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Evaluating the effect of city ordinances on the implementation and performance of green stormwater infrastructure (GSI)

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ABSTRACT

The replacement of natural pervious surfaces with impervious surfaces due to urbanization, construction, and development causes excess stormwater runoff and results in cities experiencing localized flooding events. The installation of green stormwater infrastructure (GSI) is one way of reducing flooding events and preventing downstream erosion and damage. In this study, computer rainfall-runoff simulations were performed to analyze GSI's effectiveness in mitigating stormwater runoff when applied to sites with different soil types and for which different design storms were established by regulation. A mixed-use development site was used as a hypothetical site on which to perform the analysis. The study applied the same design to six small- to medium-sized cities in the southeastern United States with different design storm magnitudes. The cities' ordinances were reviewed, and none required GSI. Therefore, this study revised some of the stormwater management requirements to stress GSI implementation, and then stormwater modeling was conducted to see how regulatory changes would affect runoff. The HydroCAD stormwater modeling tool was used to perform hydrologic simulations for the hypothetical building site in each of the six cities using the design storms and small storms of the cities. Even though GSI has been commonly implemented in large cities, small and medium-sized cities can also prevent excess stormwater by incorporating GSI in their ordinances for new developments and site retrofits. Based on the hydrologic simulation results, municipalities with lower magnitude design storms and low infiltration soils have the most to benefit from GSI and could benefit from ordinances requiring GSI. For smaller, more frequent storms, GSI alone can meet the pre-development peak flow requirements.

1. Introduction

Green stormwater infrastructure (GSI) provides environmental benefits, but the costs and burdens on development as well as regulatory limitations may restrict its use in many cities. The installation of GSI in cities is a sustainable method of addressing stormwater runoff problems (Giese et al., 2019; Kousky et al., 2013; Li et al., 2020). GSI reduces the runoff volume and velocity by promoting stormwater infiltration into the ground, which prevents downstream flooding, erosion, and environmental damage. GSI may also serve as a treatment for polluted stormwater runoff, which improves the quality of receiving water bodies (CWAA 2016; Pennino et al. 2016). In addition to managing stormwater quantity and quality, GSI has environmental and social benefits, such as providing a natural green environment, reducing exposure to toxic substances, improving air quality, and improving human well-being (EPA 2017; Gallet 2012). GSI also improves urban air quality by taking up harmful air pollutants while providing several other ecosystem services (Jayasooriya et al. 2017).

In order to meet the benefits described, GSI should be used together with, or to replace when feasible, gray stormwater infrastructure. Gray stormwater infrastructure consists of street gutters, storm drains, pipes, and underground storage structures. Gray infrastructure is designed for the important function of quickly moving stormwater away from homes, businesses, and flood-prone areas. However, gray infrastructure does not promote infiltration, evapotranspiration, and temporary storage as GSI does. GSI is different from gray infrastructure because it mimics the natural hydrologic cycle by simulating pre-development or pre-construction conditions that have more permeable surfaces.

Even though GSI has many environmental and health benefits, there are barriers that prevent cities, developers, construction contractors, and engineers from installing these practices (CWAA, 2016; Dhakal and Chevalier, 2017). These barriers usually fall into three main categories: technical, financial, and regulatory. Variability in hydrologic performance and uncertainty of the state-of-the-practice are considered technical barriers. Also, the effectiveness of GSI is very site-specific, particularly in regards to soils and climate (EPA, 2020). Financial barriers

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Table 1
General information on the six cities selected for this study. (Census, 2020).

City		Biloxi, MS	Calhoun, GA	Orange Beach, AL	Oxford, MS	Ruston, LA	Sevierville, TN
Area, mi^2 (km^2)	**Total**	67.83 (175.7)	15.00 (38.85)	15.95 (41.31)	16.50 (42.73)	20.98 (54.34)	24.27 (62.86)
	Land	38.22 (98.99)	14.93 (38.67)	14.70 (38.08)	15.83 (40.99)	20.85 (54.00)	24.14 (62.52)
	Water	29.61 (76.71)	0.07 (0.18)	1.25 (3.24)	0.67 (1.74)	0.13 (0.34)	0.13 (0.34)
Population		46,212	17,271	6235	28,122	21,859	17,117
Density per mi^2 (per km^2)		1153 (398)	1048 (361)	370 (128)	1195 (412)	1049 (362)	614 (212)
Median household income, U.S. dollars		$44,972	$35,890	$81,506	$39,886	$30,119	$40,780

include high capital, retrofit, and operation and maintenance costs of GSI. The regulatory barrier often consists of city ordinances that may restrict GSI and promote gray infrastructure (Braden and Ando, 2011; Derviş, 2013; Liberalesso et al., 2020). Mindset, unawareness, fear, attitudes, and perceptions are also other factors that discourage landowners, water resource managers, and policy-makers from using GSI (Dhakal and Chevalier, 2017; Ureta et al., 2021).

Some studies have described barriers that often limit the implementation of GSI. Derviş (2013) categorized three types of uncertainty for the implementation of GSI: variability in cost, hydrological performance, and adaptation. Braden and Ando 2021 discussed three other GSI implementation barriers. The first is that many cities have zoning ordinances and building codes that create barriers to GSI design. The second is the division of responsibility. The responsibility for initial stormwater management is on the builders, whereas ongoing stormwater management is on the property owners. Property owners might be reluctant to accept the responsibility for something they do not understand. The third barrier in the Braden and Ando study is that adopting GSI requires stakeholders to obtain new knowledge. Similarly, the Clean Water America Alliance identified four categories of barriers that often prevent the adoption of GSI: technical and physical, legal and regulatory, financial, and communities and institutional (CWAA 2016).

This paper specifically analyzes GSI barriers due to local regulations. The analysis was performed by identifying regulatory barriers and incentives in existing municipal ordinances of six southeastern United States cities with populations ranging between 6200 and 46,000. Six cities, Biloxi, MS, Calhoun, GA, Sevierville, TN, Oxford, MS, Orange Beach, AL, and Ruston, LA, were selected for this analysis. Small to medium-sized cities from similar climate regions were chosen because they experience stormwater effects but are often under-resourced compared to major cities with already well-established stormwater departments, ordinances, and staff. The design storm magnitudes of the selected cities range from 4.66 (118.36 mm) to 14.5 inches (368.3 mm) in 24 h (NOAA Hydrolometeorological Design Studies Center, 2020). The cities of Biloxi and Orange Beach represent coastal cities on the Gulf of Mexico, an area often affected by extreme storms. Consideration was taken to address the cities' zoning, flooding, and stormwater management requirements.

This paper addresses four objectives. The first objective is to identify existing municipal ordinances of those cities that reference GSI implementation either specifically, by requiring GSI, or impliedly, by suggesting green alternatives to gray infrastructure. The second objective is to quantify the runoff due to design storms cited in city ordinances by conducting rainfall-runoff analyses using the HydroCAD stormwater analysis software. Third, to suggest practical sample regulations encouraging GSI implementation to reduce runoff. The last objective is to quantify the runoff reduction based on the sample regulations.

2. Cities and hypothetical site

This section describes the cities and the study site that was modeled in each city. Table 1 shows general information about each city. These cities represent small- to medium-sized growing cities with similar climatic conditions that may have fewer financial resources than larger cities, although climatic conditions are not identical and soil groups vary.

The study was conducted by assuming a mixed-use development with the same buildings, parking lots, and landscaping built in each city, using applicable zoning requirements from each city. Fig. 1 shows the pre-development and post-development scenarios of the study site. The pre-development is the condition of the study site before the project is built. The post-development scenario is the study site with the proposed mixed-use development completed. Fig. 1(b) shows the plan view of the proposed development, with a total area of 161,136 ft^2 (14,970 m^2), including 45,526 ft^2 (4230 m^2) of rooftops, 88,280 ft^2 (8201 m^2) of parking lots, and 27,330 ft^2 (2539 m^2) of landscape. The post-development includes the construction of two three-story mixed-use buildings and the associated parking lots. Both buildings are designed to have commercial space on the first floor and residential space on the second and third floors.

Computer simulations for the rainfall-runoff analysis of the site were run for pre- and post-development conditions, with post-development simulations including scenarios of no stormwater control and scenarios implementing GSI. The same pre-development land cover was assumed for all cities. The post-development land cover was simulated based on the cities' design requirements defined in their ordinances consistent with the proposed site plan.

3. Materials and methods

3.1. Ordinance review

Each municipality's zoning and stormwater management ordinances were obtained from the Municode Library (Municode 2020). The requirements were analyzed for issues related to GSI, such as permeable surfaces, green area coverage, landscape or open space, and stormwater management incentives. Only practices that could be applied to the study site were considered for the analysis. Provisions that related to GSI were found, and then revised versions were written with stricter requirements. The revised version was crafted to be practicable for small and mid-sized cities to adopt and use on new construction sites of five acres or less in non-residential areas.

All six cities require stormwater management facilities to reduce the post-development peak flow rate from a storm to less than or equal to the pre-development peak flow rate. However, none of the cities do this by requiring GSI. Of the six cities considered in this study, two of them, Biloxi and Oxford, require a drainage/storage system to be designed for a maximum 100-year 24-hr storm. The remaining four cities require design for a maximum 25-year 24-hr storm. A summary of the design storms and ordinances related to GSI (focusing on, but not limited to, permeable surfaces and rain gardens) is presented in Table 2**.**

The ordinances were reviewed to find GSI requirements for new developments in similarly zoned areas. The regulations in the second column of Table 2 are the text passages taken from the ordinances. No city required GSI. However, all had some non-enforceable advisory provisions that emphasized green space over gray infrastructure.

GSI practices were chosen to be applicable to the hypothetical site's limited size and zoning. The GSI focuses on stormwater runoff quantity

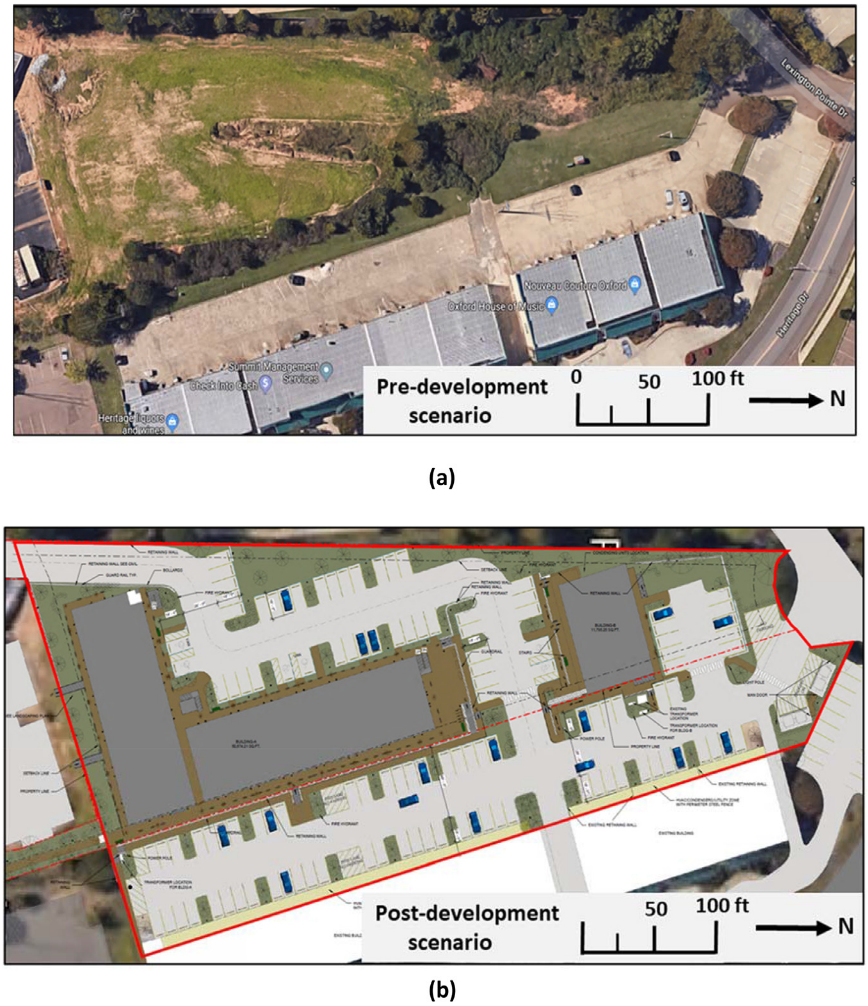

Fig. 1. (a) Pre-development and (b) post-development plan views of the study site. The solid red line outlines the site. 100 ft = 30.48 m.

management. Stormwater quality management is outside the scope of this study.

3.2. Rainfall-runoff modeling

The study site's hydrologic processes were simulated using HydroCAD 10.10–4, a stormwater modeling software. This software was selected because it is commonly used among city engineers and developers. HydroCAD uses the Natural Resources Conservation Service (NRCS) Technical Release 20 (TR-20) runoff method procedure to determine the runoff's peak flow rate and volume. The Curve Number (CN) value is a primary input parameter for the TR-20 method used by HydroCAD. The CN is an empirical parameter used to characterize the runoff potential for a particular soil group and land cover (ASCE, 1996; USDA, 1982). The CN values were determined using the CN table provided in HydroCAD. This table of CN values is based on the NRCS TR-55 reference table (USDA, 1986). Table 3 shows the CNs used in this study.

In this study, we simulated the peak flow rates of runoff leaving the site at each city by employing HydroCAD. The 24-hr rainfall distribution was used in all of the simulations. Based on the NRCS designation of rainfall regions in the United States, the cities are in locations with different storm types. Calhoun, Oxford, and Sevierville are located in the region of Type II rainfall distribution. Biloxi, Orange Beach, and Ruston are located in the region of Type III rainfall distribution. These storm types are developed by the NRCS as dimensionless synthetic rainfall distributions to characterize the rainfall patterns in the United States. The Type II storm represents most of the country. Type III represents the Gulf of Mexico and the Atlantic coastal areas (Mays, 2010; USDA, 1986). The storm magnitudes used were those required by the city ordinances and shown in Table 2.

We used the same pre-development land cover for all cities. This set the same baseline scenario. It also enabled us to study only the effect of each municipality's predominant soil group, design storms, and regulations related to GSI implementation and potential flood reduction. The pre-development land cover of the site was grass, woods-grass, paved area, and buildings. Even though the site's land cover was assumed to be the same for all cities, different CNs (see Table 3) were assigned based on each municipality's soil group. The soil groups affect how much rainwater infiltrates the ground, changing the amount of runoff that will be generated. Hydrologic soil groups were determined using the NRCS table and the EPA Stormwater Calculator soil maps (EPA, 2019; USDA, 2009). Since each city has several hydrologic soil groups, one representative soil group was selected for each.

Two post-development models were simulated for each city. The first model considered the cities' design storm requirements, keeping the same post-development land cover (post-development without GSI) (Fig. 1(b)) for all cities.

The second model simulated the application of proposed sample regulations requiring GSI. The changes in the amount of runoff generated from these two sets of models were analyzed by comparing the simulation results. The comparisons were made between post development without stormwater control and post-development with GSI following the sample GSI regulations. The results of these analyses explain the effect on runoff when GSI regulations are implemented.

Table 2
Summary of design storms and the stormwater-related GSI language in the ordinance for each municipality.

City	Stormwater-related GSI Language as stated in Ordinances	Stormwater Design Requirements
Biloxi, MS	If 20% of the total vehicular area is covered by **permeable pavement**, the size requirement for canopy and understory trees can be reduced by 5% (Article 23–6–3(D)(4)). If **permeable surfacing*** materials are used for some or all of the parking area surfaces, points that lead towards the Leadership in Energy and Environmental Design (LEED) certification will be earned. If a minimum 25% of the area is covered, 2 points will be earned. If a minimum 59% of the area is covered, 4 points will be earned (Table 23–6–12(B)). If **permeable surfacing** materials are used for all sidewalks, 2 LEED points can be achieved (Table 23–6–12(B)). If a development includes **rain gardens** where each has an area of at least 100 ft^2 (9.29 m^2), and is sized to hold stormwater runoff from between 5 and 10 percent of the impermeable area draining into it, 1 LEED point can be earned per rain garden (Table 23–6–12(B)). 30% of the total required parking is subjected to a shared parking agreement.	100-year 24-hour design storm magnitude = 14.5 in (368 mm)
Calhoun, GA	For apartment buildings, a permit may not be issued if the **impermeable cover** is more than 30% of the total area (Sec. 11.3.1(a)(3)). The purposes of the stormwater management ordinances include **encouraging** the use of nonstructural stormwater management and **stormwater better site design practices**, such as the **preservation of green space and other conservation areas**, to the maximum extent practicable (Sec. 46–300(5)). Use of **stormwater better site design practices**, including nonstructural stormwater measures, allow the applicant to reduce the water quality volume requirement (Sec. 46–336).	25-year 24-hour design storm magnitude = 6.18 in (157 mm)
Orange Beach, AL	Vehicle use areas must be constructed of concrete, asphalt, brick, cement pavers, or similar material installed and maintained per industry standard. **Alternative** all-weather surfaces such as **gravel, shell, permeable concrete, and reinforced turf** may be approved by the Planning Commission in consideration of site conditions, traffic intensity and land use (Sec. 8.0107404). Runoff should be designed and maintained using retention/detention or **exfiltration/infiltration** (Sec. 42–272(a)). Other stormwater control systems can be considered to manage runoff exceeding the detailed volume, such as **exfiltration/infiltration ponds, grass swales, and vegetated buffer strips** (Sec. 42–272(c)).	25-year 24-hour design storm magnitude = 11.8 in (300 mm)
Oxford, MS	Parking lots must be surfaced with asphalt or similar material. However, **permeable solid surfaces** may be allowed on areas of limited use at the approval of the city. (Sec 5.3.3.1) At least 75% of parking island landscape areas should be covered with **grass** or another surface approved by the city (Sec 5.3.3.6(b)). Parking lot landscaping requirements may be altered if **low impact design (LID)** stormwater management elements are approved (Sec 5.3.3.7(a)). **Permeable pavers** may replace up to 25% of landscaping requirements for the permeable surface of the lot, approvable at the discretion of the planning director (Sec 5.7.3.5). A minimum of 15% of the pervious surface of the parking lot should be **landscaped** with trees and shrubs (Sec 5.7.3.1).	For detention: 100-year 24-hr design storm magnitude = 8.75 in (222 mm) Multi-stage outlet structures ranging from the 2- to 100-year storms.
Ruston, LA	Where possible, a portion of the drainage from parking areas should be drained through swales that include deep rooted perennial ornamental grasses (Sec. 5.5.3.H.5).	25-year 24-hr design storm magnitude = 7.83 in (199 mm)
Sevierville, TN	Stormwater designs should seek to utilize **permeable** areas for stormwater treatment and to **infiltrate** stormwater runoff from impermeable surfaces and landscaped areas to protect water quality and quantity (Sec. 18–404(6)). [In areas zoned Town Center Commercial] Wherever practical, low impact development techniques shall be used and maintained (Sec. 4.13.4).	For detention: 25-year 24-hr design storm magnitude = 4.66 in (118 mm) Multi-stage outlet structures ranging from the 1- to 25-year storms.

* Words in bold indicate GSI-related terminology.

Table 3
CNs of different scenarios and effective CNs used for permeable concrete.

City	NRCS Rainfall Distribution Types	Hydrologic Soil Group	Weighted Curve Number (CN) Before Sample Regulations		Effective CN for Permeable Concrete (to be used for Sample Regulations 1 & 3*)	Weighted Curve Number (CN)	
			Pre-Dev.	Post-Dev.		Sample Regulation 1	Sample Regulation 3
Biloxi, MS	III	B	72	92	69	90	88
Calhoun, GA	II	B	72	92	69	90	88
Orange Beach, AL	III	A	55	88	64	86	83
Oxford, MS	II	B	72	92	69	90	88
Ruston, LA	III	C	81	94	71	93	90
Sevierville, TN	II	D	86	95	73	94	92

* Sample Regulation 1 and 3 are based on the implementation of permeable pavement.

It is assumed that the full designs in all of these cities would incorporate proper piping and other conveyance structures, and water storage to account for runoff not handled by GSI.

When modeling runoff based on the proposed sample regulations, we introduced to the post-development site GSI such as permeable pavement and rain gardens. Modeling runoff from permeable pavements required determining an effective CN value for the pavement (Schwartz, 2010). Although several types of permeable pavements are available, permeable concrete pavement was selected for this study site. The effective CN was estimated based on the permeable concrete area, the thickness and porosity of the permeable concrete and the sub-base layers, and the underlying soil's infiltration rate. The effective CN values (see Table 3) were estimated using the NRCS potential maximum retention equation; the values are presented in Table 3 for each soil group. The depth of the permeable concrete pavement layers, including ponding, amended soil, and gravel layers, were accounted for storage. Exfiltration through the underlying soil and overflow from the ponding layer were defined as outlets for the system.

Table 4
Sample GSI regulations with recommended modifications.

Issue	Current Language in City Ordinances	Reference	Sample Regulation with GSI
Change sidewalk requirements	Sidewalks shall be concrete or another approved surface.	City of Oxford (Sec 5.3.3.1); City of Sevierville (Sec. 4.7.1.5)	Sample Regulation 1: All sidewalks shall be covered by permeable surfacing.
	If permeable surfacing materials are used for all sidewalks, 2 LEED* points can be achieved.	City of Biloxi (Table 23–6–12(B))	
	Sidewalks shall have a concrete depth of a minimum of four inches.	City of Ruston (Sec. 24–50(a)); City of Calhoun (Sec. 82–50(b))	
Include rain garden design as a part of landscaping	If a development includes rain gardens where each has an area of at least 100 square feet, 1 LEED* point can be earned per rain garden.	City of Biloxi, Table 23–6–12(B)	Sample Regulation 2: 15% of the landscape area should be designated for a rain garden that receives water from impermeable surfaces.
Change parking spaces coverage with permeable surface	Parking lots must be surfaced with asphalt. However, permeable solid surfaces may be allowed at the approval of the city.	City of Biloxi, Table 23–6–12(B)	Sample Regulation 3: Permeable surfacing materials shall be used to cover a minimum of 25% area of parking area.
	Vehicle use areas must be constructed of concrete, asphalt, brick, cement pavers, or similar material installed.	City of Orange Beach (Sec. 8.010405)	
	All parking lots (except per Sec. 4.6.2.10 - sidewalks) shall be paved with asphalt or cementious concrete.	City of Sevierville (Sec. 4.6.3.2)	
Change parking island requirements	Parking aisles and interior dividers shall be terminated with terminal islands not less than five (5) feet in width constructed with raised curbs.	City of Sevierville (Sec. 4.6.3.10)	Sample Regulation 4: Parking islands shall be designed for rain garden to receive stormwater runoff from impervious parking surfaces.
	Where parking facilities or any other vehicular use areas are provided, they shall have concrete curbs to prevent vehicles from overhanging adjacent property or landscaped areas.	City of Ruston (Sec. 5.5.3.G)	

The rainfall-runoff modeling for the rain garden was performed by defining the rain garden using a pond node in HydroCAD with the appropriate storage and outlet structures. The pond node allows the definition of multiple storage layers. Then, the layers were arranged on top of one another to model the composite shape. The rain gardens proposed for the study site consisted of ponding, mulch, amended soil, and gravel layers, and they were defined as prismatic shapes. Except for the mulch layer, the depth of the layers was 12 inches (30.5 cm). The mulch layer was 3 inches (7.6 cm) thick. Outflow from the rain garden was defined as exfiltration and overflow.

The rainfall-runoff simulation results, the ordinance review, and the sample regulations are discussed in the Results and Discussion section.

3.3. Determination of sample ordinances

From the ordinance review and the baseline hydrologic analysis, it was observed that to benefit from implementing GSI, municipalities need to include these practices as requirements in their ordinances. If they are stated as recommendations, the implementation will depend on the developer's interest. Therefore, to show the effect of city regulations, we proposed modified sample regulations that emphasize the implementation of GSI. Table 4 shows the list of modified and proposed GSI requirements, citing similar existing ordinances that simply recommend GSI.

Sample Regulation 1 proposes permeable pavement sidewalks (Table 4, Fig. 2). Permeable pavement is one type of GSI, an alternative for paved surfaces, such as sidewalks and parking lots. There are several types of permeable pavement alternatives for sidewalk use. For this study, permeable concrete pavement was considered. The pavement's effective CN was estimated based on its layers' potential maximum water storage (Table 3). Therefore, simulations under Sample Regulation 1 were performed by assigning the effective CN of permeable concrete to the corresponding area of the sidewalks. The resulting runoff peak flows for the site at each city are shown in Fig. 3.

Because Sample Regulation 1 did not result in significant decreases in peak flows, another approach was considered. This approach designated a portion of the landscape for a rain garden, per Sample Regulation 2 (Table 4). Because the rain garden's size was fixed in this regulation to 15% of the landscape (in the case of the hypothetical site, 2.5% of the total area) the runoff amount that the rain garden could handle depended on the magnitude of the design storm. When the storm magnitude was low, the rain garden would receive and store runoff from a larger impermeable area. In contrast, when the storm magnitude was high, the rain garden would handle runoff from a smaller impermeable area.

The third sample regulation proposed to cover 25% of the paved area with permeable pavement (Table 4). Covering 25% of the parking area, 17,657 ft^2 (1640 m^2, Fig. 2), with permeable concrete was assumed for this analysis.

A fourth sample regulation was recommended, proposing the use of small rain gardens as parking islands that receive stormwater runoff from the surrounding impermeable parking surfaces, eliminating curbs (Table 4). Based on their locations, ten parking islands were selected for installation of the rain gardens (Fig. 2).

4. Results and discussion

4.1. Ordinance review

The ordinance review revealed the differences among stormwater management requirements for the municipalities. Those requirements are presented in this section.

Biloxi's ordinance promotes stormwater best management practices (BMPs) that emphasize infiltration and storage. The city puts a greater emphasis on GSI than the other cities by providing permeable pavement alternatives. Biloxi also provides detailed standards and requirements with tables and figures, which are easy to understand and interpret. For example, dimensional standards for parking spaces with different orientations are provided with a table and figure (Article 23–6–3 (D) Table 23–6-2(G) (1)). Also, several incentives and sustainable development options for earning points towards LEED certification are offered in the ordinance, as shown in Table 2. These sustainable development designs include parking area reduction, vehicular use area landscaping, permeable surfacing material, rain gardens, and site configuration (Table 23–6–12(B)) (City of Biloxi, 2021).

Oxford provides detailed design requirements for stormwater management facilities (detention, retention, underground basins, and outlet

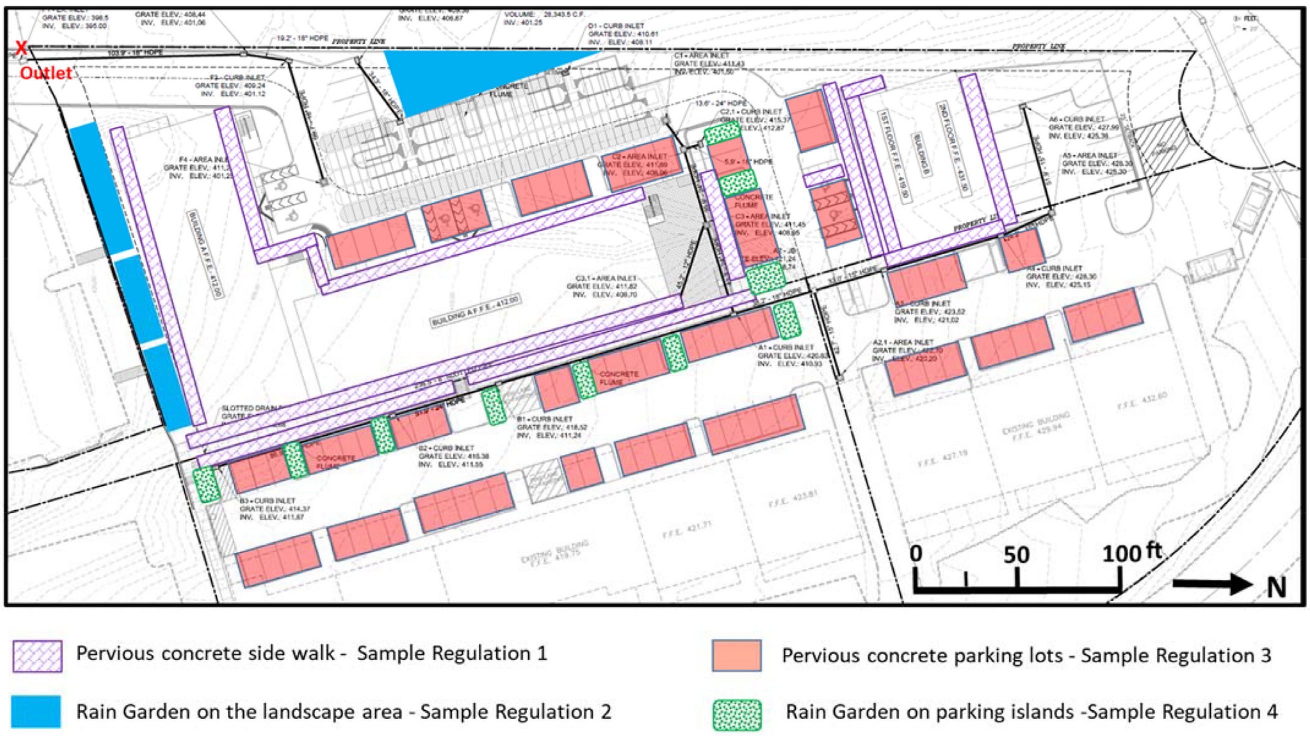

Fig. 2. Plan view of the study site with possible locations for the implementation of the GSI required by the sample regulations. The site outlet is in the southwest corner, shown by the red X. This figure also shows the potential gray infrastructure collection and detention systems.

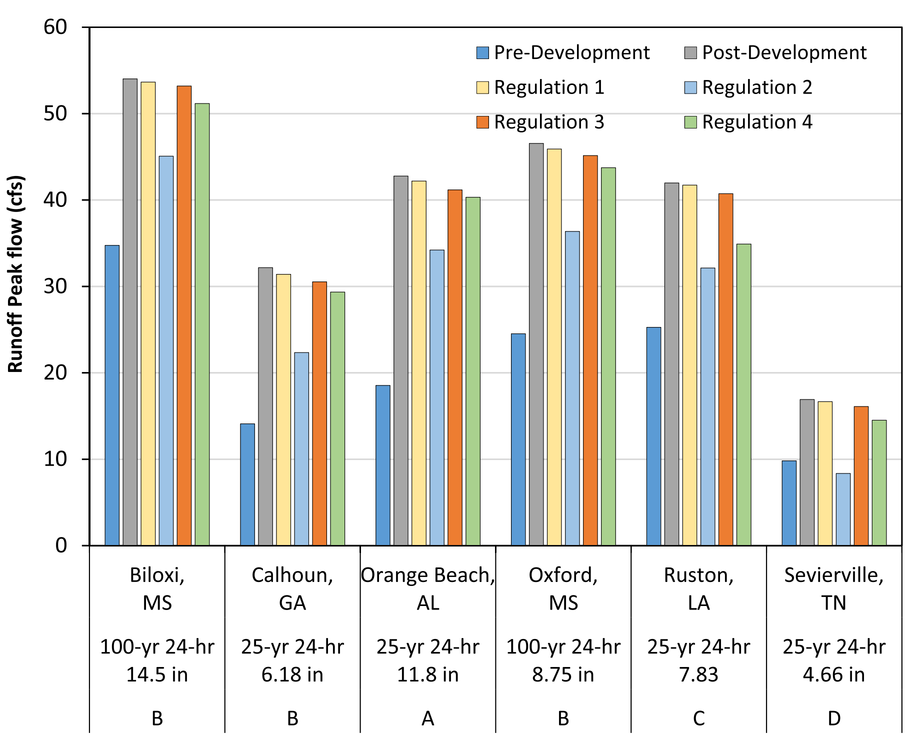

Fig. 3. Simulation results of pre- and post-development (no stormwater control) and the application of Sample Regulations 1 through 4. The horizontal axis shows the cities, their design storms, and their predominant soil group. (10 cfs = 0.28 m^3/s).

control structures). These requirements include the magnitude of design storms, time of concentration, and method for runoff analysis, which the other cities do not specify. Few GSI options are provided in the ordinance as a form of alternative to gray infrastructure. For instance, the city recommends a GSI alternative of replacing up to 15% of landscaping requirements with permeable surfaces on areas of limited use such as parking spaces and sidewalks (Sec. 5.7.3.5)(City of Oxford, 2021). Also, the term low impact design (LID) is used, which is a similar term to GSI. However, the ordinance does not set these alternatives as a mandatory implementation.

Calhoun's Zoning Ord. Sec. 11.3.1(a)(3), requires the impermeable area of a site to be less than 30 percent of the total area to obtain a building permit for any residential lot or apartment complex (City of Calhoun, 2011). Calhoun encourages "better site design practices" to preserve green space. Orange Beach's ordinances do not call specifically for use of GSI but state that exfiltration/infiltration systems may be used, upon approval, for containing stormwater, including for volumes exceeding the design retention capacity. In addition, Orange Beach provides an alternative for the vehicle use area requirement. The regulation requires vehicle use areas to be constructed of impermeable materials, such as concrete, asphalt, brick, and cement pavers, allowing alternatives, such as gravel, crushed shells, or turf, based on traffic intensity and use (City of Orange Beach, 2020). Sevierville's ordinances also do not call specifically for the use of GSI but state that structural stormwater control measures can include pervious areas for infiltration. Sevierville's ordinances have a high focus on water quality in addition to quantity (City of Sevierville, 2013). For the city of Ruston, our research did not find regulations that apply to the study site, although the city's ordinances suggest swales with native grasses for parking lot runoff (City of Ruston, 2020).

Overall, the ordinance review showed that only two municipalities (Biloxi and Oxford) mention GSI as alternatives, and none of the studied cities had GSI requirements. The language used in the municipal ordinances plays a vital role in the implementation of GSI.

4.2. Baseline hydrologic analysis

The baseline scenario analysis was performed by simulating the pre-development and post-development conditions of the study site. The pre-development simulation, which is before the construction of the project, was simulated using the land cover shown in Fig. 1(a) and the predominant soil group in that city. The post-development simulation was done by implementing the proposed development design shown in Fig. 1(b), at first using a scenario without any stormwater management infrastructure. Since all municipalities require reducing the post-development peak flow rate to less than or equal to the pre-development peak flow rate, evaluating the results of these two simulations will convey to a designer the amount of water that has to be controlled after development. The simulation results showed that the post-development peak flows were higher by 55 to 131% from the pre-development, depending on the city (see blue and gray bars in Fig. 3). This increase in peak flows was a result of the land cover change from the natural permeable surface to impermeable surfaces. The CNs increased as shown on Table 3, columns 4 and 5. The difference in the range of increased peak flows is due to the cities' different prevalent soil groups and design storm magnitudes.

To show the effect of proposed municipal regulations on the implementation of GSI and peak runoff reduction, additional analyses were performed by incorporating sample GSI regulations into the hydrologic model. The sample regulation analysis and results are discussed in the following sub-section.

4.3. Hydrologic analysis incorporating sample ordinances

The rainfall-runoff simulation results due to the sample regulations are presented in this section. The simulations were performed by implementing the GSI required by the sample regulations in each city. A total of twenty-four simulations were run for four sample regulations and six cities.

4.3.1. Sample regulation 1: all sidewalks should be covered by permeable surfacing

Based on Sample Regulation 1 simulation results, the peak runoff was reduced by an average of 1.3% from the post-development scenario (compare gray and yellow bars in Fig. 3). The peak flows resulting from this regulation, however, did not meet the pre-development peak flow requirement. All of the peak flows for post-development with permeable sidewalks were higher than the pre-development peak flows. Therefore, permeable pavement alone would not meet the cities' current ordinance requirements for the post-development peak flow to be below the pre-development peak flow.

Each city performed differently for this sample regulation. For instance, even though the CN of Sevierville was higher than the other municipalities' (Table 3), this site had the second largest percent reduction in peak flow (1.5%), with Calhoun showing the largest percent reduction (2.4%). Ruston showed the least percent reduction (0.62%). This variation is a result of the different design storm magnitudes and soil groups among the cities (Table 2).

4.3.2. Sample regulation 2: 15% of the landscape area should be designated for a rain garden that receives water from impermeable surfaces

Using the model with the rain gardens, the rainfall-runoff simulation results showed that the runoff peaks were reduced from the post-development peaks by 27% on average, as shown by the gray and light blue bars in Fig. 3. Except for Sevierville, the cities' peak flows still were higher than the pre-development peak flow. Sevierville showed a peak flow 15% lower than the pre-development. As mentioned earlier, the municipalities require the stormwater detention/retention facilities to be designed to maintain the pre-development peak flow. In the case of Sevierville, rain gardens alone would reduce the flow to below the pre-development peak flow, rendering other gray infrastructure, such as detention and retention facilities, necessary only for storm magnitudes higher than the 25-year 24-hr storm.

4.3.3. Sample regulation 3: permeable surfacing materials should be used to cover a minimum of 25% of the paved area. If more than 25% of the area is covered, a permit fee waiver will be granted

For Sample Regulation 3, 25% of the parking area was assumed to be covered by permeable concrete. After covering the parking spaces with permeable concrete in the model, the peak flow was reduced on average by 3.5% from the post-development peak flow (compare gray and orange bars in Fig. 3). Even though the peak is lower than the post-development scenario, it did not reach below the pre-development peak flow. On average, the resulting peak flow was 84% higher than the pre-development scenario. This result tells us that the site still needs a detention or retention structure to handle the remaining flow to meet the pre-development peak flow requirement.

4.3.4. Sample regulation 4: parking islands must be designed for rain gardens to receive stormwater runoff from impermeable parking surfaces

After applying Sample Regulation 4 to the model of the study site, the peak flow was reduced by 9.5% (compare gray and green bars in Fig. 3). The simulation results for this sample regulation showed that all of the cities' peak flows were higher than the pre-development. However, this regulation showed the second-highest reduction compared to the other regulations.

The rainfall-runoff analysis results showed that when municipalities incorporate GSI in their ordinances, the study site's runoff peak flows decrease. The peak flow reductions ranged from 1.3 to 27%, depending on the regulations modeled. Sample Regulations 2 and 4 showed relatively higher reductions. Both regulations are based on the implementation of rain gardens on the study site. The other two regulations considered the installation of permeable concrete pavement on paved areas. Adding rain gardens on the study site showed a greater peak flow reduction than adding permeable concrete. Rain gardens, while not occupying a large area, are deeper than permeable pavement and can store more stormwater underground.

4.3.5. Effects of sample regulations on smaller, frequent storms

All of the previous analyses were performed based on the large design storms of the cities (25- or 100-year storms shown in Table 2). For example, the design storm magnitude for Biloxi is 14.5 in, which is a 100-year 24-hour storm. However, by definition, cities mostly experience smaller, more frequent storm events known as 1-year and 2-year storms, or even smaller storms. For example, for Biloxi, the 1-year and

Table 5
Sample Regulation 2 peak flow results for the smaller, more frequent storm events.

City	Design Storm				1-Year Storm				2-Year storm			
	Magnitude (in)	Peak flow (cfs)			Magnitude (in)	Peak flow (cfs)			Magnitude (in)	Peak flow (cfs)		
		Pre-dev.	Post-dev.	Sample Regulation 2		Pre-dev.	Post-dev.	Sample Regulation 2		Pre-dev.	Post-dev.	Sample Regulation 2
Biloxi, MS	14.5	**34.75**[*]	54.02	45.08	4.93	7.00	17.17	**8.51**	5.84	9.44	20.73	**12.04**
Calhoun, GA	6.18	**14.10**	32.17	22.35	3.29	4.16	15.73	**5.83**	3.78	5.67	18.55	**8.62**
Orange Beach, AL	11.8	**18.54**	42.78	34.21	5.01	2.58	16.15	**7.76**	5.92	4.26	19.77	**11.20**
Oxford, MS	8.75	24.52	46.55	36.36	3.72	5.61	18.20	**10.35**	4.25	**7.36**	21.23	**13.17**
Ruston, LA	7.83	**25.27**	41.98	32.13	3.90	9.41	20.02	**10.33**	4.41	11.41	22.90	**13.07**
Sevierville, TN	4.66	9.81	16.92	8.36	2.31	**3.39**	7.73	**0.17**	2.75	4.54	9.47	**1.42**

[*] Bolded numbers are used for comparison along each row.

2-year 24-hr storms are 4.93 in (122 mm) and 5.84 in (148 mm), respectively. Therefore, additional simulations were performed to analyze how the sample regulation would perform for 1- and 2-year 24-hr storm events. This analysis was conducted based on the implementation of Sample Regulation 2. This regulation was selected because of its high performance on the design storm analysis. Since the area of the rain garden was fixed in the proposed regulation, the impermeable area draining into the rain garden was adjusted based on the magnitude of the 1- and 2-year storms applicable to each city. This adjustment was made in HydroCAD to use the available storage of the rain garden effectively for different storm magnitudes.

For 1- and 2-year storms, the simulation results showed that the percent reductions in the peak flows were greater than the reductions from the design storm scenarios (Table 5). For the 1-year storm, the highest peak flow reduction from the post-development scenario was 98%, and the lowest was 50%. The peaks were, on average, 69% higher than the pre-development peak. For the 2-year storm, the peak was less than the post-development peak by 51% on average, and it was higher than the pre-development by 67%. Just as occurred for the design storm analyses, Sevierville showed the highest reduction for both storm events, and the peak flows were less than the pre-development. Since every city had the same size rain garden for the simulation, the variation of the peak flows resulted from the difference in the magnitude of the storms and the soil groups.

5. Discussion

Cities with lower magnitude design storms and low permeability soils benefitted more from GSI. Rain gardens were more efficient than permeable pavement for reducing runoff.

Based on the results of the rainfall-runoff analysis for the sample regulations, cities benefited from GSI at different levels. For example, Sevierville and Calhoun had the greatest peak flow reductions in most cases, and Biloxi showed the least reductions. There was a 1% to 35% difference between the greatest and the least reductions, depending on the four sample regulations. Considering the different input variables, these differences result from the design storm magnitude and the hydrologic soil group variability. The hydrologic soil group of Sevierville is Group D, which has high runoff potential and relatively low infiltration rate and consists of clay soils. Even though soil Group D has high runoff potential, the runoff from Sevierville was the lowest for most of the scenarios. That is because the city has a less intense design storm, 4.66 in/hr (118.4 mm/hr). Calhoun and Biloxi's hydrologic soil group is Group B, which has a moderate infiltration rate and runoff potential. The only difference between these two cities was the design storm magnitude. Accordingly, similar to Sevierville, Calhoun showed a higher reduction in peak flow due to the city's less intense design storm magnitude compared with Biloxi. Therefore, based on this analysis, we can conclude that municipalities with lower magnitude design storms and low infiltration soils have the most to benefit from GSI and could benefit from ordinances requiring GSI.

Rain gardens were more effective at decreasing runoff than permeable pavements. Comparing the HydroCAD modeling results by sample regulations based on their average peak flow reduction, the highest reductions were shown with Sample Regulations 2 and 4 (both call for rain gardens), and the lowest with Sample Regulations 1 and 3. In general, installing a rain garden showed a greater reduction in peak flow than using permeable concrete over a greater area. For instance, for Sample Regulation 1, permeable concrete was used on an area of 7525 ft^2 (699 m^2), and for Sample Regulation 2, the rain garden was 4080 ft^2 (379 m^2). Despite the permeable concrete being applied to a larger area than for the rain garden, the runoff reduction from the rain garden was greater. Therefore, for this analysis, rain gardens are more effective at reducing post-development runoff than permeable pavement, even when applied to a smaller area.

Permeable concrete pavements showed a greater peak flow reduction when they covered a larger area. For instance, Sample Regulations 1 and 3 proposed implementing permeable pavements for sidewalks and parking areas. Permeable concrete pavement of 7525 ft^2 (699 m^2) and 22,070 ft^2 (2050 m^2) was used to implement Sample Regulations 1 and 3, respectively. The peak reductions under Sample Regulation 3 were higher than Sample Regulation 1 for all of the cities. But the reduction was not uniform due to the different storm magnitudes of each municipality. To reduce the same runoff volume, a larger surface area of permeable concrete is required for a high-intensity storm compared to a low-intensity storm. The most effective permeable pavement coverage design should be based on a range of storms that a particular city experiences (Abera et al., 2018). Therefore, municipalities should take their storm magnitude and the soil group into consideration to select and incorporate the more effective type of GSI in their ordinances.

The results of the HydroCAD modeling of the 1- and 2-year storms show that rain gardens per Sample Regulation 2 alone can infiltrate stormwater runoff from those storms without the need of other gray stormwater infrastructure. Table 5 shows these results for the cities' design storm and 1- and 2-year storms. Focusing first on the cities of Biloxi, Calhoun, Orange Beach, and Ruston, we see that the Sample Regulation 2 peak flows for the smaller storms are well below the pre-development peak flow for the design storms (which for Biloxi, for example, are 8.51 and 12.04 cfs for the 1- and 2-year storms, respectively, compared to 34.75 cfs for the design storm). Additionally, Sample Regulation 2 succeeds in Sevierville, which requires a stormwater outlet structure to control a 1-year storm, in addition to the design storm; Sample Regulation 2 peak flows for 1- and 2-year storms (0.17 and 1.42 cfs) are within the 1-year pre-development requirement of 3.39 cfs. However, Sample Regulation 2 does not meet Oxford's requirements to control a 2-year storm, in addition to the design storm; Sample Regulation 2 peak flows for the 1- and 2-year storms in Oxford (10.35 and 13.17 cfs, respectively) exceed that city's 2-year pre-development limit of 7.36 cfs. These results show that while GSI might not alone meet runoff requirements for the extreme design storms, GSI can comfortably meet the runoff requirements for 1- and 2-year storms for most cities.

GSI is just one element of controlling stormwater flow. Even though Sample Regulation 2 showed the highest peak flow reduction, the resulting peak flow for the design storm was higher than the pre-development for all of the cities, except Sevierville. This result shows that GSI must be combined with other stormwater gray infrastructure, such as detention/retention facilities, to meet the pre-development peak flow requirement. Using GSI will allow smaller detention facilities to be employed than without GSI. This will reduce the construction and installation costs, wear and tear, and maintenance on those gray stormwater structures, as well as offer the ecological benefits of mimicking the natural hydrologic cycle.

6. Conclusions and recommendations

This paper addressed four objectives. It first examined how municipal ordinances may help or hinder the implementation of GSI. A review of the ordinances from six cities found that they do not require, though some encourage, GSI. The second objective was to quantify the runoff due to design storms set by city ordinances. The third objective was to suggest regulations encouraging GSI implementation to reduce runoff. This objective was achieved by developing four sample regulations. The fourth objective was to quantify the runoff reduction based on the sample regulations. This objective was met by conducting rainfall-runoff, implementing the sample regulations on the study site, and then comparing them.

Overall, based on the simulation results for different scenarios, it can be understood that requiring GSI in municipal ordinances can reduce peak runoff from a development site. For both the design storm and more frequent storm analyses, the runoff peaks were reduced after implementing the GSI on the proposed study site in the different cities. Even though the reductions varied from city to city due to the magnitude differences of the storms (design, 1-year, and 2-year) and the soil groups, the HydroCAD modeling for all of the municipalities showed a reduction in the runoff peak flow when GSI was applied.

General conclusions include: (1) municipalities with lower magnitude design storms and low infiltration soils have the most to benefit from GSI and could benefit from ordinances requiring GSI; (2) rain gardens were more effective at decreasing runoff than permeable pavements; (3) for 1- and 2-year storms, GSI alone can meet the pre-development design storm peak flow requirements in many cases; and (4) GSI must be complemented by gray infrastructure to control storms of higher magnitudes.

Based on these conclusions, we offer the following recommendations:

- Most of the GSI-like terms found in the municipal ordinances are recommendations rather than requirements. Therefore, implementing GSI is at the developer's discretion. Likely the recommendations will be implemented only if the developer wants to benefit from some of the incentives, for instance, to gain some points for LEED certification, or have a reduced permit fee. Therefore, municipalities should require GSI regulations to maximize runoff reduction while gaining environmental benefits.
- Municipalities should consider the hydrologic soil group of the site and the design storm magnitude when deciding on the size and type of the GSI. Our study showed the same site plan and regulations will yield different results due to soil types.
- When applied to the same area, rain gardens offer a greater runoff reduction than permeable pavements, making them useful when size is limited on a site.
- Overall, incorporating GSI in municipalities' regulations showed a reduction in peak flow of runoff. Therefore, municipalities have the potential to reduce local flooding by designing GSI in their new developments or retrofits.

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