was impacted in a significantly different way than at least one of the other three types. Results indicated that porous pavements had significantly different maintenance ratings than bioinfiltrations and water quality treatment devices while porous pavements and basins were not significantly different in their ratings. In contrast, bioinfiltrations and water quality treatment devices were not significantly different from basins. An analysis of the adjusted p-values also emphasized a significant difference between bioinfiltration and porous pavement maintenance ratings (Table 2). While these values do not describe how these types of GSI perform, comparing these values to performance indicators would provide insight into the suitability for different types of GSI for different types of environments.

Conclusion

This study utilized ArcGIS Pro version 2.8 to download, assess, and manipulate data sets for the purpose of assessing Philadelphia's litter, leaf litter, and sediment buildup. This allowed for the mapping of high maintenance impacts to green stormwater infrastructure implementation. The goal of this study aimed to predict areas of high and low maintenance impacts based on observed data to allow for the best assessment of GSI siting and construction for the city of Philadelphia. A second goal aimed for this index to be as accurate as possible while utilizing the most recent data available. The ever-changing landscape of urban areas remains an issue for calculating an accurate sediment and soil estimate, leaving the researchers to use proxies when appropriate as well as common methods such as the RUSLE, which were built for agricultural settings (McCool et al. 1995; Shuster et al. 2021). Due to a dearth of data, a validation of the index was inconclusive, which is a limitation of this model. Additional data collection and data synthesis from published literature is required to better quantify and qualify urban sediments. For verification of this model, more frequent data collection and performance monitoring of the three impacts studied here would be beneficial to validating this spatial study. This method of creating a multifaceted maintenance model presents a framework for conceptualizing siting GSI, which is a new frame of reference for understanding and planning for GSI implementation in future studies. This type of maintenance modeling responds to a critical need by facilitating data driven GSI planning and provides a better understanding of the distribution of maintenance impacts to plan and budget for in the future. This will ensure more efficient maintenance and more sustainable infrastructure.

The conclusion of this study reveals a GSI maintenance needs index for the city of Philadelphia in which it was determined that maintenance impacts will likely be greatest in the central neighborhoods in all three areas of common maintenance issues. This study did not aim to encompass all issues related to GSI efficiency and lifespan, presumably a topic for a future study that could be very beneficial. It is also important to note that these variables of maintenance are always changing within a highly urbanized setting such as Philadelphia, this makes updated indices critical to the planning stages for GSI within the municipality. Future studies of GSI maintenance should include validation of the model presented here by collecting greater field data of maintenance variables. Continued research is also needed to improve our understanding of the relationship between GSI type and their performance in areas of different maintenance challenges. Future research could link maintenance needs, performance, and GSI type to enable the development of smart maintenance programs. To further aid this model, future work should also expand the scope of GSI maintenance research to include issues such as socioeconomic, demographic, infrastructural, or environmental impacts. To facilitate this, variables should be collected and studied on a smaller scale than neighborhoods to limit discrepancies between communities. With the inclusion of multifaceted variables that can impact GSI, municipalities and urban planners are a step closer to a more equitable method of implementing this type of infrastructure. Through thinking about implementation in a multifaceted view, the future of GSI can expand in a way that emphasizes the

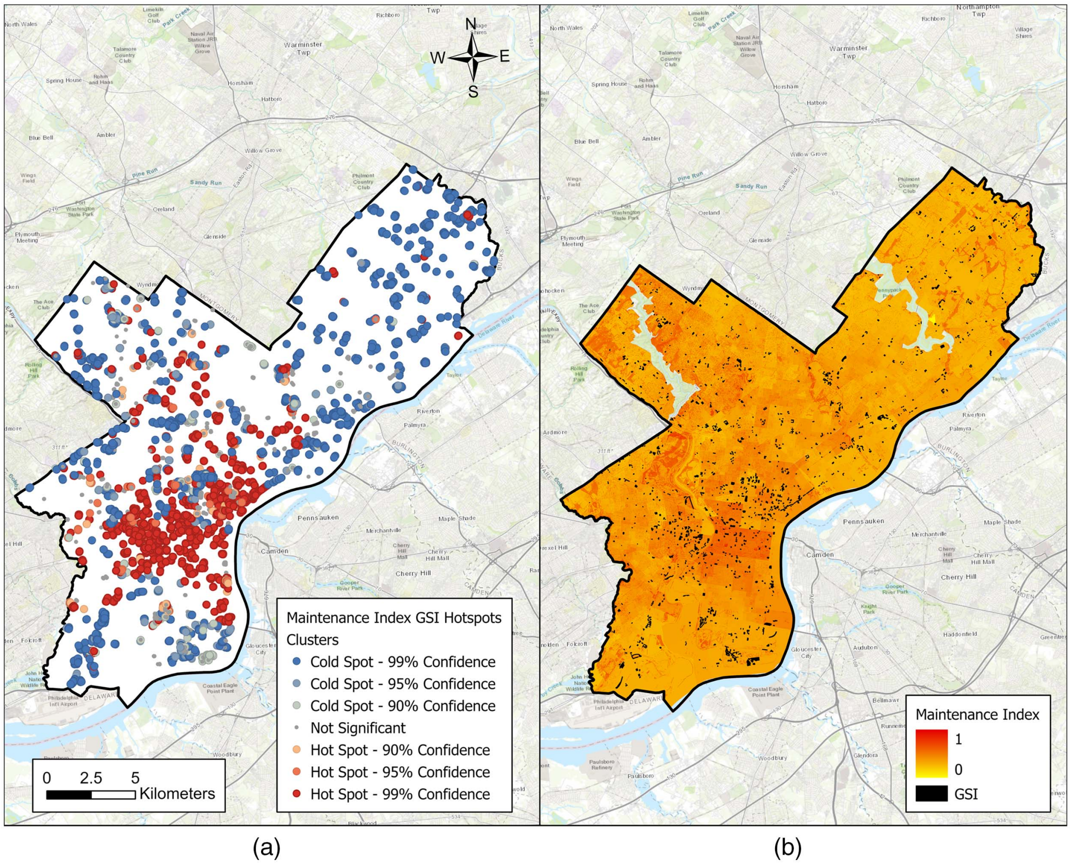


Fig. 5. (a) Optimized hotspot analysis done on the mean values of the GSI MNI that overlapped current GSI projects in the city. Red spots represent areas of significant maintenance vulnerability. If reading print version, the darker spots represent both cold and hot spots while blue spots represent areas of little to no maintenance vulnerability; and (b) Philadelphia GSI locations overlaid on the GSI MNI. [Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, and the GIS User Community.]

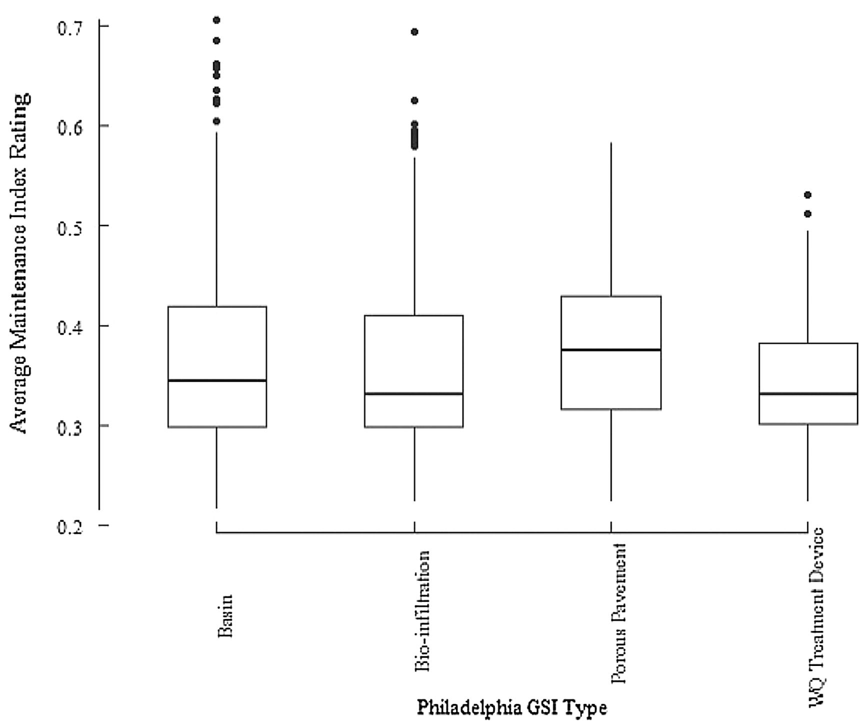


Fig. 6. Boxplot of the average maintenance rating per GSI compared to GSI type.

Table 2. Correlation matrix of the adjusted p-values (alpha = 0.05) for a pairwise comparison between the average GSI MNI ratings for each of the four GSI types used in this study

GSI type	Basin	Bioinfiltration	Porous pavement
Bioinfiltration	0.882	—	—
Porous pavement	0.064	0.030	—
WQ treatment device	0.574	0.712	0.176

social, economic, and performance sustainability of the infrastructure and not just near-future retention benefits.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., private data).

- 3 m Satellite Imagery (Planet Labs).
- Philadelphia Gentrification Data (EConsult Solutions, Inc.).
- 2018 Landcover Data (http://www.pasda.psu.edu/).
- Litter Data and GSI Shapefiles (OpenDataPhilly.com).

References

Ampomah, R. O. 2020. "Sediment dynamics in and around urban green stormwater infrastructure." Doctoral dissertation, Dept. of Civil and Environmental Engineering, Villanova Univ.

Backhaus, A., and O. Fryd. 2013. "The aesthetic performance of urban landscape-based stormwater management systems: A review of twenty projects in Northern Europe." *J. Landscape Archit.* 8 (2): 52–63. https://doi.org/10.1080/18626033.2013.864130.

Bean, E., M. Clark, and C. Barbra. 2019. *Permeable pavement systems: Technical considerations*. AE530, 4/2019. EDIS 2019.2. London: eDIS.

Beganskas, S., R. J. Ryan, E. Walters, M. Soro, E. Cushman, and L. Toran. 2021. "Coupling PCSWMM and WASP to evaluate green stormwater infrastructure impacts to storm sediment loads in an urban watershed." *J. Am. Water Resour. Assoc.* 57 (1): 134–153. https://doi.org/10.1111/1752-1688.12896.

Bierwagen, B. G., D. M. Theobald, C. R. Pyke, A. Choate, P. Groth, J. V. Thomas, and P. Morefield. 2010. "National housing and impervious surface scenarios for integrated climate impact assessments." *Proc. Natl. Acad. Sci.* 107 (49): 20887–20892. https://doi.org/10.1073/pnas.1002096107.

Brown, R. A., and W. F. Hunt. 2010. "Impacts of construction activity on bioretention performance." *J. Hydrol. Eng.* 15 (6): 386–394. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000165.

CDC (Centers for Disease Control). 2009. "Healthy places: Health effects of gentrification." Accessed October 15, 2020. https://www.cdc.gov/healthyplaces/healthtopics/gentrification.htm.

Chow, J. F., D. Savić, D. Fortune, Z. Kapelan, and N. Mebrate. 2014. "Using a systematic, multi-criteria decision support framework to evaluate sustainable drainage designs." *Procedia Eng.* 70 (Apr): 343–352. https://doi.org/10.1016/j.proeng.2014.02.039.

City of Philadelphia: Zero Waste and Litter Cabinet. 2019. "2019 progress report." Accessed October 10, 2020. https://www.phila.gov/media/20200109150118/Zero-Waste-Litter-Progress-Report-2019.pdf.

Debbage, N., B. Bereitschaft, and J. M. Shepherd. 2017. "Quantifying the spatiotemporal trends of urban sprawl among large US metropolitan areas via spatial metrics." *Appl. Spatial Anal. Policy* 10 (3): 317–345. https://doi.org/10.1007/s12061-016-9190-6.

DelGrosso, Z. L., C. C. Hodges, and R. L. Dymond. 2019. "Identifying key factors for implementation and maintenance of green stormwater infrastructure." *J. Sustainable Water Built Environ.* 5 (3): 05019002. https://doi.org/10.1061/JSWBAY.0000878.

Dietz, M. E. 2007. "Low impact development practices: A review of current research and recommendations for future directions." *Water Air Soil Pollut.* 186 (1–4): 351–363. https://doi.org/10.1007/s11270-007-9484-z.

Duan, S., K. Delaney-Newcomb, S. S. Kaushal, S. E. G. Findlay, and K. T. Belt. 2014. "Potential effects of leaf litter on water quality in urban watersheds." *Biogeochemistry* 121 (1): 61–80. https://doi.org/10.1007/s10533-014-0016-9.

EConsult Solutions, Inc. 2020. "Philadelphia housing index." Accessed October 25, 2020. https://econsultsolutions.com/philadelphia-housing-index/.

Elmes, A., J. Rogan, C. Williams, S. Ratick, D. Nowak, and D. Martin. 2017. "Effects of urban tree canopy loss on land surface temperature magnitude and timing." *ISPRS J. Photogramm. Remote Sens.* 128 (Sep): 338–353. https://doi.org/10.1016/j.isprsjprs.2017.04.011.

EPA. 2021. "Combined sewer overflows (CSOs)." Accessed May 15, 2021. https://www.epa.gov/npdes/combined-sewer-overflows-csos.

Erickson, A. J., P. T. Weiss, and J. S. Gulliver. 2013. *Optimizing stormwater treatment practices: A handbook of assessment and maintenance*. Berlin: Springer.

Esposito, N. 2020. "How to fix Philly's trash problem." Accessed October 7, 2020. https://thephiladelphiacitizen.org/how-to-fix-philly-trash-problem/.

Evans, K. 2021. *Green infrastructure site suitability analysis for Wyandotte County and Kansas City, Kansas*. Chapel Hill, NC: Univ. of North Carolina at Chapel Hill.

Fletcher, T. D., W. Shuster, W. F. Hunt, R. Ashley, D. Butler, S. Arthur, and M. Viklander. 2015. "SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage." *Urban Water J.* 12 (7): 525–542. https://doi.org/10.1080/1573062X.2014.916314.

Foster, J., A. Lowe, and S. Winkelman. 2011. "The value of green infrastructure for urban climate adaptation." *Center Clean Air Policy* 750 (1): 1–52.

Golden, H. E., and N. Hoghooghi. 2018. "Green infrastructure and its catchment-scale effects: An emerging science." *Wiley Interdiscip. Rev.: Water* 5 (1): e1254. https://doi.org/10.1002/wat2.1254.

Gosz, J. R., G. E. Likens, and F. H. Bormann. 1973. "Nutrient release from decomposing leaf and branch litter in the Hubbard Brook Forest, New Hampshire." *Ecol. Monogr.* 43 (2): 173–191. https://doi.org/10.2307/1942193.

Heckert, M., and C. D. Rosan. 2016. "Developing a green infrastructure equity index to promote equity planning." *Urban For. Urban Greening* 19 (3): 263–270. https://doi.org/10.1016/j.ufug.2015.12.011.

Hobbie, S. E., L. A. Baker, and C. Buyarski. 2014. "Decomposition of tree leaf litter on pavement: Implications for urban water quality." *Urban Ecosyst.* 17 (2): 369–385. https://doi.org/10.1007/s11252-013-0329-9.

Holt, D. E. 2021. *The sediment trap: Collecting sediment from urban stormwater runoff to inform an urban sediment budget*. Villanova, PA: Villanova Univ.

Hung, F., C. J. Harman, B. F. Hobbs, and M. Sivapalan. 2020. "Assessment of climate, sizing, and location controls on green infrastructure efficacy: A timescale framework." *Water Resour. Res.* 56 (5): e2019WR026141. https://doi.org/10.1029/2019WR026141.

Hunt, W. F., W. G. Lord, and J. T. Smith. 2005. "Determining BMP inspection and maintenance costs for structural BMPs in North Carolina." In *Impacts of global climate change*, 1–6. Reston, VA: ASCE. https://doi.org/10.1061/40792%28173%29173.

Jaramillo, C. 2020. "Philly sanitation workers blame filthy streets on 'poor management'; Apologize for rotting trash." Accessed October 7, 2020. https://whyy.org/articles/philly-sanitation-workers-blame-filthy-streets-on-poor-management-apologize-for-rotting-trash.

Jones, M., P. Mjones, H. John McLaughlin, S. Mehrotra, B. Leo, and J. Stein. 2015. *Green infrastructure in New York City: Three years of pilot implementation and post-construction monitoring*. Woburn, MA: New England Water Environment Association.

Kim, Y., and D. Maidment. 2014. *Soil erosion assessment using GIS and revised universal soil loss equation (RUSLE)*. Austin, TX: Univ. of Texas at Austin.

J. Sustainable Water Built Environ., 2022, 8(3): 05022003

Landauer, M., S. Juhola, and J. Klein. 2019. "The role of scale in integrating climate change adaptation and mitigation in cities." *J. Environ. Plann. Manage.* 62 (5): 741–765. https://doi.org/10.1080/09640568.2018.1430022.

Malter, S., J. Rockwell, and M. Maimone. 2017. "Climate change and precipitation: Applying global climate model projections to local precipitation time series data in Philadelphia." In *Proc., ASCE World Environmental and Water Resources Congress 2017*, 469–483. Reston, VA: ASCE. https://doi.org/10.1061/9780784480618.048.

Mandarano, L., and M. Meenar. 2017. "Equitable distribution of green stormwater infrastructure: A capacity-based framework for implementation in disadvantaged communities." *Local Environ.* 22 (11): 1338–1357. https://doi.org/10.1080/13549839.2017.1345878.

McCool, D., G. Foster, K. Renard, D. Yoder, and G. Weesies. 1995. *Revised universal soil loss equation (RUSLE)*. Tucson, AZ: Southwest Watershed Research Center.

McTiernan, K. B., P. Ineson, and P. A. Coward. 1997. "Respiration and nutrient release from tree leaf litter mixtures." *Oikos* 1997 (Apr): 527–538. https://doi.org/10.2307/3545614.

Meerow, S. 2020. "The politics of multifunctional green infrastructure planning in New York City." *Cities* 100 (May): 102621. https://doi.org/10.1016/j.cities.2020.102621.

National Recreation and Parks Association. 2019. "Green stormwater infrastructure in parks report." Accessed October 30, 2020. https://www.nrpa.org/globalassets/green-stormwater-infrastructure-parks-report.pdf.

Neeti, N., J. Rogan, Z. Christman, J. R. Eastman, M. Millones, L. Schneider, E. Nickl, B. Schmook, B. L. Turner, and B. Ghimire. 2011. "Mapping seasonal trends in vegetation using AVHRR-NDVI time series in the Yucatán Peninsula, Mexico." *Remote Sens. Lett.* 3 (5): 433–442. https://doi.org/10.1080/01431161.2011.616238.

Odhiambo, B. K., G. Rihl, and S. Hood-Recant. 2021. Historic land use and sedimentation in two urban reservoirs, Occoquan Reservoir and Lake Manassas, Virginia, USA. *Environ. Sci. Pollut. Res.* 29 (Sep): 11481–11492. https://doi.org/10.1007/s11356-021-16461-2.

OpenDataPhilly. 2018. "Litter index." Accessed September 15, 2020. https://www.opendataphilly.org/dataset/litter-index.

Patowary, S., and A. K. Sarma. 2018. "GIS-based estimation of soil loss from hilly urban area incorporating hill cut factor into RUSLE." *Water Resour. Manage.* 32 (10): 3535–3547. https://doi.org/10.1007/s11269-018-2006-5.

PennFuture. 2019. "What is green stormwater infrastructure?" Accessed November 7, 2020. https://www.pennfuture.org/what-is-green-stormwater-infrastructure.

Pennsylvania DOT. 2021. "Litter facts & myths." Accessed September 24, 2020. https://www.penndot.gov/about-us/RoadsideBeautification/LitterFacts/Pages/Litter-Facts-and-Myths.aspx.

Pettorelli, N. 2014. *The normalized difference vegetation index*. Oxford, UK: Oxford University Press.

Philadelphia Water Department. 2011. *Green City, clean waters—Implementation and adaptive management plan*. Philadelphia: Philadelphia Water Department.

Planet Team. 2017. "Planet application program interface." In *Space for life on earth*. San Francisco: Planet Team.

PWD (Philadelphia Water Department). 2014. "Green stormwater infrastructure maintenance manual." Accessed November 1, 2020. https://water.phila.gov/pool/GSI-Maintenance-Manual_v1.pdf.

PWD (Philadelphia Water Department). 2016. "Green stormwater infrastructure public and private projects." Accessed November 1, 2020. https://www.opendataphilly.org/.

Reynolds, H. L., L. Brandt, B. C. Fischer, B. S. Hardiman, D. J. Moxley, E. Sandweiss, and S. Fei. 2020. "Implications of climate change for managing urban green infrastructure: An Indiana, US case study." *Clim. Change* 163 (4): 1967–1984. https://doi.org/10.1007/s10584-019-02617-0.

Rush, W. D., J. T. Kiehl, C. A. Shields, and J. C. Zachos. 2021. "Increased frequency of extreme precipitation events in the North Atlantic during the PETM: Observations and theory." *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 568 (2): 110289. https://doi.org/10.1016/j.palaeo.2021.110289.

Russell, K. L., G. J. Vietz, and T. D. Fletcher. 2019. "Urban sediment supply to streams from hillslope sources." *Sci. Total Environ.* 653 (Jan): 684–697. https://doi.org/10.1016/j.scitotenv.2018.10.374.

Seattle Public Utilities. 2009. "Seattle public utilities green stormwater operations and maintenance manual." Accessed October 27, 2020. https://www.seattle.gov/util/cs/groups/public/@spu/@usm/documents/webcontent/spu02_020023.pdf.

Shuster, W., L. Schifman, C. Kelleher, H. E. Golden, A. S. Bhaskar, A. J. Parolari, R. D. Stewart, and D. L. Herrmann. 2021. "K in an urban world: New contexts for hydraulic conductivity." *J. Am. Water Resour. Assoc.* 57 (May): 493–504. https://doi.org/10.1111/1752-1688.12918.

Smith, C., R. Connolly, R. Ampomah, A. Hess, K. Sample-Lord, and V. Smith. 2021. "Temporal soil dynamics in bioinfiltration systems." *J. Irrig. Drain. Eng.* 147 (11): 04021053. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001617.

Soil Survey Staff, Natural Resources Conservation Service, USDA. 2021. "Web soil survey." Accessed October 20, 2020. http://websoilsurvey.sc.egov.usda.gov/.

Stormwater BMP Maintenance TC (Stormwater Best Management Practices Maintenance Task Committee). 2019. *Inspection and maintenance of stormwater control measures*. Reston, VA: ASCE.

Stutz, B. 2018. "With a green makeover, Philadelphia is tackling its stormwater problem." Accessed September 30, 2020. https://e360.yale.edu/features/with-a-green-makeover-philadelphia-tackles-its-stormwater-problem.

Sun, Y., and S. Zhao. 2016. "Leaf litter decomposition in urban forests: Test of the home-field advantage hypothesis." *Ann. For. Sci.* 73 (8): 1063–1072. https://doi.org/10.1007/s13595-016-0577-y.

Taguchi, V. J., P. T. Weiss, J. S. Gulliver, M. R. Klein, R. M. Hozalski, L. A. Baker, J. C. Finlay, B. L. Keeler, and J. L. Nieber. 2020. "It is not easy being green: Recognizing unintended consequences of green stormwater infrastructure." *Water* 12 (2): 522. https://doi.org/10.3390/w12020522.

Tillack, A., A. Clasen, B. Kleinschmit, and M. Förster. 2014. "Estimation of the seasonal leaf area index in an alluvial forest using high-resolution satellite-based vegetation indices." *Remote Sens. Environ.* 141 (2): 52–63. https://doi.org/10.1016/j.rse.2013.10.018.

University of Vermont Spatial Analysis Laboratory. 2018. "Philadelphia land cover 2018." Accessed October 10, 2020. http://www.pasda.psu.edu/.

US Census Bureau. 2019. "QuickFacts: Philadelphia city, Pennsylvania." Accessed November 12, 2020. https://www.census.gov/quickfacts/fact/table/philadelphiacitypennsylvania/POP060210#POP060210.

USGS. 2011. "North America climate—Monthly mean precipitation—GIS data—ScienceBase-catalog." Accessed July 21, 2020. https://www.sciencebase.gov/catalog/item/4fb55169e4b04cb937751d9b.

van der Wiel, K., S. B. Kapnick, G. J. van Oldenborgh, K. Whan, S. Philip, G. A. Vecchi, R. K. Singh, J. Arrighi, and H. Cullen. 2017. "Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change." *Hydrol. Earth Syst. Sci.* 21 (2): 897–921. https://doi.org/10.5194/hess-21-897-2017.

Wachal, D. J., K. E. Banks, P. F. Hudak, and R. D. Harmel. 2009. "Modeling erosion and sediment control practices with RUSLE 2.0: A management approach for natural gas well sites in Denton County, TX, USA." *Environ. Geol.* 56 (8): 1615–1627. https://doi.org/10.1007/s00254-008-1259-3.

Wadzuk, B., B. Gile, V. Smith, A. Ebrahimian, and R. Traver. 2021. "Call for a dynamic approach to GSI maintenance." *J. Sustainable Water Built Environ.* 7 (2): 02521001. https://doi.org/10.1061/JSWBAY.0000945.

Water Environment Research Foundation. 2008. "BMP and LID whole life cost models: Version 2.0." Accessed February 20, 2021. https://www.waterrf.org/research/projects/bmp-and-lid-whole-life-cost-models-version-20.

Wolman, M. G. 1967. "A cycle of sedimentation and erosion in urban river channels." *Geogr. Ann. Ser. A Phys. Geogr.* 49 (2–4): 385–395. https://doi.org/10.2307/520904.

Yoo, J., S. Simonit, J. P. Connors, A. P. Kinzig, and C. Perrings. 2014. "The valuation of off-site ecosystem service flows: Deforestation, erosion and the amenity value of lakes in Prescott, Arizona." *Ecol. Econ.* 97 (2): 74–83. https://doi.org/10.1016/j.ecolecon.2013.11.001.

Zhou, M., J. Deng, Y. Lin, L. Zhang, S. He, and W. Yang. 2021. "Evaluating combined effects of socio-economic development and ecological conservation policies on sediment retention service in the Qiantang River Basin, China." *J. Cleaner Prod.* 286 (23): 124961. https://doi.org/10.1016/j.jclepro.2020.124961.

Zimmer, C. A., I. W. Heathcote, H. R. Whiteley, and H. Schroter. 2007. "Low-impact-development practices for stormwater: Implications for urban hydrology." *Can. Water Resour. J.* 32 (3): 193–212. https://doi.org/10.4296/cwrj3203193.