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Retrofitting urban land through integrative, subsoils-based planning of green stormwater infrastructure: a research framework

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Abstract

We present a research framework that integrates native subsoil performance and surface retrofitting into coordinated green stormwater infrastructure (GSI) planning. This framework provides communities a strategy to move beyond opportunistic GSI, which can be limited to capturing marginal amounts of stormwater, toward more impactful, coordinated GSI planning that restores the lost hydrologic functioning of the pre-development landscape. We create this framework by establishing critical performance-based relationships among four variables: (1) saturated hydraulic conductivity of native subsoils ($\sim$upper 2 m below urban compaction and fill); (2) GSI design depth for both rain gardens and permeable pavement (in increments of 6″ from 12–30″ for planted and paved GSI); (3) loading ratio, defined as the ratio of GSI retrofit area to upstream impervious surface runoff area (from 1:2 to 1:5 for planted GSI; and 1:1 and direct infiltration for paved GSI); and (4) design storms (rainfall quantity up to 5-inches over 2 h and 24 h durations). We model the four variables using GSI models (built in the US Environmental Protection Agency's Storm Water Management Model) and reliability analysis, a risk-assessment method adapted to characterize the reliability of GSI in response to varying stormwater runoff loading. The outcome of the modeling is a set of fragility curves and design prototypes, adjustable to catchment and sub-catchment scales, to assist municipalities in early funding and investment decisions to retrofit urbanized land through GSI. We also share two piloted applications in which we use the research framework within the Chicago-Calumet region in Illinois, USA, to conduct site-specific subsoil sampling and determinations of saturated hydraulic conductivity and to develop urban-scale GSI retrofit scenarios. Our framework is transferable to other urban regions, and particularly useful where a lack of integrating native subsoil performance into GSI design hinders decision-making, coordinated GSI planning at scale, and achieving high runoff reduction targets.

1. Introduction

Chronic urban flooding plagues cities globally as population areas confront climate impacts due to changing rainfall intensity and under-capacity gray infrastructure (Gill *et al* 2007, Zhou 2014 and Rosenzweig *et al* 2018). Green stormwater infrastructure (GSI), vegetated or permeable surfaces designed to infiltrate, treat, and store

runoff, has been increasingly adopted as a means of augmenting under-capacity traditional gray stormwater infrastructure systems. Flooding made worse by rapid runoff can be attenuated by replacing imperviousness and compaction with distributed GSI in urban areas (Novotny *et al* 2010, Voskamp and Van de Ven 2015, Zellner *et al* 2016, Meerow and Newell 2017, Meerow 2019 and Li *et al* 2020). Yet, for more effective GSI planning and design to take place, we need better knowledge of native subsoils and their geologic context, in addition to understanding anthropogenic modifications of surface soils. This information is especially important in urban contexts where the spatial variability in soil properties has not been fully considered in resilient stormwater planning and land management decisions (Schindelbeck *et al* 2008, Dominati *et al* 2010 and Blanchart *et al* 2018). Understanding soils as a resource for ecosystem services function counters the typical consideration of soils in an urban context as simply a surface to be developed or exploited (Blanchart *et al* 2019).

Both the lack of native subsoils characterization and integration of these soils data into GSI research modeling frameworks are recognized barriers to advancing stormwater infrastructure design and planning, creating poor GSI performance predictive capability for commonly-used stormwater management tools and models when applied to urban areas (Morel *et al* 2014). GSI planners typically use low resolution soils data that do not adequately characterize variability; consequently, GSI plans are often poorly sited, have suboptimal performance, and miss potential opportunities for disinvested urban communities (Schifman and Shuster 2019). Addressing this soils data gap and integrating surficial soils and geological characterizations early into stormwater planning is critical to more effective GSI planning and design.
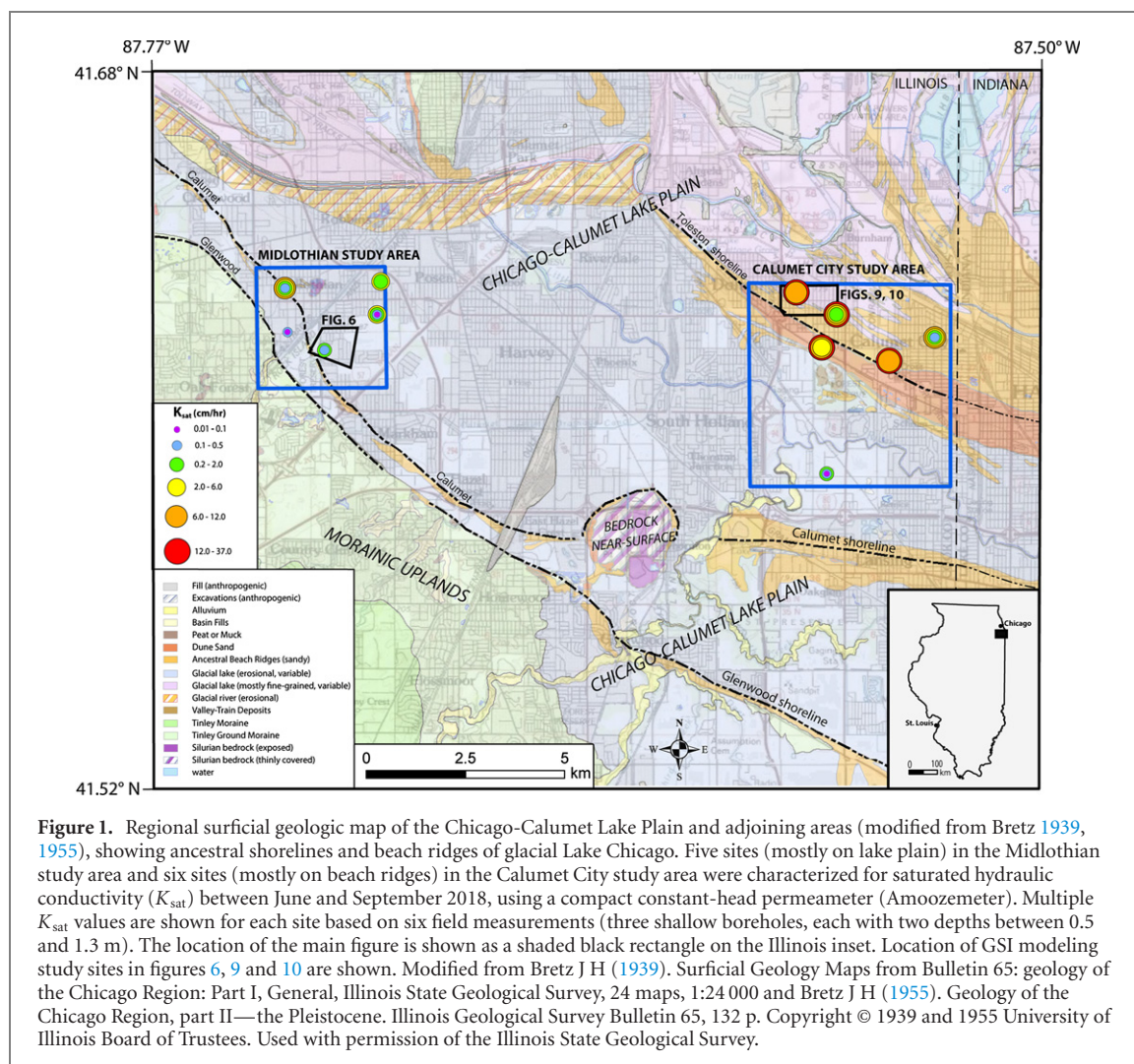
To address this knowledge gap, we present a research framework for urban communities to integrate local subsoil information into GSI planning to meet high runoff reduction targets that can alleviate flooding as well as supplement shortfalls in existing gray infrastructure. Gray infrastructure, which consists of a combination of drain inlets, pipes, tunnels, reservoirs, and/or treatment systems (in combined-sewer contexts), is aging and under-capacity in the United States (American Society of Civil Engineers 2021). Notably, in the study area for this research, the regional Tunnel and Reservoir Plan to collect stormwater is known to be under-capacity for larger storms even after the structure's anticipated completion in 2029. Increasing rain intensity from climate change is exacerbating pressure for alternatives to gray infrastructure (Grabar 2019). In addition to stormwater capture and infiltration functionality, GSI alternatives have become priorities for communities to reduce imperviousness and urban heat island effects, and to improve human health. Yet, better subsoils data and integration of that knowledge into GSI design is needed for effective planning and implementation (Calumet Stormwater Collaborative 2021 and Center for Neighborhood Technology 2013).

In response, we emphasize that the hydrogeological context of urban areas and its associated soils variability provides important knowledge that can advance GSI design in urban areas. Municipalities can use data about the variability of regional subsoils to optimize the performance of GSI within urbanized landscape contexts.

A key premise of our research framework is that coordinated GSI using native subsoils data as a design foundation is a better investment than opportunistic GSI (Golden and Hoghooghi 2018). Opportunistic GSI refers to small-scale, piecemeal implementation based on factors of convenience such as land availability, cyclic funding, and fragmented efforts by multiple organizations. We define coordinated GSI as interdisciplinary planning at multiple spatial scales that leverages the ecological functioning of the landscape, while working alongside municipal partners through the 'participatory, inclusive approach' toward GSI planning suggested by Schifman *et al* (2017). Moreover, strategic placement and design of GSI early in the planning process supports proof-of-concept and funding applications.

Our specific research questions include: (1) How do native subsoils impact or enhance runoff reduction of GSI, especially in response to increased storm intensity?; (2) Can prototype strategies improve GSI siting and sizing by better correlating design and non-design variables?; (3) How do design variables and predictive performance outcomes facilitate neighborhood-scale stormwater planning?; (4) What are the implications for planning and policy to adequately manage larger storms under climate change?

Our research focuses directly on the first three questions, and we explore the fourth question in the discussion section. We first present the regional, climate, and institutional contexts of the study area and the development of the GSI research framework. We then describe the variables integrated into the design and modeling process. Based on our research and modeling, we then discuss the application of the framework to two neighborhoods in collaboration with municipal partners, and we share the results of that application. Finally, we reflect on additional outcomes and implications from this research, including the applicability to regions outside the study region, and conclude with the potential for this research to innovate local and regional stormwater regulation in broad contexts.

Figure 1. Regional surficial geologic map of the Chicago-Calumet Lake Plain and adjoining areas (modified from Bretz 1939, 1955), showing ancestral shorelines and beach ridges of glacial Lake Chicago. Five sites (mostly on lake plain) in the Midlothian study area and six sites (mostly on beach ridges) in the Calumet City study area were characterized for saturated hydraulic conductivity (K_{sat}) between June and September 2018, using a compact constant-head permeameter (Amoozemeter). Multiple K_{sat} values are shown for each site based on six field measurements (three shallow boreholes, each with two depths between 0.5 and 1.3 m). The location of the main figure is shown as a shaded black rectangle on the Illinois inset. Location of GSI modeling study sites in figures 6, 9 and 10 are shown. Modified from Bretz J H (1939). Surficial Geology Maps from Bulletin 65: geology of the Chicago Region: Part I, General, Illinois State Geological Survey, 24 maps, 1:24 000 and Bretz J H (1955). Geology of the Chicago Region, part II—the Pleistocene. Illinois Geological Survey Bulletin 65, 132 p. Copyright © 1939 and 1955 University of Illinois Board of Trustees. Used with permission of the Illinois State Geological Survey.

2. Background

2.1. Study area: hydrogeological setting

The study site for this research is the Chicago-Calumet region (CCR), located within the Chicago-Calumet lake plain of the south Chicago region, USA (figure 1; Chrzastowski and Thompson 1994). This low-relief plain contains a rich variety of surficial soil profiles, formed in glacial to postglacial sediments, which are conducive to a range of stormwater absorption and infiltration, making this a suitable region to consider GSI retrofits of urban land.

Glacial ice was last in the CCR area about 16 000 years ago, when the Lake Michigan Lobe receded back into the Lake Michigan Basin (Curry *et al* 2011, 2020). During deglaciation, glacial Lake Chicago, a precursor to Lake Michigan, was temporarily impounded by the Tinley and Valparaiso moraines to the southwest and blocked by receding glacial ice. This condition resulted in the accumulation of fine-grained glacial lake deposits (silt, clay, and fine sand) on the lake plain (Chicago-Calumet lake plain) interspersed with sandy beach ridges (shorelines), sand dunes, fine-grained glacial till, and bedrock knobs (Bretz 1955 and Willman 1971). Thus, there is considerable lithologic heterogeneity in the study region area (figure 1), and the intercalated sandy sediments offer particular opportunities for GSI.

Within the present-day Chicago-Calumet lake plain, there are three notable beach ridges representing former shorelines of glacial Lake Chicago (Bretz 1939 and 1955). These shorelines are named the Glenwood, Calumet, and Toleston beach ridges (figure 1), with approximate calibrated radiocarbon ages of 16 000, 13 000 and 5000 years old, respectively (Chrzastowski and Thompson 1994, Curry *et al* 2018 and Curry *et al* 2020). These ancestral shorelines, predominantly sandy beach ridges, are around 0.5 km wide and extend for several km or more in arcs that parallel the modern-day shoreline (figure 1). Kay *et al* (1996, 1997) mapped type, age, and thickness of fill in the Lake Calumet area and constructed a synoptic map of the water table surface. The water table fluctuates seasonally, but typical mean annual depths in the Chicago-Calumet lake plain are in the

1 m (hydric soils) to 3 m (beach ridges) range. Hydrological conditions can vary considerably on a local level due to both natural variations in landform-sediment associations (such as ridge-swale complexes), as well as anthropogenic modifications of topography and substrate material.

2.2. Study area: background and planning context

Within this rich hydrogeological context, the modern, urban surface of the CCR is characterized by medium to high density urban land uses. The urban land itself is characterized by high percentages of imperviousness. Street flooding, sewage-laden basement backups, and combined sewer overflows into the Chicago River waterway system occur due to the imperviousness, under-capacity gray infrastructure, and low-relief topography. Dozens of communities struggle to address the continued stress and damage of urban flooding, with low-income and Black and Latinx communities affected disproportionately (Hawthorne and Greene 2019 and Knighton *et al* 2021). In spite of US Department of Housing and Urban Development (HUD) Community Development Block Grant—Disaster Recovery assistance program (CDBG-DR) and well-intended planning strategies in the region, GSI-at-scale has yet to be implemented due to lack of a comprehensive regional plan and associated research modeling to guide adoption of GSI in a coordinated manner.

A key planning strategy contained in the CDBG-DR funding work plan is the 'retrofit' of the urban conditions of high-percentages of pavement and soil compaction including altered native intermediate horizon soils that support ecosystem functionality (Herrmann *et al* 2018). Indeed, the consequences of soil sealing through urban imperviousness, for example, on hydrology and ecosystem function are complex and negative (Lee and Heaney 2003, Scalenghe and Marsan 2009, Wu and Thompson 2013 and Timm *et al* 2018).

Scaled distribution of GSI, such as surface retrofit recommendations, is a critical research concern to make the greatest impact to flooding and watershed issues (Versini *et al* 2017, McGuire 2018 and Epps and Hathaway 2019). Municipalities need tools to determine where and how much retrofitted GSI to construct based on situational flooding and runoff reduction targets. This information is particularly important in the context of stormwater regulation in our study area within Cook County. Currently, volume control and detention practices are minimal, requiring only 1-inch of stormwater capture from impervious surfaces, which only applies to new construction. Higher standards and stricter regulations are needed in the region to adapt communities to climate change, including retrofitting existing conditions that create urban flooding. Further, the Calumet Stormwater Collaborative, a consortium of public, private, and institutional partners who coordinate to advance stormwater planning in the region, specifically identified a gap in soils data as a critical barrier and high priority to developing more effective GSI in the region.

In response to this dual need for hydrogeological soils investigation and strategies for retrofitting urban land, an adaptable design method that leverages technical soils data to guide GSI retrofit design-decisions is needed. But beyond the technical role that native subsoils have in GSI evaluation, the geologic origins of those regional subsoils development is equally important to the design study, since a consideration of the role of land is often absent in stormwater planning, especially in highly urbanized contexts such as the CCR.

An important outcome of our research is a strategy to adapt soils-based GSI design to benefit other regions with heterogeneous soils and complex urbanized conditions that exacerbate flooding. The framework should inform solutions based on a subset of variables impacting GSI hydrological performance that can be strategically adapted to meet both opportunities and constraints of soil type, climate intensity, and urban-spatial conditions of potential implementation sites. With this methodological intention, the framework can be applied beyond the Calumet region, to Laurentian Great Lakes coastal communities and to urbanized coastal regions worldwide, many of which also consist of low relief landscapes constructed in ancient coastal settings.

3. Methods

3.1. Soils data, sampling, descriptions, and particle size analyses

Pre-existing water-well and engineering boring logs in southern Cook County (from Illinois State Geological Survey (ISGS) archives) were compiled into a database. Site-specific data were overlaid with LiDAR surface elevation maps (Illinois Height Modernization Program 2002–2016) and US Department of Agriculture (USDA)—Natural Resources Conservation Service (NRCS) soil survey parent material maps (Sol Survey Staff 2018) in a geographic information system dataset. Two study areas were selected in the Chicago-Calumet lake plain, with contrasting native subsoils: (1) the Village of Midlothian, with predominantly fine-grained soils, and (2) the Calumet City area, with predominantly sandy soils (in Toleston beach ridge). We selected five to seven sites in each study area to characterize the range of soil types, *in situ* hydrologic properties, and soil variability within the field areas (figure 1). The study sites were chosen to be representative of soil types in the region (fine sand to loam to silty clay), with most sites at public parks or school grounds because of accessibility.

At each site, one hand auger or shallow test core made to a depth of 1.3 to 2.0 m provided geologic context (tables S1 and S2 (https://stacks.iop.org/ERIS/1/035003/mmedia)). Soil horizon boundaries were determined in the field; samples were then described in more detail in the laboratory using standard USDA textural classifications (Schoeneberger *et al* 2012). Descriptive boring logs were entered into an ISGS database and are accessible via the ILWATER web viewer (http://isgs.illinois.edu/ilwater). For two of eleven sites, soil cores were obtained with a truck-mounted hydraulic push probe, in collaboration with the USDA-NRCS.

Subsamples from hand augers and cores were collected in the field in aluminum canisters for their natural water content determinants; these samples were subsequently used for particle size analysis. Between four and nine vertically-spaced subsamples were acquired for these analyses at each site, including at the depths of the two saturated hydraulic conductivity (K_{sat}) measurements. Water contents were determined by comparing sample weights when wet and after drying in an oven overnight at 110 °C.

Particle size fractions were analyzed at the Illinois State Water Survey by wet sieve (sand fractions) and hydrometer methods (fine fractions). The sand fraction includes particle sizes between 0.063 and 2.0 mm, the silt fraction includes 0.002 to 0.063 mm, and the clay fraction <0.002 mm. The particle size and water content data are provided in supplemental files (tables S3 and S4).

3.2. Saturated hydraulic conductivity measurements

Saturated hydraulic conductivity, K_{sat}, is a function of soil texture, structure, morphology, density, horizonation, porosity, and organic carbon content (McKenzie and Jacquier 1997 and Jarvis *et al* 2013). Field-based K_{sat} values can be affected by background soil moisture, anthropogenic soil compaction, fill material, vegetation, and land-use. Local effects can also include the presence of earthworms, insects, burrowing animals, and tree roots. Seasonal effects include the depth to water table and *in situ* soil moisture conditions. In this study, portable Amoozemeters (compact constant-head permeameters) were used to measure K_{sat} (Amoozegar 1989) in a variety of soil types. Seven sites in the Calumet City study area and five sites in the Midlothian study area were characterized in the field between June and September 2018. In this field-based method (Amoozegar 1989), a constant water height in a shallow hole within the soil vadose zone is maintained while measuring the volume of water lost to the soil. At each site, two K_{sat} measurements were collected from the subsoil in each of the three hand-augered holes, spaced about 1.5 m apart and extending to depths of 1.25–2.0 m. Data were collected from two depths between 0.5 and 1.3 m, generally within the B, BC, or upper C soil horizon (table S5), and above the observed water table. The A horizon (topsoil), generally in the upper 0.2 to 0.3 m, was not measured for K_{sat} as this horizon is typically disturbed and this material would likely be removed in any future GSI project. The K_{sat} values were calculated using a USDA-NRCS spreadsheet (based on Amoozegar 1989). Key input parameters were hole diameter (6 cm), height of water maintained in the hole (15 cm), water tank volume, and the steady-state rate of water level drop. The calculated K_{sat} values were compared with soil textural data to examine relationships between these variables (tables S5 and S6).

3.3. Multi-variable GSI design model

For modeling clarity, our approach categorized the range of GSI configurations into two types: planted and paved. Planted GSI refers to any depressed, vegetated GSI that is designed to infiltrate, treat, and store runoff into subsoils and/or a subsurface aggregate layer before discharging the overflow downstream. In this definition, we do not include GSI practices such as treatment wetlands that are designed to maintain standing water onsite, or GSI such as bioswales that are typically used to treat and convey water away from a site. Common planted GSIs include bio-infiltration cells and rain gardens, which we model in our analysis. Paved GSI refers to surfaces that are paved rather than vegetated but are still intended to rapidly infiltrate water through the pavement layer into the subsurface aggregate layer for storage. Paved GSI in our analysis includes permeable pavers, porous asphalt, and porous concrete.

Our conceptual research approach to increase predictive GSI effectiveness investigates the performance relationship among four interrelated variables: (1) infiltration rates of native subsoils, (2) design depths of GSI installations for both paved and planted GSI, (3) site loading ratios, and (4) design storms (figure 2). While many variables can potentially impact GSI performance, these four variables are selected due to their pivotal role in informing coordinated GSI design-decisions and planning at scale, as well as their alignment with the research objectives as determined by knowledge gaps identified by stormwater planning stakeholders. Specific considerations include the potential of native subsoils knowledge to enhance GSI functioning at scale; the resulting design-decisions regarding depth-to-site loading ratio tradeoffs necessary for achieving coordinated GSI design at scale; and providing insights into how these relationships can help to achieve higher runoff reduction targets in the face of increasing rain intensity.

The first relationship is between the GSI surface retrofit and underlying native subsoils: rain interactions such as infiltration happen through the GSI surface medium, composed of either a planted layer or a paved layer (e.g., permeable pavers over open-graded stone), that overlies native subsoils. The physical depths of both
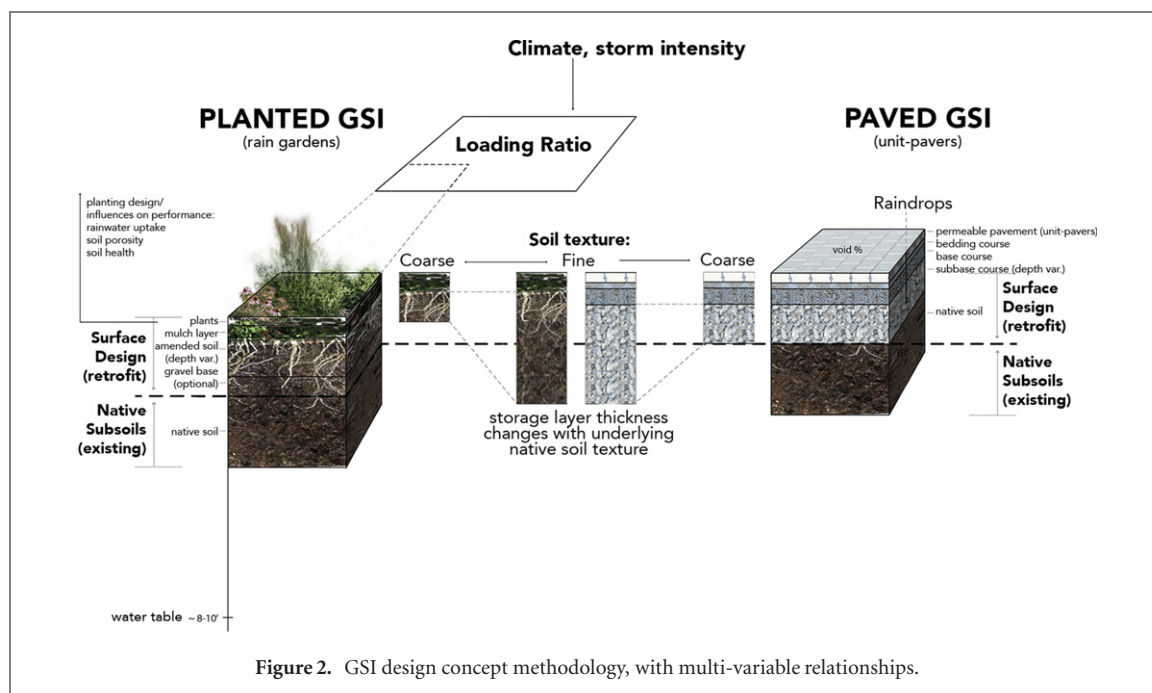
Figure 2. GSI design concept methodology, with multi-variable relationships.

planted and paved GSI are variable depending on the desired performance. In this research, GSI storage thickness, which varies depending on desired performance, is modeled at depths of 12″, 18″, 24″, and 30″. In the south Chicago region, these depths generally correspond to a zone within the native soil B horizon (or subsoil; table S2), except in areas that are highly disturbed or have excessively thick A horizons. We model these depth variations in coordination with saturated hydraulic conductivity measurements for underlying native subsoils (described in section 4.1) at depths of 20″ to 50″ (B or upper C horizon). The minimum GSI storage thickness of 12″ was selected to allow infiltration and storage of runoff during large magnitude, short duration rainfall events. The 12″ depth reflects industry standard minimum aggregate for depths for surfaces that experience potential vehicular loadings in the case of paved GSI. We increase the depths by 6″ increments to evaluate the additional volume control potential in larger storms.

The second relationship is between the GSI surface retrofit and the upstream impervious area, representing the loading ratio: the loading ratio is defined as a ratio of GSI surface area to the upstream impervious surface area flowing to the GSI (e.g., a 10 ft^2 upstream impervious area flowing to a 5 ft^2 rain garden would have a 1:2 loading ratio). A key GSI design goal is to minimize runoff and maximize rain infiltration, storage, and evapotranspiration by siting and/or distributing GSI upstream in the catchment rather than as downstream solutions only. Loading ratios of 1:2, 1:3, and 1:5 were used for the planted GSI type, and ratios of 1:1 and direct infiltration (with no upstream impervious area) were used for the permeable paved GSI type, based on maintenance recommendations (Clary and Piza 2017, Pennsylvania Department of Environmental Protection 2006 and Minnesota Pollution Control Agency 2021).

The third relationship is between the GSI retrofit and the design storms: in addition to the variables of underlying subsoils and loading ratio, the GSI retrofit can also be adjusted (in vertical and horizontal dimensions) for climate variability, represented as rainfall measured in inches over different storm event durations. We used rainfalls of 1″, 2″, 3″, 4″, and 5″, modeled as triangular hyetographs (Yen and Chow 1980), in events with durations of 2 h and 24 h as typical design storms for the region, based on a severe storm in April 2013 during which 7″ of rain fell across the region with 5″ in the final 24 h period. The storm serves as a reference event for the issue of failing stormwater infrastructure in the face of increasing rainfall intensity across the region (Hawthorne and Greene 2019).

3.4. Green stormwater infrastructure hydrologic modeling

GSI performance was represented using reliability as a quantitative metric, ranging from 0 to 1, indicating the probability of reducing runoff by a given reduction standard, when compared to an impervious surface of the same area (William and Stillwell 2017, William, *et al* 2019a and William *et al* 2019b). Reliability is the complement of the probability of GSI failure (Pf): reliability $= 1 - Pf$. Here we designate simulated runoff volume from the GSI installations in response to different rainfall conditions, r, as V_{GSI}, with corresponding

runoff volume from an impervious surface of identical size as $V_{\text{impervious}}$, such that

$$\text{reliability} = 1 - Pf = 1 - P\left(\alpha V_{\text{impervious}} - V_{\text{GSI}} < 0 | r\right) \tag{1}$$

where α is a parameter representing the fraction of runoff in relation to the reduction standard (William *et al* 2019a). For the selected 80% reduction standard[6], $\alpha = 1 - 0.8 = 0.2$, as the remaining runoff. Rainfall conditions, r, are simulated for two storm durations (2 h and 24 h) for precipitation ranging from 0 to 5 inches. Use of a design storm approach for sizing GSI is consistent with prior literature (Sadeghi *et al* 2018).

We simulate GSI hydrologic functionality via calibrated models created using the US Environmental Protection Agency's Storm Water Management Model (EPA-SWMM) (US Environmental Protection Agency 2020). These EPA-SWMM models represent both the planted (e.g., rain gardens) and permeable paved surfaces of GSI installations. In the planted GSI models, we represent rain gardens using the EPA-SWMM low-impact development module as two subcatchments: one representing the upstream impermeable area and one as a bioretention cell. We calibrated the bioretention cell model variables, including GSI thickness, porosity, hydraulic conductivity, seepage rate, and void ratio (reported in William *et al* (2019a), reproduced in the supporting information), based on observed runoff data from instrumented GSI sites in the Midwest United States (Selbig 2018). Complete details on the planted GSI model are reported in William *et al* (2019a). The planted GSI model includes loading ratios of 1:2, 1:3, and 1:5 to represent a range of surface conditions with moderate maintenance to prevent clogging (William *et al* 2019a).

In our paved GSI model, we similarly represent permeable pavement in the EPA-SWMM low-impact development module as continuous permeable pavement systems. Using data from installed and monitored permeable pavement (Bailey 2018), we adjust the paved GSI model parameters (storage layer thickness, seepage rate, initial saturated soil fraction, and drain offset height (only present in the fine soils)) to represent runoff conditions in response to rainfall observed in the monitored installation. We did not change the parameters for the pavement layer (i.e., the infiltration rate through the permeable pavers, porous concrete media, etc) in EPA-SWMM since our focus is on the role of native subsoils, more than the pavement design itself. Using the same rainfall conditions, r, for the planted GSI model, we simulate the runoff from the paved GSI model, in response to different storm conditions, representing a range of extreme events over both 2 h and 24 h storm durations. The paved GSI model included loading ratios of 1:1 and direct infiltration (with no upstream impervious area) only to limit the risk of clogging from additional runoff from upstream impervious surfaces and alleviate stakeholder concerns about maintenance expense; however, some studies demonstrate that permeable pavement can have reasonable hydrologic performance with larger upstream impervious areas (Winston *et al* 2018).
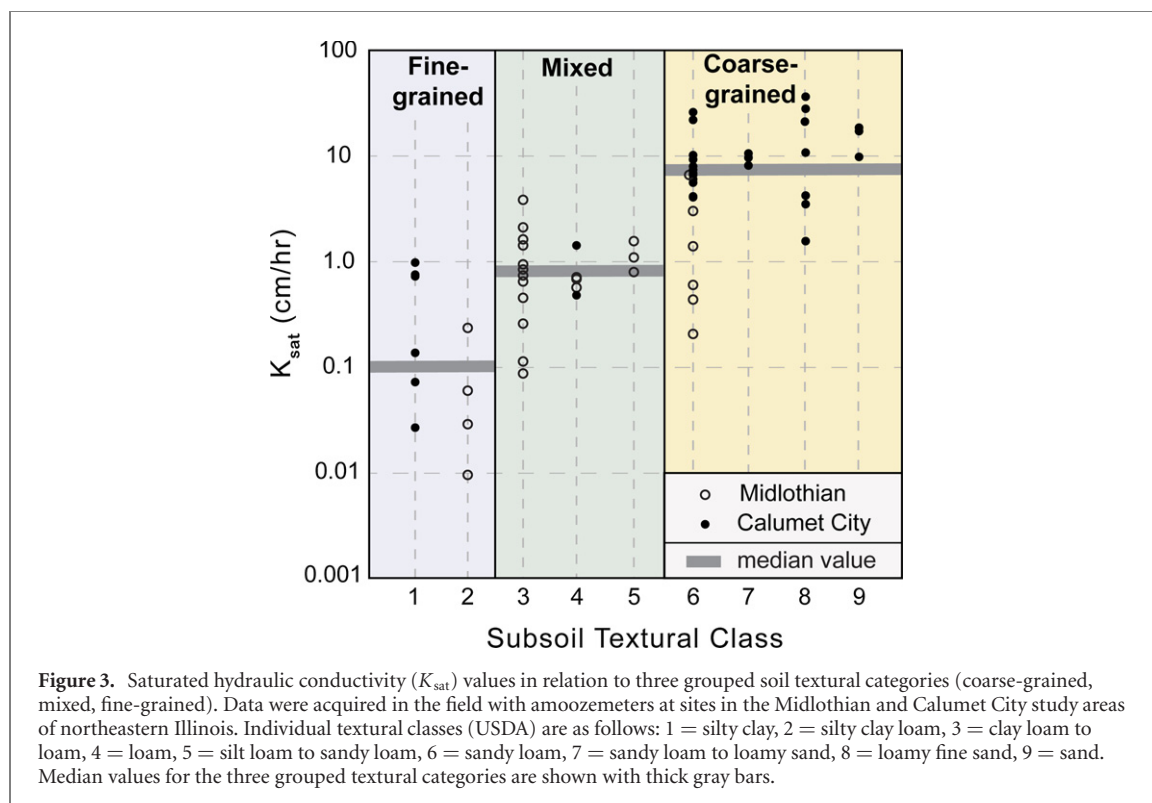
4. Results

4.1. Particle size and saturated hydraulic conductivity of subsoil

Based on statistical analyses of the 12 sites in the Midlothian and Calumet City study areas (figure 1), as well as practical considerations, we group several soil textural types into three general categories (figure 3): coarse-grained (sand, loamy sand, and sandy loam textures), mixed (loamy to clay loam textures), and fine-grained (silty clay loam to silty clay textures). The coarse-grained, mixed, and fine-grained subsoil texture categories have sand contents of about 75%–95%, 30%–65%, and 5%–30%, respectively, and $<2~\mu$m clay content of 30%–50%, 20%–28%, and 4%–11%, respectively (table S3).

The calculated K_{sat} values have a strong relationship with the generalized soil texture classes, although texture alone does not fully explain subsoil K_{sat} variability. T-tests confirmed significant differences in K_{sat} distributions between the three textural categories. The mean K_{sat} values of the fine-grained, mixed, and coarse-grained soil categories are 0.27 ± 0.26 cm h^{-1} ($n = 10$), 1.1 ± 0.6 cm h^{-1} ($n = 21$), and 13 ± 7 cm h^{-1} ($n = 31$), respectively (figure 3, table S6). Although half of our dataset consist of coarse-grained soils (mainly on the Toleston beach ridge of Calumet City), most locations in southern Cook County (glacial Lake Chicago plain) are fine-to mixed-grained in the upper 2 m (Bretz 1955 and Soil Survey Staff 2018). Both study areas include a range of soil types, but coarse-grained (sandy) soils and surficial sediments are more widespread in the Calumet City region compared to Midlothian. Higher K_{sat} values occur generally within beach ridges, whereas the low K_{sat} values occur in clayey soils of the glacial lake bottom. The three soil texture groupings are

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[6] In November 2018, the research team met with a policy leader at the Metropolitan Planning Council (MPC) to discuss the regulatory environment and our model aiming for an 80% runoff reduction. We established the target of 80% to maximize runoff reduction for long-term resilient green stormwater infrastructure design and planning in the region mimicking a pre-urbanization performance ratio. He agreed with our research approach given the need for higher standards and stricter policy recommendations to advance green stormwater infrastructure practices throughout the region.

Figure 3. Saturated hydraulic conductivity (K_{sat}) values in relation to three grouped soil textural categories (coarse-grained, mixed, fine-grained). Data were acquired in the field with amoozemeters at sites in the Midlothian and Calumet City study areas of northeastern Illinois. Individual textural classes (USDA) are as follows: 1 = silty clay, 2 = silty clay loam, 3 = clay loam to loam, 4 = loam, 5 = silt loam to sandy loam, 6 = sandy loam, 7 = sandy loam to loamy sand, 8 = loamy fine sand, 9 = sand. Median values for the three grouped textural categories are shown with thick gray bars.

also mapped in detail within the study areas so that K_{sat} mean values can be extrapolated from here to other parts of the Chicago-Calumet Lake Plain region.

4.2. Fragility curves

We visualize the runoff reduction performance results for different GSI design depths through fragility curves, shown in figure 4 representing reliability as a function of rainfall for the design storm duration, native subsoil type, and loading ratio conditions. Fragility curves are useful for communicating the probabilistic functionality of infrastructure in response to varying input conditions (William and Stillwell 2017, Bai *et al* 2009, Stewart 2012 and Sayers *et al* 2012), conveying multiple GSI design parameters together in different sets of curves. We include our field-collected soils data in the creation of the fragility curves to represent saturated hydraulic conductivity variability. Using probabilistic reliability analysis techniques and Monte Carlo simulations (based on William *et al* 2019a and William *et al* 2019b), we quantify reliability (as $1 - Pf$) reflecting simulated rainfall inputs and runoff from both paved and planted GSI surfaces.

In the fragility curve results depicted in figure 4, each panel (a)–(d) represents different scenarios for the planted and paved GSI under 2 h and 24 h duration rainfall design storms, with varying amounts of rainfall depicted on the horizontal axes. The columns within each panel represent the native subsoil categories from figure 3, reflecting our field-collected soils data. The rows within each panel reflect different loading ratios as design conditions that could be varied within the study surface. For each combination of loading ratio and native subsoil category, we visualize the hydrologic performance of GSI as reliability (shown on the vertical axes) of achieving an 80% runoff reduction standard, with different line styles corresponding to different GSI design depths.

The fragility curves in figures 4(b) and (d) show that the reliability of achieving an 80% runoff reduction standard over a 24 h duration storm is high for both planted and paved GSI, whereas the reliability of achieving an 80% runoff reduction target for rainfall over a 2 h duration (figures 4(a) and (c)) is also promising but more variable, depending on subsoil type and loading ratio. For the 24 h duration storms, our fragility curve results show near 100% reliability (represented as 1.0 on the vertical axes of figure 4) for all of the loading ratio and native subsoil conditions with simulated storms up to 5″, achieving the 80% runoff reduction standard. The simulated 2 h duration storms, however, have less reliable runoff reduction performance with increasing rainfall, shown in the curved lines in figures 4(a) and (c). Loading ratio, native subsoil category (reflecting different K_{sat} values), and GSI design depth or storage thickness (indicated with different line styles in figure 4) affect runoff reduction performance in both the planted and paved GSI. For a given native subsoil, greater reliability in achieving an 80% runoff reduction standard is possible by reducing the loading ratio (e.g., from 1:5 to 1:2) and/or increasing the GSI design depth or storage thickness (e.g., from 12 in to 30 in).
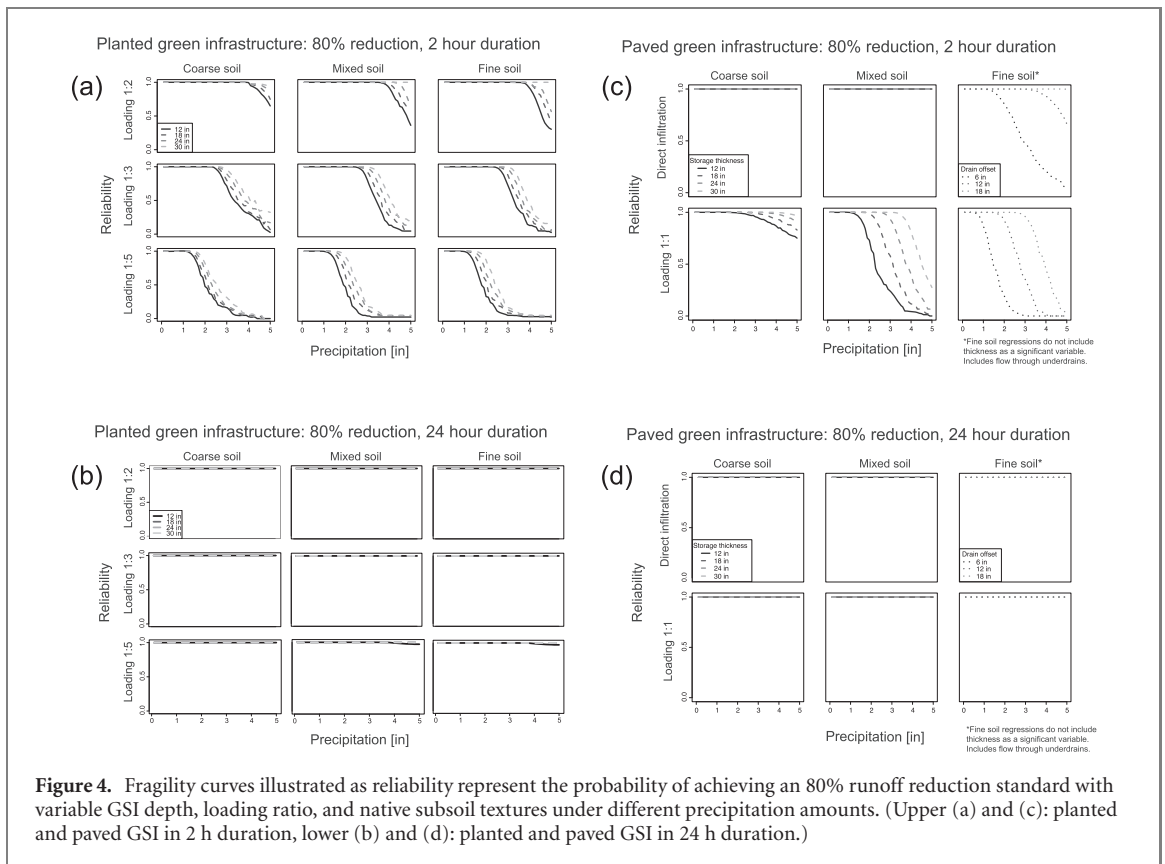
Figure 4. Fragility curves illustrated as reliability represent the probability of achieving an 80% runoff reduction standard with variable GSI depth, loading ratio, and native subsoil textures under different precipitation amounts. (Upper (a) and (c): planted and paved GSI in 2 h duration, lower (b) and (d): planted and paved GSI in 24 h duration.)
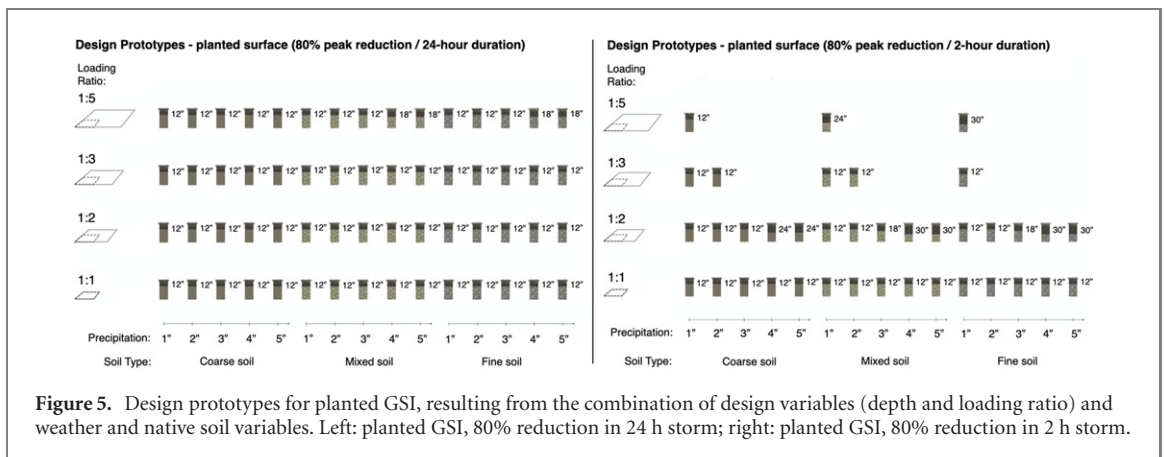

Figure 5. Design prototypes for planted GSI, resulting from the combination of design variables (depth and loading ratio) and weather and native soil variables. Left: planted GSI, 80% reduction in 24 h storm; right: planted GSI, 80% reduction in 2 h storm.

4.3. Layer cake design prototypes

The modeling results shown in the fragility curves (figure 4) are expressed through GSI prototypes we term 'layer cakes' for both paved and planted GSI (figure 5). The prototypes represent a range of possible GSI surface designs in response to the related parameters of native subsoil type and K_{sat} values, loading ratios, and design storm. The prototypes allow municipalities to visualize correlations among design inputs to guide formal, material, and spatial design decisions across a variety of site types with varying soil characteristics under increasing rainfall conditions. The prototypes can be aggregated within urban retrofit design scenarios at various spatial scales to respond to site- and district-wide loading ratios and other design conditions, while incorporating land-use planning considerations. For example, reducing the loading ratio and increasing the surface design thickness can both improve GSI performance under high storm intensities; and these design variables can be adjusted relative to one another to accommodate site design constraints, opportunities, and community input vis-à-vis plan and section relationships across a given design area. This approach provides flexibility in how the framework can be applied to benefit other cities and regions. Once K_{sat} values and design storms are established, the loading ratio and its associated surface areas can be used to design GSI depths and surface retrofit in other contexts where subsoils will function in the design.

Notably for 24 h storm durations, 12″ of surface retrofit depth is effective in all native subsoil contexts, including fine soils, with loading ratios of 1:5 or lower, shown numerically in figure 4 and illustrated in figure 5. Further, it is worth emphasizing that for short storm durations, native subsoil variation plays a role in storm attenuation such that additional GSI design depth is needed to achieve high reliability in mixed and fine soils. In addition, lowering the loading ratio to 1:2 or lower (i.e., increasing the scale of urban retrofit) has the greatest potential to increase overall GSI runoff reduction performance in all subsoil types for rainfall over 1″ over 2 h (figures 4(a) and (c)), highlighting the desirability of distributed GSI within the urban landscape.

4.4. Application to two Illinois (USA) municipalities

The research results are applied to the two participating municipalities, the Village of Midlothian and Calumet City, to test the probable functionality of GSI in place. Soils fieldwork took place in summer 2018, and in winter 2019. Municipal leaders and volunteers selected one urban neighborhood in each municipality where problematic and recurring flooding has been observed for application of the framework (Steering Committee Meetings 2018, 2019). While participating municipalities stated during the GSI planning-stage that cost is a concern, this research studies the feasibility of the GSI to address increasing storm intensity in the subject communities where GSI is preferred for its co-benefits over gray infrastructure. Cost analysis is being studied in a subsequent phase of research to refine prototype application, as described in section 5.4

4.4.1. Village of Midlothian: GSI design

The Village of Midlothian, located along the southwest side of the lake plain corridor and on the proximal side of a glacial end moraine (figure 1), is underlain by mainly fine-grained to mixed to locally sandy textured sub-soil and sediments. Within the selected design site of the Jolly Homes neighborhood, the native subsoils are a mixed-texture loam to sandy loam. Parts of this area include sandy sediment deposited in association with the Calumet beach ridge and may have inherently more rapid infiltration; other areas are more fine-grained. The project site is a residential neighborhood (225 acres) situated between Midlothian Meadows (a Cook County Forest Preserve) and Sundrop Prairie Nature Preserve. Flooding in this neighborhood is due to both its natural landscape context and urban development pattern. 151st Street, the centerline of the design area, was constructed along the upper reach of a stream that was part of the pre-urban hydrological drainage pattern. In response to rainfall, runoff drains along this street-to-stream line and floods the street surface. Site visits in February 2019 revealed that the apparent flatness of the landscape can be strategically redesigned to integrate selective spatial distribution of retrofits using the fragility curves and prototypes.

The municipality requested that we study retrofitting public land (versus private land); we therefore focused on the redesign of impervious pavements (predominantly streets, street rights-of-way, and adjacent surface pavements) that contribute to runoff and flooding, to replace them with permeable pavements lined and integrated with an extensive series of rain gardens and bioinfiltration cells (figure 6, and as shown in figure S1-3 and table S2 in the supporting information). Within each sub-drainage area, we applied the specified GSI design depths using the fragility curves (figure 4). 151st Street, the physical spine of the design area with the most severe at-grade flooding, was designed with deeper yet variable GSI depths to maximize infiltration and storage of rain in 2 h storm durations (figure 7). Native plant communities of the region that would adapt well to the urban conditions were selected by their 'conservative' value, an indicator of sensitivity to urban adaptation (Labus 2019 and Swink and Wilhelm 1994).

4.4.2. Village of Midlothian: performance modeling

In the GSI model for Jolly Homes, we determined overland flow was a key driver for flooding. We modeled overland flow in the MIKE URBAN software package in combination with the fragility curves (figure 4) to represent GSI performance within the Midlothian neighborhood and flooding depths downstream, based on existing digital elevation models (Illinois Height Modernization Program 2002−2016) and storms simulated as triangular hyetographs (Yen and Chow 1980). The depth of flooding before and after the simulated GSI installation are shown in figure 8, revealing the need to design for infiltration of rain upstream in the catchment, thus reducing the aggregate loading ratio at points farther downstream in the neighborhood catchment.

By designing and modeling GSI on public land only, flooded areas were significantly reduced in 24 h storms, based on our fragility curve results (shown in figures 4(c) and (d)), but some flooded areas still remained with simulated large, short-duration rain events (i.e., 2 to 5 inches in 2 h, shown in figure S4 in the supporting information) in the Jolly Homes catchment. Therefore, although on private land, the team separately identified backyard depression areas as an important additional retrofit opportunity for private property and suggested that neighbors collectively allocate these areas as wet zones for backyard woodlands. We then investigated the role of GSI installation when we include private backyards for a single subcatchment in the northwest area of the Midlothian neighborhood, shown in figure S5 of the supporting information. With private backyard GSI installed as rain gardens, the example subcatchment could prevent an additional 65 800 gallons of stormwater

Figure 6. Midlothian, IL, network of GSI interventions throughout streets, rights-of-way, and public land, with some private land opportunity shown, to address neighborhood-wide flooding with concentrated flooding along 151st Street.
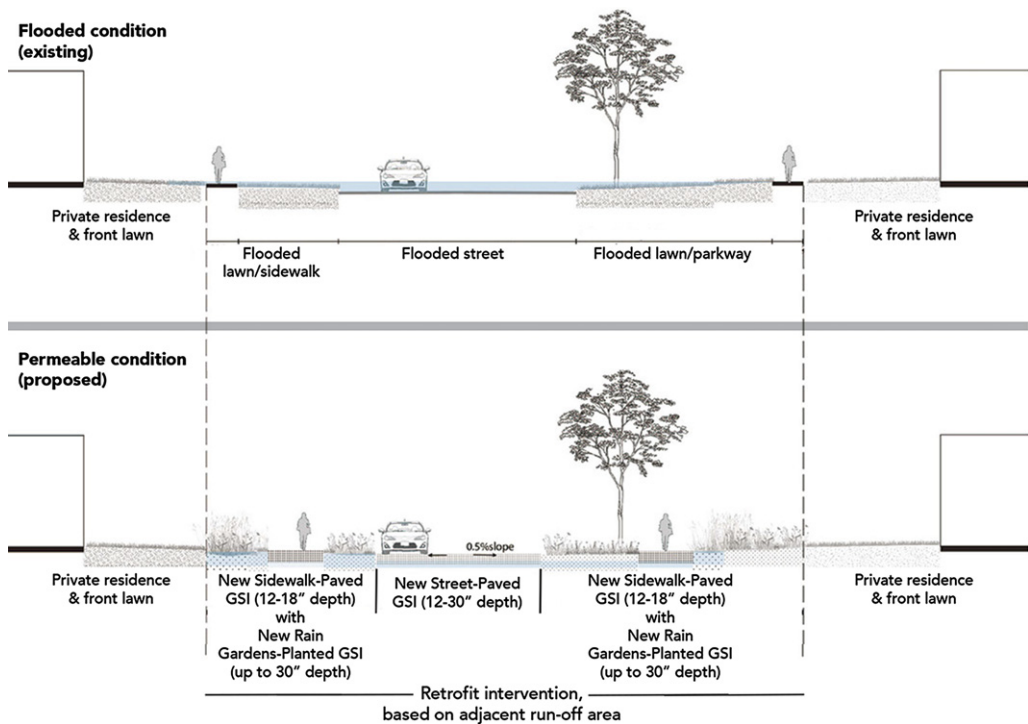

Figure 7. Midlothian, IL, typical retrofit strategy combinations consisting of paved and planted GSI with specified depth variations to accommodate various loading ratios.

from entering the downstream subcatchment in response to a 2-inch, 2 h storm, achieving the 80% runoff reduction design. We thus show, for this Midlothian catchment, that including private lands with upstream locations in GSI design would substantially increase the overall performance.

4.4.3. Calumet City: GSI design

The GSI design for Calumet City, located at the far east edge of the Calumet Corridor, sits in a low-lying area of land just lakeward of the ancient Toleston beach ridge, which extends northwest-southeast and parallel with the shores of Lake Michigan (figure 1). The selected 250-acre neighborhood experiences frequent flooding because its under-capacity sewer system and low-relief topography cannot convey water to the large central
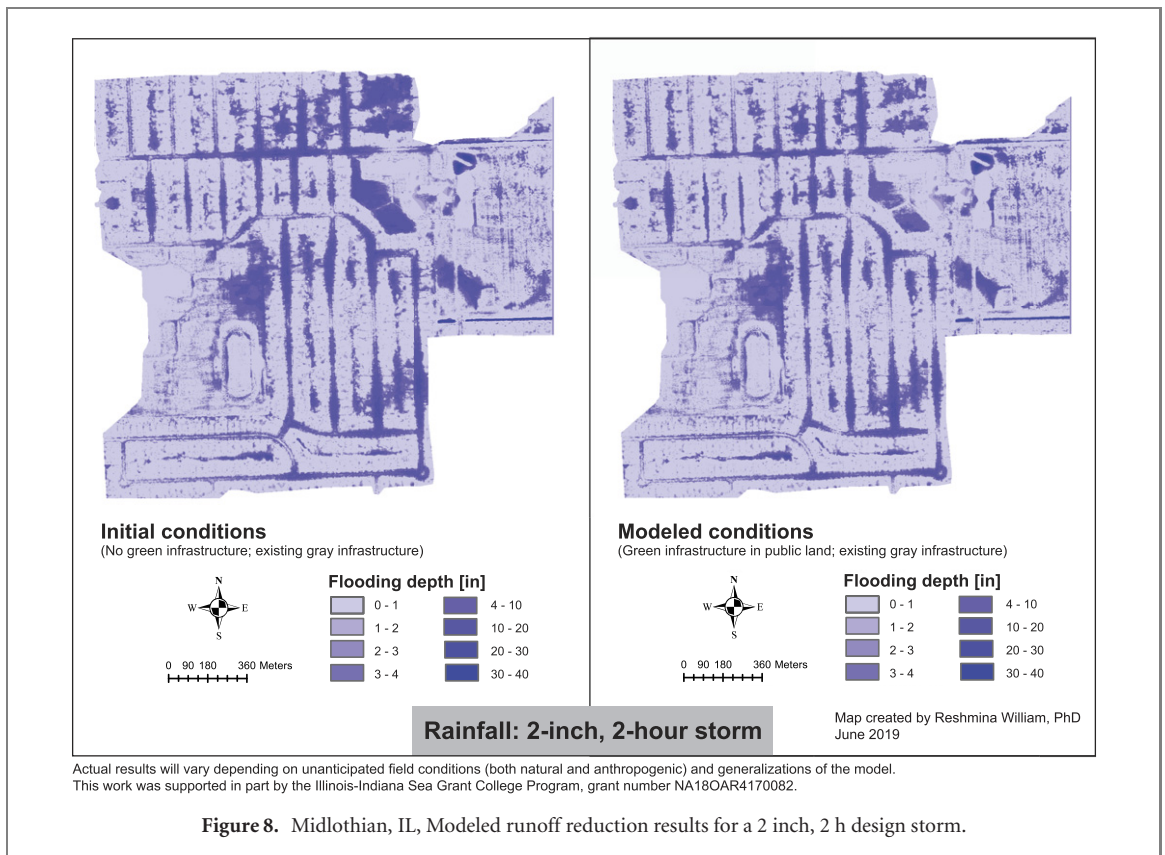
Figure 8. Midlothian, IL, Modeled runoff reduction results for a 2 inch, 2 h design storm.
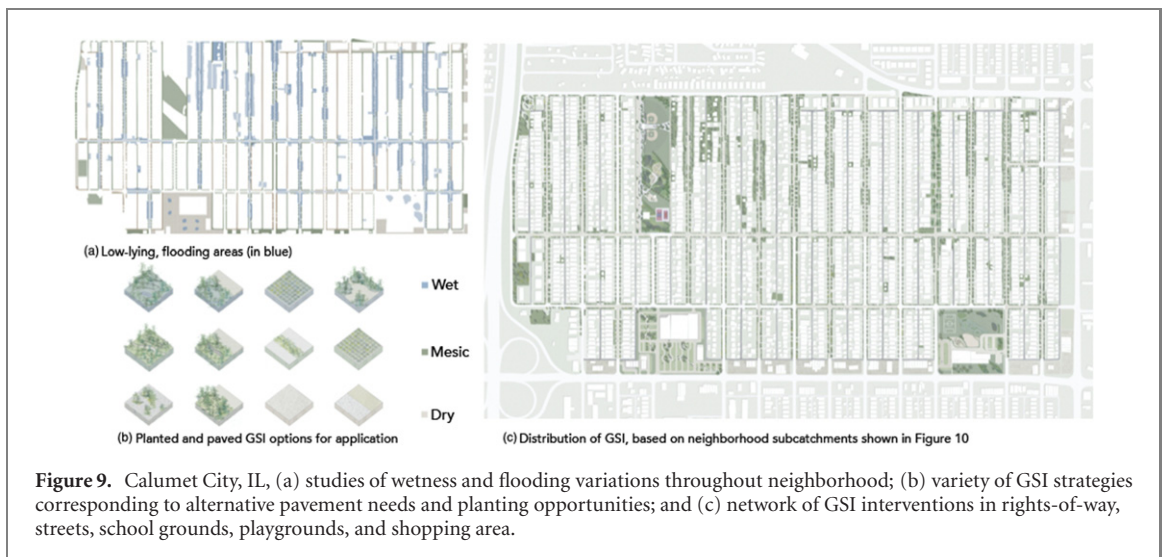
Figure 9. Calumet City, IL, (a) studies of wetness and flooding variations throughout neighborhood; (b) variety of GSI strategies corresponding to alternative pavement needs and planting opportunities; and (c) network of GSI interventions in rights-of-way, streets, school grounds, playgrounds, and shopping area.

detention basin located north of the site. Soil investigations in summer 2018 revealed that much of the near-surface soils in the site consists of loamy fine sand to loose, coarse beach sand, typical of former shoreline deposits in the coastal region. In addition, a few localized areas of peat occur in depression areas and finer-grained sediments occur southwest of the beach ridge, on the plains of glacial Lake Chicago. The sandy soils in the location have high infiltration capacity, and when layered beneath GSI—for both planted and paved upper surface designs—promote direct infiltration.

With the alternating patterns of the region's ridges and dune-swale geological origins as a reference, we studied the pattern of low and high areas in the neighborhood tied to the street and block patterns and identified design opportunities to implement GSI design to address areas of flooding across the neighborhood (figure 9, and as shown in figure S6-8 and table S3 in the supporting information). Streets and their rights-of-way constitute the primary area of intervention and are designed to maximize infiltration and storage of rainwater in 2 h storm durations. As in the Midlothian design site, the plant palette for Calumet City contains species native to the region.
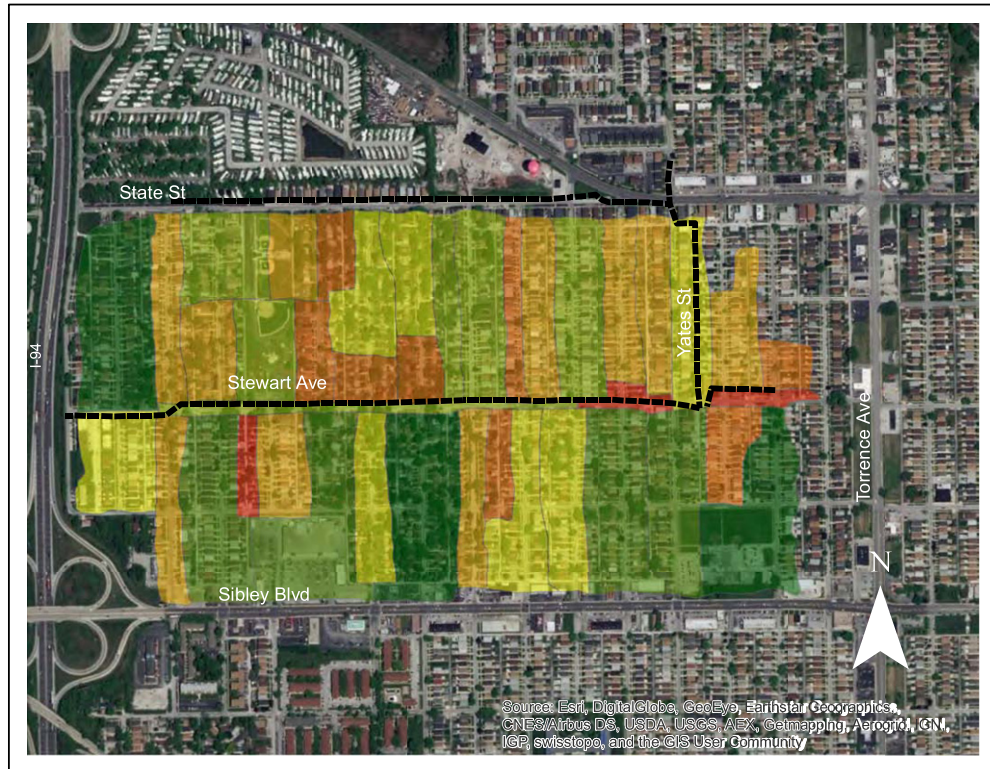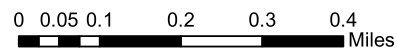
Figure 10. Calumet City, IL: modeled runoff reduction results for a 2-inch, 2 h design storm.

4.4.4. Calumet City: performance modeling

In the GSI model for Calumet City, the land parcels in the Calumet City catchment drain primarily to the street, rather than presenting overland flow conditions like the Midlothian catchment. A lack of detailed information about the existing Calumet City storm sewer, along with known undersized portions of the storm sewer, presented different flooding challenges and required a different modeling approach. Therefore, we calculated the volume of water removed via the GSI design in public areas (figure 10) using the Green-Ampt infiltration equation:

$$F(t) - \psi \Delta\theta \ln\left(1 + \frac{F(t)}{\psi \Delta\theta}\right) = Kt \tag{2}$$

for cumulative infiltration $F(t)$, wetting front suction head ψ, and change in water content $\Delta\theta$ over time t for a specified local hydraulic conductivity K. $\Delta\theta$ is comprised of two terms, θ_i and θ_s, representing the initial soil water content and the saturated soil water content. These two parameters are varied as part of the Monte Carlo modeling analysis described in section 3.4. The wetting front suction head was set to $\psi = 121$ mm and was determined using average soil texture characteristics as described in Rawls *et al* (1983).

With the simulated design for a 2-inch, 2 h storm, we estimate that GSI could prevent 1.43, 1.72, and 3.35 million gallons of stormwater from entering the sewer mains along Yates Street, State Street, and Stewart Avenue, respectively, with all of these areas achieving 80% runoff reduction, per our design. In the

Calumet City catchment, additional engineering details are needed regarding the existing storm sewer to proceed with GSI implementation. Calumet City is using this research to apply for further funding toward GSI implementation.

5. Discussion: outcomes and implications

Based on our research framework and application to two municipalities, we share two outcomes, immediately usable by the broader research and planning community, and suggest policy implications. We also discuss the applicability of this research to other urban areas and the production of a design-decision toolkit for use by communities and researchers.

5.1. GSI performance improves by reducing loading ratio and decreasing upstream imperviousness

An active and ongoing area of research are the catchment-scale effects of GSI, especially regarding placement of GSI installations within the catchment landscape (Golden and Hoghooghi 2018, Lim and Welty 2017 and Fiori and Volpi 2020). In our catchment-scale work, impervious surface conditions are a critical factor in the functionality of GSI, particularly related to the loading ratio. Decreasing upstream impervious surface (e.g., moving from a loading ratio of 1:5 to 1:2) greatly improves the reliability of GSI installations in achieving 80% runoff reduction standards, as shown in the fragility curves (figure 4). The saturated hydraulic conductivity of native subsoils and GSI design depth also both play a role in runoff reduction. GSI design with additional depth can leverage native subsoils, even in areas with fine-grained soils, by incorporating additional storage into planted and paved installations, leading to high runoff reduction. Our results show that GSI can be effective in mitigating urban flooding, as demonstrated in these two study areas, using quantitative engineering modeling to inform surface design.

5.2. A soils-based approach yields both increased GSI performance and context-specific GSI siting and form-making

From a landscape design and planning perspective, a soils-based approach integrates two important scales of retrofit consideration. First, design sites, analyzed within a broad urban regional context, reveal topographic patterns formed geologically that were later altered by urbanization. Analyzing the relationship between pre-settlement topography and development patterns is useful in finding retrofit solutions, through the existing complexity of site-scaled conditions, materials, and configurations (Wentz *et al* 2018). In our two pilot municipalities, one design retrofit slows 'upstream' drainage in a former creekbed (now a street) and one mimics the regional dune-swale ecology to reduce water flowing into an under-capacity subsurface sewer.

Second, the native landform-sediment associations have a range of hydraulic conductivity characteristics for each soil type. Designers and planners can assess design options from the fragility curves, but these need to be based on site-specific soil characterization. As such, design prototypes that account for rain events (quantity and duration) and underlying native subsoils (hydraulic conductivity) can be combined with design variables of loading ratio (impervious runoff area and GSI surface area) and surface design (surface type and depth) to generate alternative combinations within multi-scalar scenarios. Retrofitting from the neighborhood scale to the urban and regional scales can bring geologic-, topographic-, urban-, and soils-based aspects together to maximize GSI performance. This is especially true in short storm durations where the role of native subsoils plays an increasingly critical role in climate-adaptive stormwater management.

This landscape and soils-based approach is applicable to other urban-geological settings. Flood-prone communities in other cities and regions can use an understanding of their hydro-geological context to inform how to build back functionality to the land. Once local subsoils are tested for K_{sat} values, the fragility curves can be referenced to calculate the required GSI intervention to meet stormwater performance goals. The distribution, organization, and specific design of those GSI features can be further informed by regional, pre-urban ecological reference landscapes and native soil-plant ecosystems.

5.3. Policy implications

Implementation of GSI at the systems scale remains slow due to institutional approaches that exclude interdisciplinary or multi-factorial research methods for GSI planning and investment (Li *et al* 2020). In the Chicago region, there are also divergent attitudes about whether GSI solutions should be institution-based or infrastructure-based (Cousins 2017), made more difficult by Chicago's natural landscape being severely altered and rendered dysfunctional by an historic, path dependence on gray infrastructure (Adelman 1998). Further, soils-based approaches are challenging in regions that do not currently include native sediment or soil hydraulic conductivity data in their stormwater permitting systems. Currently in Cook County, Illinois, new project development is required to provide GSI performance to infiltrate or store only the first $1''$ of rainfall draining from impervious surfaces. The watershed management ordinance (WMO), which applies

to all development within Cook County boundaries, further specifies that permit applications provide for retention-based practices, when used, to mimic pre-development conditions. Neither loading ratio nor soil textures and their hydraulic properties are explicitly taken into account by this regulation, leaving permit applicants to retroactively and incompletely assess soil properties. If these technical considerations were proactively included in calculations for the potential of sites to provide GSI, this approach might lead to different, site-specific, and more effective requirements for each new development. The approach suggested by this research is particularly relevant given recent revisions to the WMO enabling a stormwater credit trading pilot, that could result in better matching of GSI installations to areas with higher performing soils. Given the range of soil textures and infiltration rates across the region, this approach might also bear consequences on policy revisions. Areas of soil with higher infiltration rates could provide higher-performing GSI, even in smaller ratios of site design. With financial incentives from water or wastewater utilities, municipalities could implement a greater runoff reduction standard, and likely achieve highly-functional GSI rather than relying on repairs to already inadequate gray infrastructure systems. As suggested by Rosenzweig *et al* (2018), our work addresses the potential for larger urban district-scale pilot projects to capture more extreme rain events on site.

5.4. Creating the research framework as a toolkit

Although our research method contributes a quantitative method for GSI siting and design, our research framework is not purely technical, since there are issues that drive objective and subjective decisions for GSI design and adoption (Coleman *et al* 2018). These issues include perceptions that gray infrastructure is more reliable and simultaneously that there are limitations for GSI funding in capital planning. These concerns and challenges currently lie outside the scope of this research, but also represent issues and barriers that these results might help alleviate. Another important consideration not addressed in this research is the costing of GSI at a neighborhood scale, which also presents a critical follow-on decision-point for GSI implementation. In response to these issues and barriers, we are currently developing a design decision toolkit to share with stormwater planners and managers. This toolkit will help in three key areas: (1) to better understand the role that spatially varying native subsoil types has in GSI performance, (2) to provide greater resources for GSI analysis including cost parameter tools to assess the economic tradeoffs between surface area and depth in siting GSI, and (3) to integrate native subsoils data and the use of fragility curves in coordinated GSI designs that will maximize long-term returns on initial investments. The toolkit aims to facilitate access to numerical datasets and resources for soils research and analysis, adaptation of GSI prototypes at various scales, and support for GSI decisions at a community scale since a socio-ecological driver of GSI includes supporting new healthy places through optimized siting for co-benefits to communities and ecosystems (Meerow and Newell 2017).

6. Conclusion

Urban flooding remains an overwhelming challenge globally and constitutes a top priority for design research. More robust GSI solutions are needed to reconnect the current fragmentation of infrastructure systems in relationship with ecosystems, communities, and landscape function (Czechowski *et al* 2014). We demonstrate that an understanding of the geological history, urban surface patterns, and subsurface soil properties can greatly assist regions and communities with the issue of systemic, regional urban flooding. Specifically, our research concludes the following:

(a) Collecting field data to better characterize native subsurface soils can enhance predictive hydrologic functionality of potential GSI installations under different storm intensities, which is critical in climate adaptation.

(b) Prototype planted and paved GSI models demonstrate surface retrofit design opportunities and limitations that account for spatially variable saturated hydraulic conductivity of native soils and design rainfall conditions that support early stormwater planning and design stages.

(c) Public engagement and co-creation of research knowledge with the local community advances stormwater planning through an understanding of the efficacy of soils-based GSI, but also suggests that further research for funding and maintenance of urban-scale GSI will be required, especially in low-income communities.

In two southern great lakes coastal communities, our model results show that GSI runoff reduction performance can be significantly improved even for high intensity rainfall if design prototypes consider the local variability in native subsoil distributions (and K_{sat} values) and situate GSI accordingly. By rooting stormwater adaptation in native subsoils and locating solutions inherent in the landscape and substrate, we can rebuild ecosystem function to address climate disturbance and storm intensity impacts on urban areas. Our integrated

research framework presents a systematic, multi-variable design method that can be utilized by municipalities and research teams in urbanized landscapes internationally to creatively and effectively retrofit flood-prone urban land.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Conflict of interest

The authors have no conflict of interest in submitting this research for publication.

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