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Accelerating Cost-Effective Green Stormwater Infrastructure:

LEARNING FROM LOCAL IMPLEMENTATION

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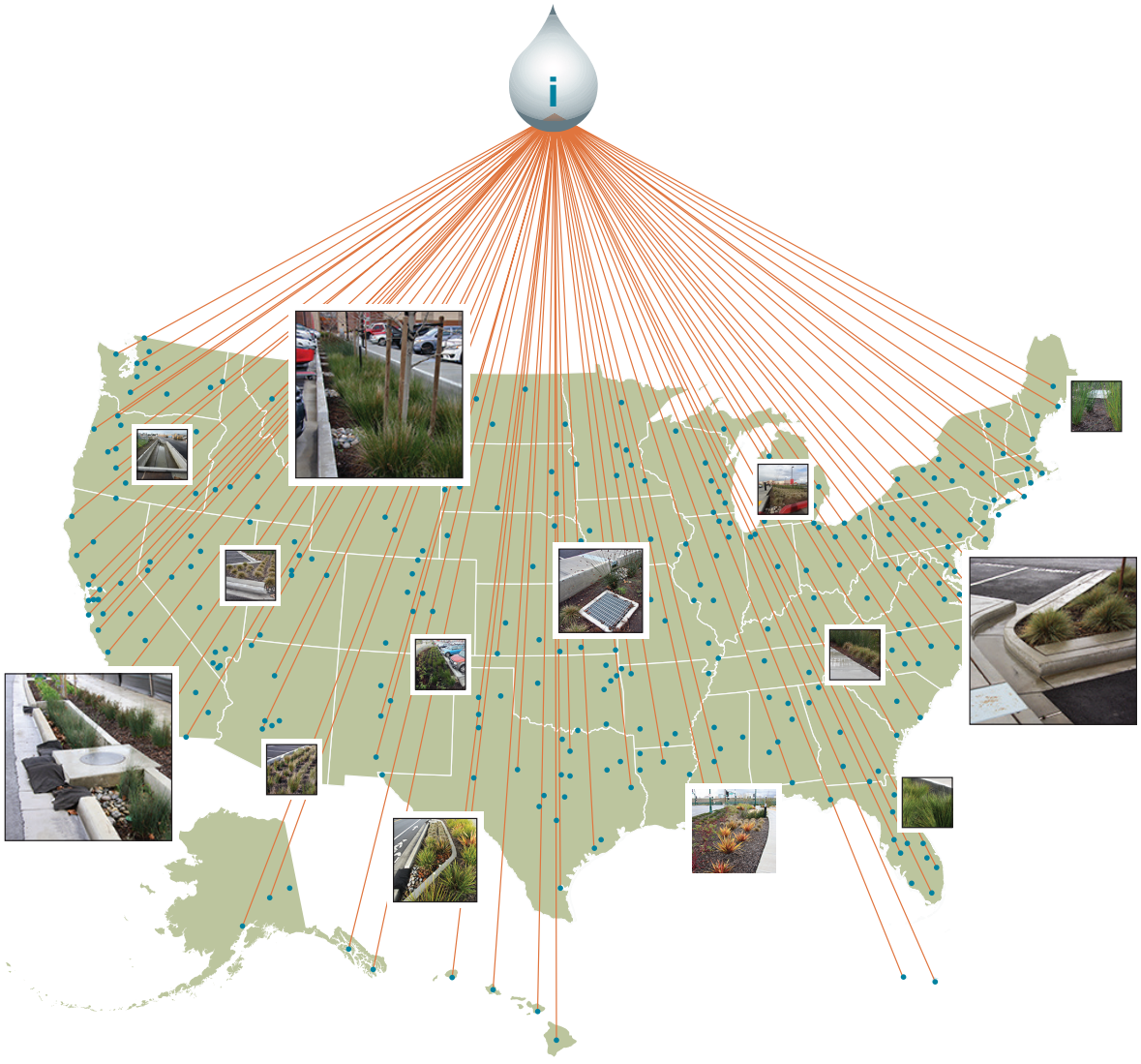
Wheeler Institute for Water Law & Policy



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I. Executive Summary

Ineffective stormwater management is a serious problem nationwide

Conventional stormwater management strategies based around "gray" collection and conveyance systems—networks of gutters, storm drains, and sewers—have not solved persistent stormwater problems. Instead they have shifted, and in many cases exacerbated, the impacts of stormwater runoff, trading urban flooding for pollution and hydromodification of nearby rivers, streams, lakes, and estuaries.

Green stormwater infrastructure (GSI) is an important part of the solution

A different approach to stormwater management is needed. Effective management requires a holistic approach that employs a locally tailored mix of on-site and off-site retention, treatment, and use along with pollutant source controls to protect local waters and meet other community and regulatory objectives.

GSI is a crucial piece of the stormwater-management puzzle. GSI works by addressing stormwater where rain or snow falls. It uses distributed installations to mimic natural stormwater retention and treatment processes. The goal is to minimize the quantity and maximize the quality of runoff that flows to local waters. GSI can be a powerful tool for managing stormwater while achieving a host of additional benefits.

With this in mind, the U.S. Environmental Protection Agency (EPA) and state regulators are beginning to encourage, and sometimes to require, expanded use of GSI to meet Clean Water Act goals. Requirements for using GSI in development projects, and increasingly stringent water-quality requirements for discharges to local waters, are helping to drive local GSI planning and implementation efforts.

Barriers to GSI implementation include uncertainty about performance and cost

Although its importance as a component of future stormwater management is difficult to overstate, there are many potential barriers to widespread, timely, efficient, and effective GSI implementation. These include informational, technical, legal, institutional, social, political, and financial barriers. This report focuses on the challenges posed by information limitations, which impede cost-effective GSI deployment by perpetuating uncertainty about performance and cost.

While robust information is important in any field, it is especially critical here because GSI is evolving technology. Good performance cannot simply be assumed. Each installation is a local experiment in which site-specific conditions and design specifications heavily influence what runoff-volume and pollutant reductions are actually achieved, whether these reductions are adequate to meet community objectives and regulatory requirements, and at what initial and long-term cost.

Many communities are still analyzing how to most efficiently use local resources to implement GSI. Cost-effectiveness is a primary consideration for stormwater managers who are trying to decide how to employ GSI in their communities. Uncertainty about either life-cycle costs or performance—both of which linger today—can impede decision making, leading communities to underinvest in GSI or to overspend on less cost-effective GSI. Either result is problematic for a community with limited funds and unaddressed stormwater needs.

While many cities with combined sewer systems already recognize that distributed GSI offers clear financial benefits over exclusively gray infrastructure, most municipalities with separate storm sewer systems (MS4s) do not yet face such obvious fiscal incentives. However, as stormwater permits trend toward stronger retention and water-quality requirements, more communities with MS4s will likely be weighing specific compliance scenarios that include different types, placements, and amounts of GSI. Reducing uncertainty about performance and costs would help clarify financial incentives and speed cost-effective GSI deployment across the board.

Monitoring and sharing data can reduce uncertainty and open the door for greater design standardization

Monitoring locally implemented GSI and sharing the results can provide information that is crucial for addressing the uncertainty that surrounds GSI

performance and cost. Monitoring data, and the lessons they can teach, reduce uncertainty, aid the development of cheaper and more reliable GSI designs, and give decision makers the information they need to more cost-effectively plan and deploy GSI at a scale sufficient to meet community and regulatory objectives.

As experience implementing different GSI designs under a variety of local site conditions accumulates, understanding of what variables are most important to proper function in different contexts, and how much GSI actually costs to install and maintain, will improve. This knowledge will enable development of GSI designs that achieve better reliability at lower cost.

Greater design standardization would help reduce costs further. Site variability makes true plug-and-play GSI designs impracticable. However, standardization could take the form of libraries of customizable basic designs and specifications that consistently deliver good performance for common sets of site conditions and community objectives.

State and federal regulators can boost local data collection and sharing to accelerate cost-effective GSI deployment

Without a concerted effort to reduce uncertainty about cost and performance, GSI deployment over the coming decades will be less extensive and less effective than communities need it to be. More and better data are crucial to reducing uncertainty and accelerating the development of GSI technology. Specifically, it is essential to increase collective learning from early GSI installations through sustained monitoring of performance, maintenance needs, and costs, paired with effective data sharing.

So far the extent of data collected and shared has been limited. Local implementers often informally collect information for their own tracking and management purposes (or, if not, they should). However, these data are rarely formally recorded or made accessible to others.

Although state and federal regulators are already promoting GSI, they have the authority to play a more active role in accelerating and improving it. More and more frequently, stormwater permits and combined sewer overflow (CSO) consent decrees now include requirements for municipalities to manage runoff using GSI. In connection with these requirements, regulators should require GSI monitoring, capturing relevant qualitative and quantitative information in an accessible, centralized database.

Specifically, the EPA and state water quality authorities should take the following seven actions:

Action 1: Incentivize and highlight the importance of voluntary GSI monitoring and data contributions to the International Stormwater Best Management Practices Database (ISBMPD). Given that **Actions 2**, **3**, and **4** may take time, this is critical.

Action 2: Identify quantitative and qualitative GSI monitoring priorities at the national, regional, and watershed level.

Action 3: Adopt standardized GSI monitoring and reporting protocols and guidance.

Action 4: Attach specific monitoring and reporting requirements to GSI required by National Pollutant Discharge Elimination System (NPDES) permits and consent decrees. Some requirements would be broadly applicable (e.g., context, cost, maintenance, and qualitative performance data and lessons learned). However, a limited subset of GSI installations (consistent with the priorities identified in **Action 2**) would also require quantitative performance monitoring.

Action 5: Capture required GSI monitoring data in the ISBMPD. This could involve requiring individual implementers to submit data directly to the ISBMPD, collecting information first in state or regional databases that regularly feed accumulated data into the ISBMPD, or coordinating data submission with implementation of the NPDES Electronic Reporting Rule by redesigning the NPDES Integrated Compliance Information System to facilitate carryover of monitoring data to the ISBMPD.

Action 6: Feed water-quality related GSI monitoring data into the National Stormwater Quality Database (NSQD).

Action 7: Prioritize ongoing support for quantitative GSI performance monitoring, database upkeep, and timely meta-analysis of accumulated monitoring data.

Opportunities to improve knowledge about GSI are inherent in local implementation efforts. Leveraging such efforts to expand organized monitoring and information sharing would reduce uncertainty about performance and cost, helping to speed widespread, cost-effective GSI deployment to achieve social and environmental goals.

ACRONYMS USED IN THIS REPORT

BMP	Best management practice
CSO	Combined sewer overflow
EPA	U.S. Environmental Protection Agency
GSI	Green stormwater infrastructure
ISBMPD	International Stormwater Best Management Practices Database
LID	Low impact development
MS4	Municipal separate storm sewer system
NPDES	National Pollutant Discharge Elimination System
NSQD	National Stormwater Quality Database
TMDL	Total Maximum Daily Load

II. GSI can improve stormwater management

Conventional stormwater management strategies based around "gray" collection and conveyance systems have not solved persistent stormwater problems related to development and impervious surfaces. Instead they have simply shifted, and in many cases exacerbated, the impacts of stormwater runoff, trading urban flooding for pollution and hydromodification of nearby rivers, streams, lakes, and estuaries. Properly implemented GSI can lessen stormwater's impacts on local waters and enhance communities in other ways.

BOX 1. CONVENTIONAL STORMWATER MANAGEMENT

CONVENTIONAL ("GRAY") STORMWATER INFRASTRUCTURE: Conventional stormwater infrastructure—a network of gutters, storm drains, and sewers—achieves flood control at the cost of surface-water health and reduced groundwater recharge.[1] Gray infrastructure conveys untreated runoff and pollutants from pavements, construction sites, and industry directly to surface waters, exposing aquatic ecosystems to physical, chemical, and biological stressors.[2] This is often true for combined sewer systems as well as for separate storm sewer systems (BOX 4).

CONVENTIONAL STORMWATER POLLUTION CONTROLS: Conventional methods of addressing stormwater pollution include source controls and treatment controls. Source control measures—like public education campaigns, street sweeping, and product restrictions—aim to prevent pollutants from contaminating stormwater in the first place. By contrast, treatment controls—like hydrodynamic separators,[3] sediment basins,[4] and diversions to sewage treatment plants[5]—remove pollutants from stormwater. While conventional controls have reduced the loads of some pollutants in local waters,[6] other pollutants are more difficult to manage, and stormwater pollution remains a serious problem.[7] Additionally, conventional controls do not mitigate the volume- and temperature-related impacts of stormwater discharges.[8]

The overarching goal of GSI is to reduce the hydrologic and water-quality impacts of development by mimicking natural, distributed stormwater retention and treatment processes.[9] Well-implemented GSI keeps stormwater local, infiltrating or evaporating stormwater where rain or snow falls, or capturing it for later use; it minimizes the quantity and maximizes the quality of runoff that flows to local waters.[10] GSI can complement or replace gray infrastructure.[11]

Thoughtfully planned and executed GSI can have multiple benefits, helping local governments "make the most of limited public dollars and achieve multiple goals with a single investment."[12] In addition to reducing runoff volume and flood risk and protecting local water quality, GSI can provide other social, public health, economic, and environmental benefits.[13] It can replenish groundwater and contribute to stream base flow; enhance community aesthetics, livability, and property values; improve wildlife habitat, air quality, and public health; reduce "urban heat island" effects, energy use, and greenhouse gases; and decrease municipal capital, operations, maintenance, and energy costs.[14] Furthermore, communities that decide to implement GSI on a large scale can create viable "green collar" jobs based around designing, building, and maintaining GSI.[15]

Given its potential to improve stormwater management, the EPA and state water quality authorities are encouraging, and sometimes requiring, cities and other stormwater managers to begin implementing GSI to meet Clean Water Act requirements.[16]

BOX 2. CATEGORIES OF GSI[17]

GSI works by addressing stormwater on site, increasing infiltration, evaporation, transpiration (evaporation from plants), or capture and use of stormwater.[18] This approach is also known as low impact development (LID).[19] Properly implemented GSI reduces the quantity and improves the quality of stormwater that flows to local waters. GSI can be tailored to enhance removal of particular pollutants or designed around broad-spectrum pollutant-reduction goals that are difficult to accomplish conventionally.[20] The main categories of GSI, grouped topically, include the following:

BIORETENTION SYSTEMS use vegetation and soils to filter, infiltrate, and evapotranspire stormwater runoff. They include **biofiltration systems**, which have underdrains that collect and carry some or all filtered stormwater to a storm sewer system, and **bioinfiltration systems**, which do not.[21]

- **Bioretention cells/basins** (FIGURE 1) are shallow, vegetated depressions underlain by amended soils that facilitate stormwater infiltration and evapotranspiration.[22] They can be designed to receive runoff from downspouts, parking lots, and roads.[23]
- **Bioswales** (also known as **vegetated swales**) are drainage channels—often used adjacent to roads or parking lots—designed to slow, filter, and infiltrate runoff.[24]
- **Vegetated filter strips** are gently sloped, often grass-covered, surfaces that slow sheet-flow runoff from adjacent impervious surfaces, like roads.[25] Filter strips can help "pretreat" stormwater before it enters bioswales or bioretention basins.[26]

UNVEGETATED INFILTRATION SYSTEMS reduce runoff by promoting stormwater infiltration.

- **Permeable/pervious pavements** include abundant pore space that allows stormwater to drain through.[27] **Permeable paver systems** drain stormwater through gaps between impervious pavers.[28]
- **Infiltration trenches** are rock-lined surface trenches without drainage outlets that receive and infiltrate runoff.[29] **Exfiltration tanks** and **exfiltration trenches** (also known as **dry wells** or **soakaways**) introduce collected stormwater directly into native soils, with no internal treatment.[30]

GREEN ROOFS use vegetation and soils to intercept and slow the flow of stormwater from rooftops or retain it for later evapotranspiration.[31]

STORMWATER HARVESTING SYSTEMS employ rain barrels or cisterns to collect rainwater (often from roofs) for later landscape irrigation or other use.[32]

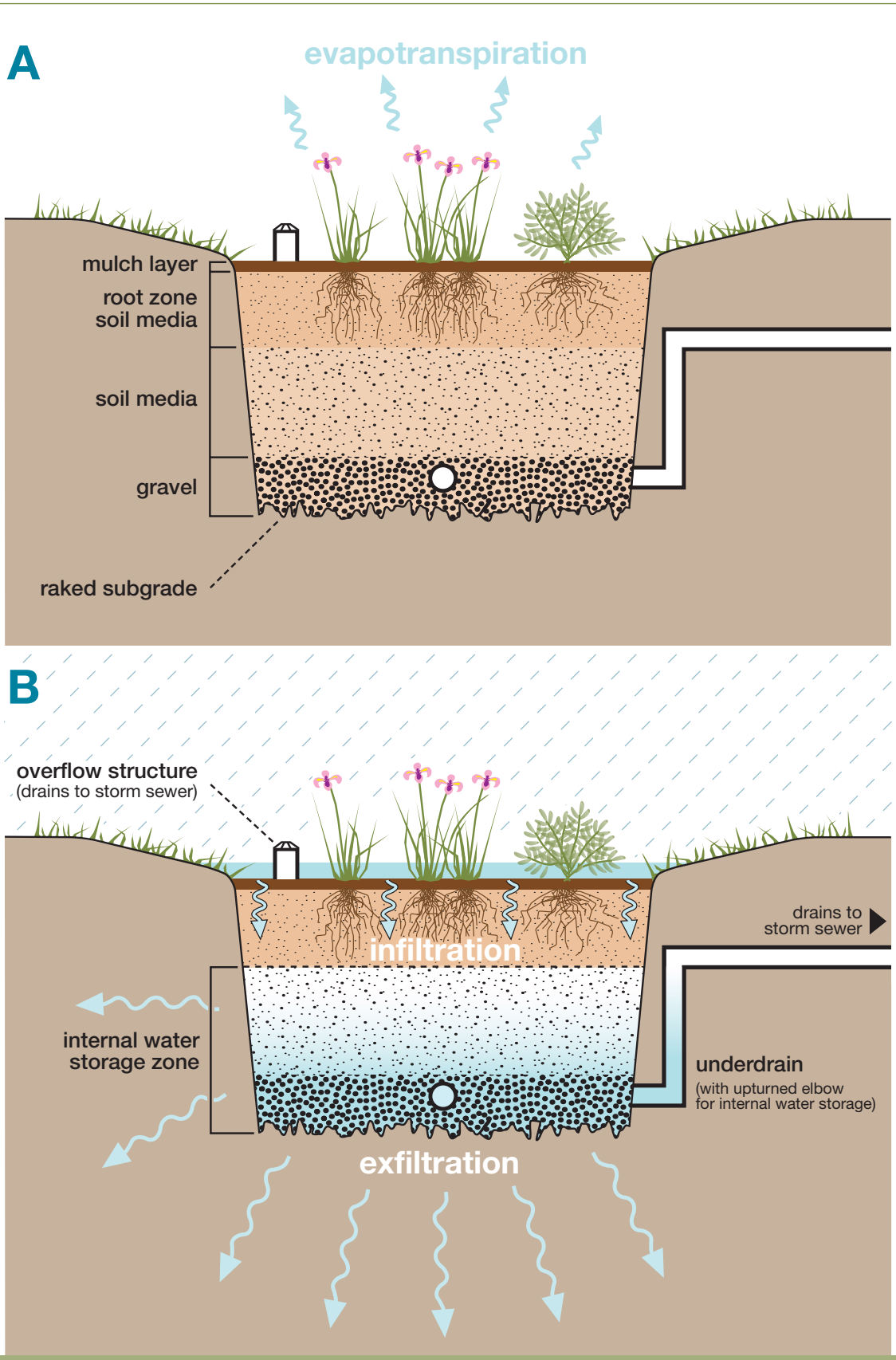


FIGURE 1. Schematic cross section (not to scale) of a bioretention cell, one of the most widely used types of GSI, during (A) dry and (B) wet weather.[33] In this design, water that enters the raised overflow structure remains untreated, but water that flows through the cell and either (1) enters the underdrain or (2) exits (exfiltrates) the cell, moving into (infiltrating) the surrounding soil, has the benefit of treatment.[34]

III. Uncertainty about performance and cost impedes GSI implementation

Implementing GSI is rarely straightforward. Although its importance as a component of future stormwater management is difficult to overstate, there are many barriers—both perceived and real—to widespread, timely, efficient, and effective implementation.

Among the barriers implementers face are a broad spectrum of informational, technical, and institutional issues, including legal, social, political, and financial challenges.[35] For example, GSI designs that work well in some cases may not be appropriate in others, leading to uncertainty about GSI's effectiveness under specific local conditions. Relevant local, state, and federal rules, standards, and guidance may effectively prohibit or fail to address GSI.[36] Limited local expertise[37] or perceived high materials, construction, and maintenance costs may discourage GSI implementation. Potential loan and grant funding sources may support only traditional construction practices or discourage multi-benefit projects.[38] Additionally, municipalities wanting to institute or increase stormwater-related taxes or fees may face substantial political hurdles, including voter approval requirements.[39]

In this report, we focus on an under-addressed problem: the challenges posed by information limitations. Information limitations impede decision making by perpetuating uncertainty about GSI performance and the life-cycle costs of GSI. Accurate information about both is essential for those contemplating implementing GSI in their communities. Without it, decision makers cannot evaluate and compare the cost-effectiveness of GSI and other options for meeting regulatory requirements and achieving community goals.

The cost-effectiveness of a given stormwater management scenario is the ratio of (1) how much it will cost to design, install, and maintain and (2) the benefits it will achieve (e.g., stormwater volume reduction, pollutant removal, etc.).[40] The chief impediment to carrying out such analysis is that it requires robust technical and financial data based on prior experience, and such data are currently limited. This report is intended to motivate increased availability of both types of data with the goal of enabling more accurate cost-effectiveness analyses going forward.

As the following sections explain, GSI has proven effective in many situations, but it is evolving technology, and performance to date has been inconsistent. In many parts of the United States, GSI is still in the pilot- or demonstration-project stage.[41] Every installation is influenced by local priorities and regulatory requirements and has unique site-specific constraints.[42] Although available data show that, on average, many types of GSI are capable of reducing runoff volume and pollutant load, actual performance varies substantially from site to site and from pollutant to pollutant. Additionally, long-term data about performance, maintenance needs, and costs are currently sparse.

BOX 3. WHO IMPLEMENTS GSI?

While regulators may require or encourage GSI, specific implementation decisions are generally made at the local level. Local implementers include cities and counties; federal, state, and local agencies; private developers; neighborhood groups; and individual landowners.[43] State and local governments can mandate or influence private implementation with generally applicable rules (like GSI regulations or ordinances) and specific permitting decisions.[44]

A. Communities have different goals and expectations for GSI

Because communities implement GSI for different reasons, they may have different perspectives of what successful implementation looks like. A few examples:

Reason 1: CSO control. The Clean Water Act requires permits for municipal wastewater discharges to waters of the United States.[45] It also requires cities with combined sewer systems to design and carry out long-term control plans to reduce CSOs and their associated water quality impacts.[46] With

the EPA's encouragement, more of these plans[47] (as well as consent decrees that settle CSO enforcement actions[48]) incorporate distributed GSI instead of, or in addition to, new gray infrastructure. For example, the city of Philadelphia has committed to substantially reducing its CSOs by 2036 through extensive GSI implementation.[49]

Where CSOs are a major concern, the primary objective of GSI is to reduce the amount of stormwater entering the combined sewer system using distributed infiltration, retention, and evapotranspiration.[50] Reducing the amount of raw sewage that enters local waters is the main water-quality benefit of relieving the burden on the sewage collection and treatment system.[51] Therefore, the direct pollutant-capture capabilities of GSI may be considered peripheral.

Reason 2: Stormwater permit compliance. The Clean Water Act also requires permits for stormwater discharges to waters of the United States.[52] Successive updates to some stormwater permits are beginning to explicitly require GSI solutions or are making them look more inviting to municipalities with MS4s[53] and other stormwater permittees, including state departments of transportation,[54] industrial permittees,[55] and construction permittees.[56]

The Act requires municipal stormwater permittees to limit the amount of pollutants they discharge to local waters through their MS4s to the "maximum extent practicable" and to comply with other permit requirements, including those aimed at achieving applicable water quality standards and effluent limitations.[57] Implemented appropriately, GSI can help them fulfill a variety of general requirements.[58]

Additionally, some permits require or encourage the use of GSI in new- and re-development projects[59] or to achieve water-quality-based effluent limitations.[60]

If GSI does not retain all stormwater—for example, where some fraction of the stormwater that enters a bioretention cell exits to the storm sewer system via an underdrain (**Figure 1.B**)—an MS4 permittee may need to affirmatively demonstrate that the collective pollutant-removal capabilities of its GSI installations are adequate to meet permit requirements.[61] (See **Parts III.C.2** and **V.B** for more.) On the other hand, GSI that captures and retains stormwater on site is assumed to keep that stormwater, and the pollutants it carries, out of the MS4, helping dischargers meet retention standards, water quality standards, and water-quality-based effluent limitations.[62]

Reason 3: Groundwater recharge. Areas with limited local surface-water supplies or depleted groundwater are increasingly recognizing stormwater as a potential resource.[63] Under these circumstances, distributed GSI that enhances infiltration[64] could play an important role in local groundwater recharge that complements, or in some cases stands in for, centralized recharge facilities.[65]

Growing interest in resilience to climate and water-supply variability, enhanced by the severe drought currently impacting California and other parts of the western United States, may motivate many communities to more seriously pursue GSI for groundwater recharge. In California, specifically, the state's freshly minted Sustainable Groundwater Management Act[66] could lead to substantial new commitments to implement GSI by local and regional management agencies.

BOX 4. HOW STORMWATER TRAVELS TO LOCAL WATERS

MS4 DISCHARGES: Most communities in the United States distinguish stormwater from wastewater. In these communities, residential, commercial, and industrial wastewater travels to a sewage treatment plant via the sanitary sewer system, while a physically distinct storm sewer system delivers untreated stormwater directly to local waters.[67]

CSOs: Combined sewer systems are still used in more than 770 older communities throughout the United States (most in the Northeast, the Great Lakes region, and the Pacific Northwest).[68] In these communities, stormwater, domestic sewage, and industrial wastewater are piped together to a sewage treatment facility.[69] By design, combined sewers can overflow during wet weather, discharging raw sewage into local waters.[70]

DIRECT OVERLAND FLOW: Runoff from an adjacent developed area may flow over the land surface and enter local waters directly, without passing through a storm or combined sewer system.[71]

In addition, Safe Drinking Water Act requirements[72] may motiviate implementers to be sensitive to the potential for aquifer contamination, leading them to value effective pollutant capture within GSI, as well as infiltration.

While stormwater control, regulatory compliance, and groundwater recharge are often the primary drivers behind GSI, communities may have additional social, public health, economic, and environmental goals for local implementation (see **Part II**, above). Each community's particular set of local priorities and regulatory requirements shapes its expectations and needs for GSI.

B. Site-specific factors influence GSI design and performance

Deciding where and how to implement GSI is more complex than for gray infrastructure.[73] Effective GSI implementation plans and installations acknowledge site-specific conditions, using them to advantage where possible and actively mitigating important deficiencies. Therefore, selecting wisely among potential sites, designs, treatment trains (which employ multiple GSI elements in series), and watershed-scale deployment scenarios requires a thorough understanding of how site characteristics affect performance.[74]

BOX 5. RELEVANT SITE CONDITIONS

Whether a particular design will work well in a specific location often depends on a variety of site-specific factors. These include local climate, land use, stormwater pollutants, soil properties, vegetation types, the presence of impervious soil or bedrock layers, the depth of the groundwater table, subsurface flow, surface topography, drainage area, existing soil or groundwater contamination, connectivity with aquifers or surface waters, the proximity of building foundations, and the space available for implementation.[75]

Because GSI is part of an integrated management and development approach that attempts to approximate the predevelopment water balance in an area (or to improve upon it),[76] site conditions that influence the effectiveness of infiltration and evapotranspiration are important. These include both internal factors (like soil infiltration rates and capacity) and external factors (like local rainfall and runoff patterns).[77]

Similarly, both internally and externally driven site characteristics—like soil composition and catchment pollutant load—influence water-quality performance.

Site conditions can vary regionally. For example, green roofs tend to evapotranspire a larger fraction of the rainfall they intercept in areas with sunnier, drier climates (like Southern California) than in moister areas with frequent cloud cover (like the Pacific Northwest).[78] Similarly, regional geology[79] and climate[80] can govern native soil and vegetation characteristics. Somewhat counterintuitively, infiltration can be difficult in arid regions due to poor soil development and high-intensity rainfall events.[81] However, conditions at a particular site may differ from regional conditions in ways that affect how well certain GSI designs work.

Because site-specific factors influence GSI design and performance, monitoring GSI installed under a variety of site conditions can boost understanding of what designs work best under what conditions.

C. GSI can be highly effective, but results are inconsistent

Experience to date shows that GSI is a potentially powerful tool for managing stormwater volume and water quality, but that good performance cannot be assumed in any particular case.

1. Stormwater-quantity performance

On the whole, the available information suggests that a variety of GSI designs can successfully reduce stormwater volume, especially for smaller storm events.[82] For example, existing data indicate that bioretention systems often effectively reduce runoff volume and peak flow rate.[83]

However, the performance of individual installations varies due to differences in site conditions (see **Part III.B**), design, installation, and maintenance.[84] GSI may not meet expectations for stormwater volume reductions if important site conditions are overlooked during GSI design or construction or if it is poorly maintained.

For example, monitoring of recently installed bioretention cells along a single block of San Pablo Avenue in El Cerrito, California, revealed that (1) similarly designed cells in the system received significantly different volumes of runoff and infiltrated different volumes of water; (2) even very small

storms caused stormwater bypass; (3) plantings inadvertently interfered with stormwater inlets; (4) inlet maintenance was needed "to ensure unimpeded inflow"; and (5) improperly placed overflow drains caused unnecessary bypass.[85] These results suggest that the project did not fully account for local runoff patterns and that plantings and overflow drain placement could have been planned and executed more carefully.

This example highlights the value of monitoring, both for providing valuable feedback for adaptively managing the San Pablo Avenue site and for generating lessons applicable elsewhere.

2. Stormwater-quality performance

Reducing stormwater volume, by itself, can reduce the amount of pollutants reaching local waters,[86] but other concerns are relevant to understanding GSI's water-quality performance.

The type and abundance of pollutants in a catchment area affect the suitability of different GSI options.[87] How effectively GSI captures a specific pollutant depends on a variety of factors, including whether the pollutant is associated with particles or dissolved in runoff and how the pollutant responds to the physical, chemical, and biological microenvironments within the installation.[88]

Table 1 summarizes some of the treatment processes that GSI can foster and the types of pollutants each impacts. Some of these processes are well understood under controlled conditions, like those in sewage treatment plants.[89] However, understanding of the hazard, transport, and fate of pollutants under complex environmental conditions is more limited.[90] Due to constantly changing conditions, including temperature, moisture, and pollution loads, treatment processes perform less predictably in GSI.[91]

TABLE 1. Major treatment processes potentially available through GSI, some of the factors that influence their effectiveness, and the major categories of pollutants affected.[92]

GSI TREATMENT PROCESS	AFFECTED POLLUTANT CATEGORIES
SETTLING AND / OR FILTRATION • Depends on particle size, the time and space available for settling and / or filtration, filter type (e.g., vegetation, gravel, soil), and filter properties.[93]	• Particulate matter • Adsorbed metals • Adsorbed organic compounds • "Particulate" phosphorus • Particle-associated pathogens
COOLING • Depends on shading, the depth and time of infiltration or ponding, etc.	• Thermal pollution
SORPTION OR PRECIPITATION • Depends on soil properties including pH, Fe/Al-oxide content, organic content, effective surface area, etc.	• Dissolved metals • Dissolved organic compounds • Orthophosphate • Ammonia • Pathogens
MICROBIOLOGICAL BREAKDOWN / TRANSFORMATION • Depends on oxygen availability, pH, salinity, substrate properties, nutrients, temperature, etc. • Often occurs more slowly (between storms).	• Organic compounds • Ammonia • Nitrate • Pathogens
VEGETATION UPTAKE • Depends on vegetation type. • Nutrient removal requires harvesting.	• Nutrients • Metals • Hydrocarbons

Most categories of GSI appear to be capable of improving stormwater quality by capturing or degrading pollutants. **Table 2** summarizes the effects of different categories of GSI on various pollutants (based on ISBMPD data).

However, pollutant-removal performance varies from category to category. Available data suggest that most GSI categories generally do a good job of capturing sediments and reducing the concentration of total suspended solids in outflow.[94] GSI facilities may remove particle-associated pollutants more effectively than they remove dissolved pollutants, which can more easily flow through or overflow GSI to reach underdrains or groundwater.[95] Nutrient removal

TABLE 2. Some categories of GSI and related stormwater control measures show statistically significant reductions R or increases I in effluent pollutant concentrations (based on data in the ISBMPD as of July 2012).[96] The number of bioretention studies that analyzed each pollutant is shown in parentheses.

O No statistically significant difference between inflow and outflow concentration.

– No data available for this pollutant/category combination.

O or I Little data available (data for 3 or more storm events available for less than 3 facilities).

			STORMWATER CONTROL MEASURE (total # studies in database)											
		POLLUTANT	Grass strip (45)	Bioretention (30)	Bioswale (41)	Composite (25)	Detention basin (39)	Green roof (13)	Manufactured device (79) [97]	Media filter (37)	Permeable pavement (35)	Retention pond (68)	Wetland basin (31)	Wetland channel (19)
TOTAL SUSPENDED SOLIDS (TSS)			R	$R_{(14)}$	R	R	R	O	R	R	R	R	R	R
METALS	Arsenic	Total As	O	–	R	–	R	O	O	O	O	R	–	–
		Dissolved As	O	–	O	–	O	O	O	O	–	–	–	–
	Cadmium	Total Cd	R	$R_{(3)}$	R	R	O	O	R	R	O	R	R	O
		Dissolved Cd	O	–	R	–	I	O	O	O	R	O	–	–
	Chromium	Total Cr	R	–	O	–	R	O	R	R	O	R	–	O
		Dissolved Cr	O	–	O	–	O	–	O	O	I	R	–	–
	Copper	Total Cu	R	$R_{(4)}$	R	R	R	O	R	R	R	R	R	O
		Dissolved Cu	R	–	O	O	O	O	O	O	O	R	–	–
	Iron	Total Fe	O	$O_{(3)}$	O	R	–	–	–	R	–	R	–	–
		Dissolved Fe	I	–	–	–	–	–	–	–	O	O	–	–
	Lead	Total Pb	R	$O_{(3)}$	R	R	O	O	R	R	R	R	R	O
		Dissolved Pb	O	–	O	O	O	O	O	O	O	O	–	R
	Nickel	Total Ni	R	–	R	–	R	–	O	R	R	R	–	O
		Dissolved Ni	R	–	R	–	O	–	O	O	R	O	–	–
	Zinc	Total Zn	R	$R_{(6)}$	R	R	R	O	R	R	R	R	R	O
		Dissolved Zn	R	–	R	R	O	O	O	R	R	R	–	O
BACTERIA	Enterrococcus		–	$R_{(3)}$	–	–	–	–	RO-	–	–	R	R	–
	Escherichia coli		–	$O_{(3)}$	O	–	R	O	–	–	–	R	O	–
	Fecal coliform		O	–	O	O	O	–	OOO	R	–	R	O	–
NUTRIENTS	Phosphorus	Total P	I	$O_{(18)}$	I	R	R	I	R	R	R	R	R	O
		Ortho-P	I	$I_{(13)}$	I	O	O	I	R	R	O	R	R	I
		Dissolved P	O	$O_{(1)}$	I	R	O	–	O	O	O	R	R	O
	Nitrogen	Total N	O	$R_{(12)}$	O	R	I	–	O	R	O	R	O	O
		TKN	O	$R_{(14)}$	O	R	O	O	O	R	R	R	O	R
		Nitrate + nitrite	R	$R_{(17)}$	O	R	R	O	O	I	I	R	R	R

appears to be highly variable, with some forms of nitrogen and phosphorous showing more consistent removal than others, and some categories of GSI actually causing increases, rather than reductions, in outflow nutrient levels.[98] Fewer performance data are available for some pollutants or forms of pollutants that may be locally or regionally important—like bacteria,[99] organic compounds,[100] chloride,[101] and some metals. (Mercury, polychlorinated biphenyls (PCBs), and pesticides—pollutants of concern in the San Francisco Bay area[102]—and mercury, PCBs, PAHs, and pesticides—pollutants of concern in the Great Lakes region[103]—are some examples.) Few data exist for dissolved pollutants in general.[104]

In addition to differences *between* categories of GSI, there is often substantial variation in pollutant reduction *within* particular categories of GSI. For example, **Figure 2** summarizes pollutant-removal data from peer-reviewed literature for bioretention systems. It describes pollutant removal in terms of percent reductions, by mass or concentration, in outflow relative to inflow. Such "removal efficiencies" give an incomplete picture of pollutant-reduction performance,[105] but they illustrate the variability of existing water-quality performance data and highlight the need for more information about GSI effectiveness. **Figure 2** shows that, for the same pollutant, some bioretention facilities can operate as net sources—effectively adding pollution to system outflow—while others operate as net sinks.[106] Differences in site conditions, design, installation, maintenance, monitoring, and reporting may all contribute to observed variability. However, without more data, disentangling the influences of each may not be possible.

GSI can be tailored to enhance removal of particular pollutants of concern, but it also has the potential to achieve a broad spectrum of pollutant reduction goals that may be difficult to accomplish through conventional pollution controls alone.[107] This potential is especially important in light of the variability of stormwater pollution even at a single location and incomplete understanding of the individual and cumulative risks stormwater pollutants pose to people and ecosystems.[108]

Nonetheless, in many cases, implementers may need to weigh trade-offs between competing priorities. For instance, there is tension between the priorities of rapid infiltration and pollutant reduction.[109] Organic-rich soils with significant microbial activity can trap or degrade many pollutants of concern, including metals and hydrophobic organic compounds.[110] Therefore, GSI that allows stormwater to percolate slowly through a substantial depth of fine-grained organic-rich soil is likely to be more effective at reducing these pollutants than GSI that relies on rapid infiltration or that bypasses surface soils completely (like infiltration trenches or dry wells).[111]

Similarly, because different pollutants require different conditions for removal, GSI designs and media compositions that effectively remove some pollutants may unintentionally exacerbate others. For example, although highly organic soils can effectively capture particle-associated metals and many organic compounds, they also contribute to nutrient leaching.[112] Likewise, an anaerobic saturation zone within GSI can enhance nitrate removal but may have the undesirable side effect of increasing phosphate mobility.[113]

The good news is that careful implementers can often reconcile competing priorities using creative GSI designs that incorporate special soil amendments, produce microenvironments that target different pollutants or different forms of a pollutant (like ammonia and nitrate) in different zones, or employ several different technologies in series.[114] Similarly, proper sizing can help reconcile treatment and infiltration goals. Consequently, creative design solutions are the subject of significant ongoing interest and innovation.[115]

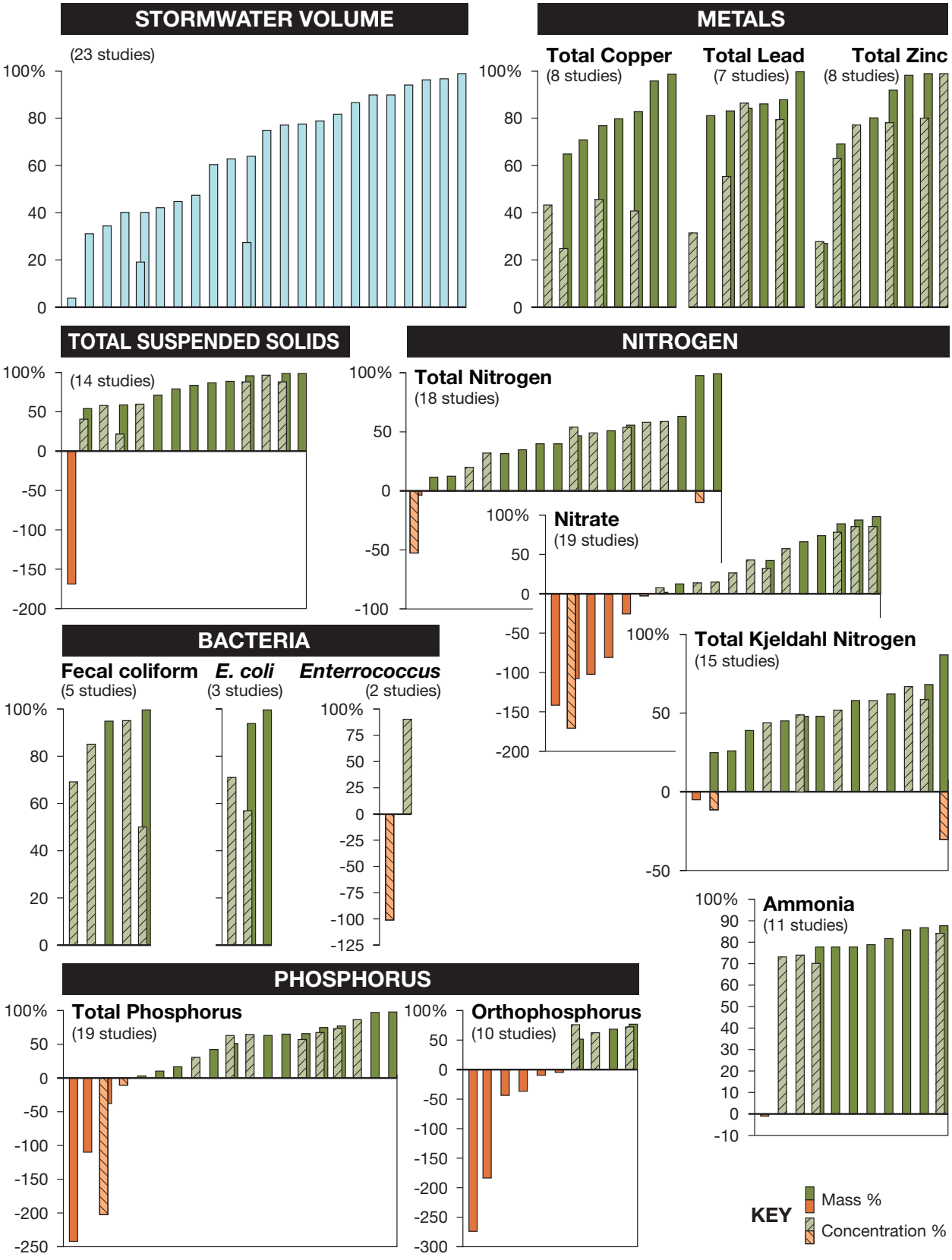
Although performance monitoring results to date are inconsistent, they leave no doubt that GSI can be highly effective in reducing the quantity and increasing the quality of stormwater runoff. As more field and laboratory results accumulate, understanding of what makes GSI function well in different circumstances will grow, enabling smarter implementation that achieves consistently good results. Expanding monitoring and information sharing will be critical to increasing the pace of technologic improvements.

D. Summary of knowledge gaps about GSI performance, maintenance, and cost

Currently, much remains to be learned about how to implement and maintain GSI effectively under a range of real-world conditions,[116] and how much it costs.

Numerous reports agree that there are important knowledge gaps. These include an incomplete

FIGURE 2. Percent reductions reported in peer-reviewed sources for bioretention systems.[117] Where two bars overlap, a single study used two different quantification methods



understanding of how particular pollutants move through and interact with GSI facilities,[118] how certain regional and site-specific conditions influence performance,[119] how to increase water-quality performance and reliability,[120] and how to target GSI designs to address specific regulatory needs.[121]

Major knowledge gaps also include the long-term performance of individual GSI installations, the cumulative performance of distributed GSI across watersheds, and GSI's life-cycle maintenance requirements and costs. Although time frame and physical scale matter, information about long-term and cumulative performance, maintenance needs, and costs is currently limited.[122]

For GSI to meet regulatory and community objectives, it must function well over time and space. However, most performance monitoring takes place over a short time frame relative to the intended lifespan of GSI.[123] Additionally, there is a notable lack of watershed-level data about the cumulative impacts of distributed GSI.[124] A 2013 literature review found "[n]o evaluation of implementation of [GSI] on a scale broader than pilot residential plat scale . . . except by modeling," even though the scale and time frame of implementation will significantly influence cumulative performance.[125]

Sustaining adequate pollutant capture and runoff-volume reductions takes ongoing performance assessment and maintenance.[126] Together, site conditions and design specifications control the nature, scope, and frequency of maintenance needs. For example, permeable pavements may require regular sweeping with suction to maintain adequate infiltration capacity, while bioretention systems may need weeding, mulching, and debris removal.[127] Soil media, mulch, and amendments may need periodic replacement.[128] However, there are very few data addressing (1) whether GSI installations are being adequately maintained, (2) how they perform under different maintenance scenarios, and (3) how much adequate maintenance costs.[129]

Making cost-effective choices about where and how to implement GSI requires an understanding of the likely lifecycle costs of individual installation options and watershed-scale deployment possibilities. Therefore, both initial cost outlays required to achieve desired performance levels and maintenance costs related to effective upkeep are important for comparing location, type, and design possibilities.[130]

To begin to address the need for short- and long-term cost information, the EPA and others have gathered and publicized cost and cost-benefit analyses by municipalities and developers.[131] These analyses are important beginnings, but there is substantial room for improvement. First, most existing analyses are based on projections derived from very limited cost and performance data.[132] Additionally, many of the analyses have occurred in the CSO context, where cities with combined sewer systems are facing a clear choice between making substantial new commitments to specific gray infrastructure with readily identifiable costs and achieving the same goals more cheaply by relying, at least in part, on distributed GSI solutions.[133]

Many municipalities with MS4s may not yet face such obvious fiscal incentives for GSI. However, as stormwater permits trend toward stronger water-quality-based requirements—including narrative or numeric effluent limitations related to Total Maximum Daily Loads (TMDLs) for impaired waters[134]—more communities with MS4s will likely be weighing specific compliance scenarios that include different types, placements, and amounts of GSI.[135]

Reducing uncertainty about performance and costs would help clarify financial incentives for potential implementers, speeding GSI deployment in general.

BOX 6. MORE DATA, FROM MORE GSI INSTALLATIONS IN MORE PLACES, ARE NEEDED

Actual performance data for GSI are still very limited. Available data come from relatively few GSI installations that cover a limited range of site conditions and geographic areas.

Again bioretention data are illustrative. Although bioretention systems are one of the most common forms of GSI currently being implemented, bioretention monitoring results reported in peer-reviewed literature[136] and the ISBMPD[137] come from just 40 field sites in the United States; about 78% of these sites are on the east coast, and more than one third are in North Carolina.[138] Data coverage for particular pollutants can be sparse and often contains important holes (e.g., the lack of dissolved-metals data for bioretention systems in the ISBMPD, seen in TABLE 2).

IV. Monitoring and information sharing are essential for progress on GSI

Expanding monitoring and information sharing would reduce uncertainty about GSI performance and cost and open the door for greater design standardization.

As we described in **Part III**, uncertainty about performance and cost can make cost-effectively implementing GSI challenging. The primary source of GSI's benefits over gray stormwater solutions—that GSI works with site hydrology to achieve stormwater quantity and quality improvements—is also a potential stumbling block to widespread implementation. GSI must be matched to site-specific conditions, so an implementer cannot simply select an existing design, install it, and confidently assume it will function as intended over its lifespan. No one-size-fits-all approach exists, and the need for tailored designs increases up-front costs.

Much of the performance, maintenance, and cost data necessary to address existing knowledge gaps can come from monitoring local GSI implementation and then sharing and comparing results.

A. Monitoring benefits both current and future implementation

Monitoring offers both immediate and longer-term benefits for stormwater managers. Data gathered from monitoring current installations enable learning about how to implement GSI efficiently and effectively in different contexts. This knowledge can guide initial location and design decisions, inform maintenance and improvements, and aid decisions about future implementation.

Some benefits are local. Confirming and measuring progress is crucial when implementing promising but evolving technology to achieve community and regulatory goals.[139] As one report put it, "[d]ue to a lack of structured monitoring," distributed GSI is often simply "assumed to impart long lists of anticipated benefits."[140] Monitoring can provide immediate feedback for local implementers, functioning as a crucial check on their initial assumptions about expected performance and maintenance needs.[141] The lessons learned from monitoring enable adaptive management that continually improves existing installations.[142]

Other benefits of monitoring accrue at multiple scales—locally, regionally, and nationally. Although decisions about where and how to implement GSI are inherently local, guided by local priorities and conditions, managers are likely to make better decisions when armed with information about what has worked (or not worked) under similar site conditions in other areas. Lessons learned from earlier installations can inform those that come later, both locally and across the nation. Over time, monitoring the performance and cost of many individual installations, as well as the cumulative impacts of broader implement efforts, creates data that can help answer important questions like:

- How can GSI be best implemented to meet current and future regulatory requirements and community needs?
- How do site, local, and regional conditions affect GSI effectiveness, design needs, installation costs, maintenance needs and costs, and effective lifespan?
- How does GSI design influence stormwater volume and water-quality performance, installation costs, maintenance needs and costs, and effective lifespan?
- How do "gray" and "green" alternatives compare in terms of cost, maintenance needs, and effectiveness under different conditions?
- What mix of "gray" and "green" infrastructure makes sense in a watershed, given local conditions and priorities?
- To what extent can GSI design and construction costs be streamlined by developing standardized designs that address common sets of conditions?

The information obtained through consistent monitoring can improve the accuracy of GSI siting and assessment models. It can also inform updates to zoning and building codes, stormwater management manuals, funding eligibility criteria, and other legal, policy, and institutional mechanisms that influence or limit the use of GSI.

BOX 7. A "BIG DATA" APPROACH CAN HELP TO MAKE GSI MORE EFFECTIVE

Analysis of context-rich monitoring data from GSI installations across the country would bring to light connections between site conditions, design parameters, cost, and performance, easing the path to broader, more cost-effective implementation.

There are a number of different ways to learn more about how GSI design influences performance. These include:

- Controlled laboratory experiments that attempt to simulate GSI function under different combinations of design parameters and site conditions (varying a single design parameter or site condition at a time).[143]
- Semi-controlled field experiments (e.g., testing the performance of different bioretention soil media, different lengths of bioswales, or different widths of grass strips under otherwise similar conditions).[144]
- Cumulative analysis of monitoring results from many different GSI installations with a range of site conditions and design parameters.

Although many valuable insights can come from the first two methods of inquiry, we expect the last method to become increasingly important and powerful. This "big data"[145] approach uses statistical analysis to help identify relationships between design specifications, site conditions, costs, and performance outcomes. It can also identify important knowledge gaps—for example, particular climate regions, pollutant types/loads, and GSI designs and categories for which more or better monitoring data are needed—allowing regulators and implementers to cost-effectively prioritize future quantitative monitoring efforts.

B. Expanded monitoring opens the door for greater design standardization

GSI monitoring is not a goal unto itself. Instead, it is a prerequisite for making headway towards the real goal: cost-effective stormwater management. Monitoring provides performance, cost, and context data that—when shared and compared with other data—increase understanding of how GSI works now and where there is room for improvement. This knowledge enables development of GSI designs that achieve better reliability at lower cost and opens the door for increased design standardization.

Developing standard design options that reliably and cost-effectively address important sets of site variables and pollutants of concern would be a major step in facilitating widespread, distributed GSI implementation.[146]

Greater design standardization could further lower costs and increase reliability, reducing the risk associated with implementing GSI and allowing local implementers to more straightforwardly plan and deploy it at a scale adequate to meet community needs and satisfy regulatory requirements. Helping along more rapid and widespread deployment in this way would achieve bigger near-term water-quality gains, and, ultimately, better progress toward Clean Water Act goals.

While fully standardized designs are not possible, given the need for GSI implementation to be responsive and adaptive to site variability, increased standardization could take the form of libraries of customizable basic designs and specifications that deliver consistently good performance for common sets of site conditions and community objectives. These could be accompanied by detailed guidance for tailoring GSI to meet special local needs or to address unusual site conditions.

To get to the point of confidently creating and implementing more-standardized designs, additional monitoring data are needed. This information can help identify which designs have successfully addressed which combinations of pollutants under which sets of site conditions. The goal is to understand in what contexts—and why—specific design features work.

C. Monitoring considerations:

1. Quantitative and qualitative data matter

Quantitative and qualitative GSI performance data can both be valuable. Quantitative performance data include measurements of the quantity and quality of GSI inflow and outflow. Qualitative performance data can include observations about an installation's apparent condition or function and community feedback regarding perceived benefits.

Beyond performance data, many other types of data are useful, including quantitative or qualitative information about initial and ongoing costs and maintenance needs and site- and design-characterization data.

2. Context is critical

Performance data alone are not enough. Knowing that, somewhere, a GSI installation achieved excellent (or poor) pollutant reduction is not specific enough information to guide future decisions. In contrast, it is more helpful to know that a bioretention cell with particular specifications, built at a site with certain soil, climate, and land use characteristics, effectively captured a particular pollutant of concern, resulting in good outflow water quality. Contextual data such as detailed descriptions of site conditions and design specifications enhance performance data's utility.[147]

3. "Lessons learned" are broadly useful

Monitoring should capture lessons learned, even if they don't fit neatly into another data category. This information, which may be a mixture of qualitative and quantitative data, can serve many purposes. For example, in addition to supporting site-specific adaptive management, it can highlight easily overlooked design and construction issues or suggest solutions for commonly encountered stumbling blocks.

4. Long-term monitoring is necessary

Long-term monitoring helps ensure that GSI actually accomplishes community and regulatory goals. It also provides data that cumulatively build knowledge about (1) how hydrologic and pollutant-removal performance change over time, (2) how GSI can effectively facilitate other benefits (like groundwater replenishment, green jobs, air-quality improvements, and wildlife habitat),[148] (3) the type, frequency, and cost of maintenance needed for good function, and (4) how lifecycle costs for potential alternatives (both "green" and "gray") compare.

BOX 8. COULD GSI BE MORE LIKE SOFTWARE?

Skimping on monitoring and information sharing during the early stages of GSI implementation would ultimately waste scarce resources[149] by hindering the large-scale transition to more effective and sustainable stormwater management. It may be useful to compare GSI implementation with software development.

Software developers write code they expect will function in a certain way. However, the first version of the code is unlikely to perform predictably. Developers gather performance data on early versions, including user-volunteered and automatically generated feedback. This information shows how software functions under real-world conditions. It can reveal issues that require maintenance or design changes and help identify the most appropriate responses.[150] Developers take what they learn into account in subsequent revisions.

In principle, GSI should work the same way, with stormwater managers actively amassing performance data now to enable more effective, more resource-efficient implementation in the near future.

5. Watershed-scale monitoring can address the cumulative benefits of GSI deployment

Where there are multiple installations deployed across a development or within a larger watershed, monitoring their cumulative impacts to receiving waters and local communities over time can address key unknowns. Such monitoring can aid assessment of progress toward meeting community and regulatory goals. Indeed, it is the only way to directly measure the overall effectiveness of a complex array of stormwater control measures. The results of long-term, larger-scale monitoring are highly relevant to municipalities and developers contemplating important infrastructure planning and investment decisions. This type of monitoring can complement and serve as a reality check for cost-effectiveness modeling based on initial assumptions about the cost and performance of individual GSI installations and other stormwater control measures.

6. Data must be effectively shared

Data are most useful when they are easily accessible and readily comparable with other data.[151] Standardized monitoring and reporting protocols can help achieve these goals and support information diffusion.[152]

It can be difficult for prospective implementers to find and interpret others' monitoring results. Currently, scattered monitoring data are available in sources including peer-reviewed scientific literature, white papers, masters theses, dissertations, and the ISBMPD. Data collection methods vary, and important contextual information is often absent, either because no one collected it in the first place or it was not reported. Review articles[153] provide valuable coverage of the information available from field and laboratory studies of GSI, but the limited extent of currently accessible data constrains even the best attempts at synthesis.

BOX 9. MONITORING PROGRAM DESIGN, IMPLEMENTATION, AND FUNDING CHALLENGES

GSI implementers need more detailed guidance from state and federal regulators for designing monitoring programs to address important information needs—including for demonstrating regulatory compliance—within the constraints of technical and financial feasibility. Today, those looking to implement an effective GSI monitoring program must invest substantial resources in designing it from scratch. Although the EPA provides a guidance manual[154] to help with the process, for many implementers this document may spark more questions than answers.

It takes substantial experience and expertise to design an effective monitoring program, and careful work to properly implement it. Challenges include significant variability in the monitored system, selecting and faithfully implementing design-/treatment-train-appropriate monitoring methods and parameters, and accurately characterizing performance relative to important objectives. Since stormwater quality and quantity are highly variable, an effective program must monitor performance over a representative range of storm events, preferably on a long-term basis.[155] Not just average performance, but performance during high-flow events is important for determining surface-water impacts. Different designs may require different monitoring techniques and strategies. For example, pollutant-reduction performance is most straightforward to monitor when GSI has a well-defined inlet and a well-defined outlet, but many categories of GSI (like bioretention cells or vegetated filter strips) may lack one or both, complicating data collection.[156]

Effective monitoring meaningfully gauges GSI's performance relative to specific community and regulatory objectives, so monitoring programs should be targeted to accurately "measure what counts."[157] For example, to understand the impact of GSI on stormwater volume and pollutant load, monitoring needs to address stormwater that bypasses or overflows the system in addition to stormwater the system actually treats.[158] In addition to monitoring individual installations, larger-scale monitoring is necessary to understand the cumulative performance and cost of stormwater management practices in a watershed.[159]

A major challenge for funding GSI monitoring is that regulators and implementers may see it as drawing scarce resources away from actual implementation efforts.[160] However, there is truth in the adage that "you get what you measure."[161] Without monitoring GSI performance, maintenance, and costs, there is no way to tell whether initial assumptions bear out in practice and no data to fuel improvements.

V. Regulators can boost local data collection and sharing

Despite GSI's substantial promise and its embrace by the EPA,[162] some stakeholder groups,[163] and some cities,[164] GSI remains evolving technology in limited use across most of the United States.[165]

Ramping up GSI deployment to the level necessary to achieve important community and regulatory goals will take decades. Reducing uncertainty about immediate and long-term performance, maintenance needs, and costs would facilitate the decision-making process, allowing communities to reap the benefits of GSI more quickly and cost effectively.[166] Given long infrastructure lifespans and investment cycles, accelerating the pace of implementation should be a key priority.

We suggest that the best way to reduce uncertainty in both the numerator and the denominator of the cost-effectiveness ratio—accelerating smarter, more cost-effective GSI planning and implementation—is for regulators to require local implementers to monitor and broadly share data and lessons learned. Federal and state regulators are already supporting GSI, but they have the authority to play a more active role by using Clean Water Act implementation and enforcement to boost data collection and sharing. Specifically, regulators can use NPDES permits for stormwater discharges and CSO consent decrees to increase GSI monitoring and capture relevant quantitative and qualitative information in a broadly accessible, centralized database.

A. Local implementers need incentives to monitor and share information

Stormwater permit requirements and CSO consent decrees often act as direct or indirect drivers for GSI implementation,[167] but local implementers generally decide where and how to incorporate GSI. Decentralized decision making provides important flexibility to tailor stormwater management solutions to local priorities and conditions. It also leaves most questions about where, when, and how to monitor in local hands. Where formal monitoring and performance evaluation occur, they are conducted piecemeal by nonprofits, universities, product manufacturers, municipalities, and (occasionally) state or regional testing and evaluation programs.[168] For some sites monitoring is extensive, while others receive little attention. Monitoring results are not always shared or provided in a useful format.

Although hydrologic performance is important for all implementers, some install GSI without monitoring it or execute inappropriately designed monitoring programs that don't accurately characterize hydrologic performance. Unfortunately, improper monitoring can obscure or exaggerate performance problems.[169]

Some implementers monitor hydrologic performance, but not pollutant removal, on the assumption that stormwater volume acts as an effective proxy for stormwater impacts to local waters. They may assume that runoff reductions automatically translate into surface-water water-quality improvements. From a regulatory-compliance standpoint, this assumption makes sense for addressing water quality violations caused by CSOs.[170] Municipalities with combined sewer systems have engaged in some of the most extensive GSI planning and deployment to date, but they may not capture information on the pollutant-removal capabilities of GSI, which are seen as peripheral.[171] Stormwater permittees may invoke similar logic to infer that GSI stormwater volume reductions automatically translate into decreased pollutant loads to local waters. However, given the widespread use of underdrains that connect with existing storm-sewer infrastructure (**Figure 1**) and the fact that improperly designed, installed, or maintained GSI may not be effective (**Figure 2**),[172] this reasoning may not be fully justified.

Furthermore, implementers who are focused on meeting surface-water water-quality requirements may not recognize a need to monitor GSI's potential groundwater water-quality impacts. Yet, the groundwater water-quality implications of GSI are of general long-term importance, whether or not local priorities currently include groundwater recharge. Stormwater pollution has contributed to urban aquifer contamination in some cases.[173] In many states, one-

third or more of water withdrawals for public supply are from groundwater, and, in all states, groundwater withdrawals are the dominant source of domestic self-supplied water.[174] Reliance on local groundwater is expected to grow as climate variability and population growth intensify pressure on surface-water supplies.[175]

When GSI implementation does include performance monitoring, resource constraints may mean it covers a very limited set of pollutants and other parameters, happens for only a short time, or both.

Even if implementers do collect broadly relevant data, the data may not be easily accessible, accessible data may lack important contextual information, or they may be difficult to compare with data from other installations due to differing monitoring and reporting protocols.

Providing new incentives for local implementers to gather and effectively share information about their implementation efforts would harness opportunities for knowledge building, facilitating cost-effective GSI implementation and speeding the pace of deployment.

B. Clean Water Act permitting and enforcement can drive monitoring and information sharing

The EPA and state water quality authorities are already encouraging or requiring GSI implementation through stormwater permits and CSO consent decrees.[176] A natural extension would be to add or expand associated monitoring and reporting requirements.

Congress passed the Clean Water Act "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters."[177] The Act bars the unpermitted point-source discharge of pollutants into waters of the United States[178] and sets a national policy prohibiting "the discharge of toxic pollutants in toxic amounts."[179] The eventual goal is to eliminate the discharge of pollutants to U.S. waters.[180]

The EPA or an approved state program can issue NPDES permits for discharges from sewage treatment plants, industrial facilities, MS4s, and other point sources.[181] Stormwater permits generally require MS4 operators to plan and implement a suite of "best management practices" (BMPs) to provide for the attainment of water quality standards[182] and include, where applicable, water-quality-based effluent limitations that are consistent with the wasteload allocations identified in TMDLs developed for impaired waters.[183] BMPs are "structural and nonstructural controls and operation and maintenance procedures" that "reduce or eliminate the introduction of pollutants into receiving waters,"[184] including GSI.

More and more MS4 permits include explicit requirements for municipalities to manage runoff with GSI, most often by requiring new and redevelopment projects to incorporate the technology.[185] California municipal stormwater permits provide examples of various approaches.[186]

The Clean Water Act and related regulations establish monitoring and reporting requirements for NPDES permits.[187] Permits must include "conditions . . . to assure compliance" with permit limitations, "including conditions on data and information collection, reporting, and such other requirements as [the permitting authority] deems appropriate."[188] These conditions can include detailed monitoring and reporting protocols.[189]

Stormwater permittees must evaluate the effectiveness of their stormwater programs and BMPs.[190] What constitutes an adequate evaluation or demonstration of effectiveness depends on the stringency and specificity of the particular permit's requirements. For example, demonstrating compliance with a permit that includes firm numeric water-quality-based effluent limitations (e.g., related to TMDLs for waters impaired by particular pollutants), would likely require more water-quality-related monitoring than would demonstrating compliance with narrative effluent limitations or minimum BMP requirements.[191]

The EPA has made clear that GSI, like other BMPs, requires effectiveness evaluation, stating:

> NPDES permits and enforcement agreements that incorporate green or gray infrastructure solutions require enforceable performance criteria, implementation schedules, monitoring plans and protocols, progress tracking and reporting, and operation and maintenance requirements.[192]

Despite this guidance, many permits lack monitoring and reporting requirements for mandated GSI.

Other permits already include GSI monitoring and reporting requirements, but these could be made more detailed, more expansive, and, ultimately, more useful.

Two examples are the San Francisco Bay and Los Angeles municipal regional stormwater permits.

The current San Francisco Bay municipal regional stormwater permit requires permittees to "cumulatively complete ten pilot green-streets projects that incorporate LID techniques for site design and treatment" and to "conduct appropriate monitoring of these projects to document the water quality benefits achieved."[193] The permit suggests "appropriate monitoring" could consist solely of modeling based on design specifications and site-specific conditions, without any actual performance monitoring at all.[194] However, modeling results could be misleading, given that relationships between design specifications, site conditions, and performance may not be well characterized or understood.[195] The permit's green-streets pilot-project reporting requirements include project maps, capital costs, operation and maintenance costs, funding sources, and lessons learned.[196] There is a separate requirement for the permittees to collectively "[i]nvestigate the effectiveness of one BMP for stormwater treatment or hydrograph modification control."[197] This investigation must address "the range of pollutants generally found in urban runoff."[198] There are no more specifics about the effectiveness investigation.

The San Francisco Bay permit's GSI monitoring and reporting requirements have some positive features, but they could be considerably stronger. While the reporting requirements for the green streets projects include much useful information, there is little guidance for what constitutes "appropriate monitoring," the scope and content of an appropriate "effectiveness investigation," or what monitoring and reporting protocols should be followed. In addition, little actual performance data is required, only a very small number of GSI installations are affected, and the resulting data are not explicitly incorporated into a broadly accessible database. These limitations add up to substantial missed opportunity for knowledge gain.

The Los Angeles municipal regional stormwater permit makes a good start, with mandates for certification, tracking, and inspection of GSI implemented to meet new and redevelopment requirements.[199] LA-area permittees must demand "an operation and maintenance plan, monitoring plan, where required, and verification of ongoing maintenance provisions for [GSI]."[200] Permittees must also "verify proper maintenance and operation" of previously approved GSI.[201] However, it is unclear how "operation" is verified or when a monitoring plan is actually required. Furthermore, the effectiveness-tracking requirement appears to be satisfied if the permittee maintains a database of design-storm related information for new and re-development projects / BMPs.[202] In other words, there are no obvious requirements for actual performance monitoring, detailed site characterization (i.e., context) data, or actual cost data, and effectiveness-tracking data are not intended to be made widely available. Again, the permit has missed opportunities to require collection and sharing of useful information about GSI performance and lifecycle costs.

Like NPDES permits, CSO consent decrees could incorporate more useful monitoring and reporting requirements for GSI.

C. Existing databases can house and provide access to monitoring data

A centralized database already exists that could house expanded GSI monitoring data: the ISBMPD. The EPA supported its creation in the late 1990s in order to "provide scientifically sound information to improve the design, selection and performance of BMPs."[203] In addition to serving as a public repository for voluntarily reported data that researchers and implementers can contribute to and draw on, the website provides monitoring and reporting guidance.[204]

Substantial planning and effort have gone into the database, but it needs more data to fulfill its promise (see **Boxes 6**, **7**, **9**, and **10**). An organizing principle and major goal is "continued growth to enable compilation of a robust data set that is ultimately appropriate for evaluating BMP design parameters and site-specific factors contributing to BMP performance."[205] Today the database contains information about more than 500 stormwater control measures, including GSI,[206] but more, more complete, and more consistently gathered and formatted data for GSI installations are needed. The available data derive from a small fraction of the GSI installations that currently exist, and the information contributed is often very incomplete (see **Table 2**, **Boxes 6** and **10**).

The water-quality and water-volume performance data in the ISBMPD undergo periodic statistical

analysis and summarization.[207] (For examples, see **Table 2** and **Box 10**.)

GSI monitoring can also contribute data to a second EPA-supported and nationally important database: the NSQD.[208] The NSQD collects stormwater runoff characterization data gathered by MS4 permittees around the country.[209] Influent and effluent water-quality data are valuable not only for understanding GSI pollutant-removal performance but also for their utility in characterizing and tracking changes in ambient stormwater pollution over time.[210] Therefore, these, and other water-quality-related data should find a second home in the NSQD.

With expanded, up-to-date content, both databases would be invaluable sources of information to drive more effective GSI modeling,[211] decision making, and implementation. Therefore, increasing the flow of incoming data should be a priority. Meaningfully boosting submission quantity, breadth, and quality will require hands-on guidance and support from the EPA and state water quality authorities.

D. Specific recommendations

To boost local data collection and sharing, with the aim of accelerating cost-effective GSI deployment, we recommend that state and federal regulators take the following seven basic actions.

BOX 10. EXPANDING THE ISBMPD WILL HELP LINK GSI DESIGN WITH PERFORMANCE

Increasing the quantity and quality of data in the ISBMPD could speed identification of the most cost-effective GSI designs for different sets of site constraints.

A 2013 review of ISBMPD that sought to identify relationships between specific BMP design variables and pollutant-reduction performance concluded that design-related content was "relatively limited."[212] As might be expected, the review failed to identify any statistically significant relationships between bioretention design variables and pollutant-reduction performance.[213] It focused on 6 pollutants and 3 design variables,[214] noting that the effects of a fourth, likely very important, parameter (soil media composition) could not be evaluated due to "inconsistent and incomplete" information.[215] Similarly, there were not enough data available to meaningfully analyze 2 of the 6 pollutants initially targeted.[216] Many of the 30 bioretention studies in the database lacked one or more types of relevant design or water-quality data.[217]

This example illustrates the current data deficit and hints at what could be gained from collecting and sharing more and better contextualized GSI data.

Action 1. Incentivize voluntary monitoring and reporting

Monitoring and data sharing are important today. However, it may take some time to accomplish **Actions 2**, **3**, and **4**. Therefore, as an initial step, regulators should highlight the importance of voluntarily monitoring GSI and contributing data to the ISBMPD and should encourage implementers to do both.

Action 2. Identify quantitative and qualitative monitoring priorities

State and federal regulators should develop quantitative and qualitative monitoring priorities through intensive discussions with stakeholders, including the regulated community, environmental organizations, other state and federal agencies, and other parties with relevant scientific and technical expertise.

Some monitoring priorities may be feasible for all required implementers to address. These include actual costs, maintenance performed, and qualitative performance measures—information that local implementers should be collecting already.

On the other hand, it may not be feasible to require extensive quantitative performance monitoring of every GSI installation required by an NPDES permit or consent decree. Therefore, regulators (in consultation with the stakeholders mentioned above) will need to decide where quantitative performance monitoring can be focused most fruitfully (e.g., all GSI facilities in environmentally sensitive or especially polluted areas, some fraction of the GSI facilities in the permit

region, etc.) in light of national, regional, and local or watershed-based objectives and information gaps.

Ideally, monitoring priorities will be nested or layered, with regional- and watershed-level priorities supplementing national priorities developed with EPA leadership. For example, national priorities would include a core water-quality monitoring suite that state or regional regulatory authorities would build upon to ensure that local objectives and pollutants of concern are addressed.

Action 3. Adopt standardized monitoring and reporting protocols and guidance

Because monitoring and reporting that follow standard protocols are most useful, after consulting with stakeholders (as for **Action 2**), state and federal authorities should jointly adopt consistent monitoring and reporting protocols.

These should be explained in detail in an updated EPA monitoring manual that describes acceptable monitoring methods, equipment and specifications, data collection frequency, reporting requirements, etc., for different categories of GSI. The manual should include modified protocols, as needed, for different climates and other relevant site characteristics. It should also explain which data are suitable for demonstrating compliance in different regulatory contexts.

Action 4. Include specific monitoring and reporting requirements in NPDES permits and consent decrees

State and federal regulators should attach specific data collection and reporting requirements[218] to GSI required by NPDES permits and consent decrees.

Low-hanging fruit include information that local implementers already are—or should be—producing and tracking for their own internal accounting and management purposes (e.g., for confirming proper installation, assessing whether GSI is functioning as intended, determining when maintenance is needed, and keeping track of expenses). Therefore, we recommend that standard monitoring and reporting requirements address the following:

- Relevant site conditions
- Community and regulatory goals
- As-built GSI plans/specifications and later modifications
- Initial and ongoing qualitative performance (e.g., based on visual inspections, community feedback, etc.)
- Frequency and type of maintenance performed
- Actual costs:
  - Installation costs
  - Operations and maintenance costs
  - Monitoring and reporting costs
- Estimated avoided costs (e.g., cost-savings achieved by using GSI to address multiple community needs)
- Lessons learned (e.g., about design, installation, performance, costs, public response, etc.)

Note that the details of these requirements would largely be determined through **Actions 2** and **3**.

In addition to these standard, broadly applicable monitoring and reporting requirements, regulators should impose supplemental requirements for quantitative performance monitoring on a subset of GSI installations, consistent with the monitoring priorities identified in **Action 2**. These should address:

- Initial and long-term hydrologic performance[219]
- Initial and long-term pollutant-removal performance (for both a suite of pollutants of general interest and pollutants of special local interest)[220]

Permits and consent decrees should make clear what role specific data will play in demonstrating regulatory compliance.

Action 5. Capture required monitoring data in the ISBMPD

Permits and consent decrees should require implementers to submit monitoring data for inclusion in the ISBMPD.[221]

Regulators could require individual implementers to submit data directly to the ISBMPD or require reporting to state- or regional-level databases that regularly feed accumulated data into the ISBMPD.[222] The latter method might make it easier for state permitting authorities to oversee compliance and confirm data quality. Furthermore, supplying and accessing data that are more locally focused might be more palatable to permittees.

On the other hand, coordinating GSI monitoring-data submission with the implementation of EPA's upcoming NPDES Electronic Reporting Rule[223]

could prevent time and labor duplication. This might entail redesigning the NPDES Integrated Compliance Information System[224] to facilitate the carryover of monitoring data to the ISBMPD.

Action 6. Feed water-quality-related monitoring data into the NSQD

Data that characterize stormwater pollution—including influent and effluent water-quality data—should also be included in the NSQD. To streamline the process for data contributors, these data could be supplied to the NSQD through the ISBMPD.

Action 7. Prioritize sustained support for quantitative monitoring, database upkeep, and meta-analysis

Finally, we recommend that state and federal regulators prioritize funding and other resources (1) to help lessen the financial and technical burden on local implementers tasked with quantitative monitoring and (2) to ensure that the ISBMPD and the NSQD are able to provide timely, relevant data and meta-analysis over the coming decades.

While we understand that funds are limited at all levels of government, sustained financial support for quantitative performance monitoring priorities—which benefit all but will likely be undertaken by a limited range of implementers—could be crucial for speeding learning. Furthermore, without database maintenance and periodic meta-analysis of accumulated data, even the most comprehensive monitoring efforts could have limited utility.

Prioritizing resources for these activities will most efficiently achieve the broad public benefits regulators seek.

VI. Conclusion

In sum, our argument is a simple one. GSI is critical to solving stormwater management challenges. Barriers, including uncertainty about performance and cost, impede widespread, cost-effective implementation. More extensive and effective monitoring and data sharing will enable learning about what works best, reducing uncertainty. State and federal regulators can actively accelerate cost-effective GSI deployment by requiring local implementers to monitor performance, maintenance, and costs and to broadly share their data and lessons learned.

Over the coming decades, GSI will be increasingly important for stormwater management. However, developing best practices for using GSI—and demonstrating its role in regulatory compliance—will require more thorough understanding of performance, maintenance needs, and costs. Uncertainty about the life-cycle costs or the effectiveness of green- and gray-infrastructure options makes it hard to accurately compare them. This impairs decision making about where and how to implement GSI, increasing the likelihood of underinvestment in GSI or overspending on inappropriate GSI. Improved understanding of which techniques are effective under different circumstances will facilitate more accurate cost-effectiveness comparisons, support better decision making, and open the door for increased design standardization.

The EPA and state water quality authorities can take a more active role in growing the collective GSI knowledge base to speed cost-effective deployment. Specifically, they can harness—and amplify—the potential for collective learning from each instance of local implementation by adopting the recommendations detailed in this report and summarized below.

The first step (**Action 1**) is for regulators to more actively promote voluntary monitoring and data sharing, but **Actions 2** and **3** should also begin immediately. Fleshing out monitoring priorities, more detailed monitoring and reporting requirements, and the practical guidance that will aid implementers in carrying them out will require deep and thoughtful consideration and input from many sources.

We offer these recommendations as a starting point that we hope will spark further discussion and action.

RECOMMENDED ACTIONS FOR STATE AND FEDERAL REGULATORS:	
1	As an initial step, incentivize and highlight the importance of voluntary GSI monitoring and data contribution to the ISBMPD.
2	Identify quantitative and qualitative GSI monitoring priorities through intensive discussions with stakeholders.
3	Adopt standardized GSI monitoring and reporting protocols and guidance.
4	Attach monitoring and reporting requirements to GSI required by NPDES permits and consent decrees. • Require all implementers to gather and report relevant site, design, and cost data; qualitative performance data; maintenance data; and lessons learned according to standardized protocols. • Assign additional requirements for collection and reporting of quantitative performance data to a subset of GSI installations, consistent with identified monitoring priorities.
5	Capture required GSI monitoring data in the ISBMPD. Options for accomplishing this include: • Requiring individual implementers to submit data directly to the ISBMPD. • Collecting data in state or regional databases that regularly feed accumulated data into the ISBMPD. • Coordinating data submission with implementation of the NPDES Electronic Reporting Rule by redesigning the NPDES Integrated Compliance Information System to facilitate carryover of monitoring data to the ISBMPD.
6	Feed water-quality-related GSI monitoring data into the NSQD.
7	Prioritize sustained financial and technical support for quantitative GSI performance monitoring, database upkeep, and timely meta-analysis of accumulated monitoring data.

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Any errors are the responsibility of the authors alone.

VIII. Endnotes

[1] *See* Nat'l Research Council, Urban Stormwater Management in the United States 25, 340–41, 343 (2009), *available at* http://www.nap.edu/catalog/12465/urban-stormwater-management-in-the-united-states (describing the advent of "the modern urban drainage system" and its impacts); Reg'l Plan Ass'n, 9 Ways to Make Green Infrastructure Work in Cities & Towns 3 (2012), *available at* http://www.rpa.org/library/pdf/RPA-9-Ways-to-Make-Green-Infrastructure-Work.pdf (identifying adverse development-related impacts from decreased local stormwater infiltration).

[2] *See* Seth J. Wenger et al., *Twenty-Six Key Research Questions in Urban Stream Ecology: An Assessment of the State of the Science*, 28 J. N. Amer. Benthological Soc'y, 1080, 1086–1089 (2009) (describing physical, chemical, and biological urban stream stressors); Nat'l Research Council, *supra* note 1, at 28–30, 231–33 (summarizing the hydrologic, geomorphic, and biological effects of urbanization and urban stormwater on watersheds); Christopher J. Walsh et al., *The Urban Stream Syndrome: Current Knowledge and the Search for a Cure*, 24 J. N. Amer. Benthological Soc'y 706, 713 (2005); G. Allen Burton, Jr. & Robert E. Pitt, Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers 63–64 (2001) (describing stormwater-induced changes in stream flow, stream and floodplain morphology, riparian vegetation, and sediment loading). Stormwater burden appears to be a root cause of "urban stream syndrome," the "cascade of changes" that occurs in urbanized watersheds. Wenger et al., *supra*, at 1081; *see also* Walsh et al., *supra*, at 706, 713 ("The mechanisms driving the syndrome are complex and interactive, but most impacts can be ascribed to a few major large-scale sources, primarily urban stormwater runoff delivered to streams by hydraulically efficient drainage systems."). These consistently "include a flashier hydrograph, elevated concentrations of nutrients and contaminants, altered channel morphology and stability, and reduced biotic richness, with increased dominance of tolerant species," and often include "other symptoms . . , such as reduced baseflow or increased suspended solids." Walsh et al., *supra*, at 707, 708 tbl.1, 709 fig.1. Human activities have increased stormwater runoff by replacing natural pervious surfaces with impervious surfaces like pavements, roofs, and compacted sediments. *See generally* David J. Nowak & Eric J. Greenfield, *Tree and Impervious Cover in the United States*, 107 Landscape & Urban Planning 21, 22, 28–29 (2012). Aquatic ecosystem degradation can accompany even very low levels (a few percent) of directly connected impervious cover in a watershed. *See* U.S. Envtl. Prot. Agency, Estimating Change in Impervious Area (IA) and Directly Connected Impervious Areas (DCIA) for New Hampshire Small MS4 Permit 1 (revised 2014), *available at* http://www.epa.gov/region1/npdes/stormwater/nh/NHDCIA.pdf ("Typically watersheds with 4–6% IA start to show [negative] impacts, though recent work has found lower % IA threshold values for sensitive species. Watersheds exceeding 12% IA often fail to meet aquatic life criteria and narrative standards." (internal citations omitted)); Seth J. Wenger et al., *Stream Fish Occurrence in Response to Impervious Cover, Historic Land Use , and Hydrogeomorphic Factors*, 65 Can. J. Fish. Aquat. Sci. 1250, 1253, 1260, 1260 fig.4 (2008) (reporting that some fish species become rare at effective (directly connected) impervious area coverage of as low as 2%); *see also* Walsh et al., *supra*, at 715, 715 fig.2. "Directly connected impervious cover" is the portion of impervious cover that has a direct hydraulic connection to a storm sewer system or body of surface water "via continuous paved surfaces, gutters, drain pipes, or other conventional conveyance and detention structures that do not reduce runoff volume." U.S. Envtl. Prot. Agency, *supra*, at 1.

[3] *See* Matthew A. Wilson et al., *Assessment of Hydrodynamic Separators for Storm-Water Treatment,* 135 J. Hydraulic Eng'g 383 (2009) (describing hydrodynamic separators as "proprietary underground devices designed to remove floatable debris (e.g., leaves, trash, oil) and to remove suspended solids from storm-water runoff by sedimentation").

[4] *See* Mich. Dep't Envtl. Quality, Michigan Nonpoint Source Best Management Practices Manual: Sediment Basin, SB-1 (2014), *available at* http://www.michigan.gov/documents/deq/nps-sediment-basin_332133_7.pdf (describing a sediment basin as "a temporary pond with appropriate control structures built on a construction site, to capture eroded or disturbed soil that is washed off during rain storms; designed to protect neighboring properties from damage; and to protect the water quality of nearby streams, rivers, lakes, and wetlands").

[5] In areas with combined sewer systems, mixed stormwater and sewage are treated at a wastewater treatment plant unless stormwater overwhelms the collection/treatment system's capacity. *See* discussion *infra* **Part III.A**, including **Box 4**.

[6] For example, switching to unleaded gasoline in the United States "resulted in an order-of-magnitude reduction of lead levels in stormwater runoff in a decade." Nat'l Research Council, *supra* note 1, at 358; *see also, e.g.*, Peter C. Van Metre & Barbara J. Mahler, *PAH Concentrations in Lake Sediment Decline Following Ban on Coal-Tar-Based Pavement Sealants in Austin, Texas*, 48 Envtl. Sci. & Tech. 7222, 7226 (2014) (noting that, "although PAH concentrations are declining, existing stocks of coal-tar sealants continue to contribute the largest proportion of PAHs to the lake sediments, implying that PAH concentrations should continue to decrease as those stocks are depleted"). However, more and better source control is possible. For example, the 2009 NRC Report noted that EPA has not used "its existing licensing authority to regulate . . . products [like de-icing chemicals, materials used in brake linings, motor fuels, asphalt sealants, and fertilizers] in a way that minimizes their contribution to stormwater contamination." Nat'l Research Council, *supra* note 1, at 4.

[7] Pollutants "remaining even in 'treated' stormwater represent a substantial, but largely unappreciated, impact to downstream watercourses." Nat'l Research Council, *supra* note 1, at 25. A broad spectrum of sources contributes to urban stormwater pollution. *See id.* at 32. For example, trash accumulates on pavements and in storm drains. Exhaust components, brake dust, motor oil, gasoline, and diesel fuel come from motor vehicles. Road salts, other deicers, and traction sand run off of roads, sidewalks, and driveways. Plant debris, soil, fertilizers, and pesticides run off of lawns, gardens, and landscaped areas. Pavements, pavement sealants, and road paint erode. Rainwater leaches roofing and building materials and rinses pet and other animal wastes from roofs, sidewalks, and landscaped areas. *See, e.g.,* Nat'l Research Council, *supra* note 1, at 176–207. The composition and concentration of pollutants in stormwater and the volume of stormwater runoff vary over time and depend on climate, weather, watershed characteristics, and the type, intensity, and history of local and regional land uses. *See* Jartun et al., *Runoff of Particle Bound Pollutants from Urban Impervious Surfaces Studied by Analysis of Sediments from Stormwater Traps*, 396 Sci. Total Env't 147, 147 (2008). Stormwater exposes aquatic ecosystems to many different pollutants at once, including sediments, metals, organic compounds, nutrients, pesticides,

bacteria, salts, and trash. *See* Nat'l Research Council, *supra* note 1, at 232; Andrew J. Erickson et al., Optimizing Stormwater Treatment Practices: A Handbook of Assessment and Maintenance 11–22 (2013) (describing stormwater pollutant impacts and composition); Seattle Dep't of Planning & Dev. & Seattle Pub. Utils., Stormwater Manual Vol. 1: Source Control Technical Requirements Manual 1-2–1-4 (2009), *available at* http://www.seattle.gov/dpd/codes/dr/DR2009-15.pdf (summarizing typical stormwater pollutants, their hazards, and common sources); Natural Res. Def. Council, Stormwater Strategies: Community Responses to Runoff Pollution ch. 2 (1999), *available at* http://www.nrdc.org/water/pollution/storm/stoinx.asp. The impacts of this combined pollutant load are not fully understood. *Cf.* M. Moiz Mumtaz et al., *Introduction to Mixtures Toxicology and Risk Assessment, in* Principles & Practice of Mixtures in Toxicology 1 (Moiz Mumtaz ed., 2010). However, stormwater is often toxic to aquatic organisms. *See, e.g.*, Janet Y. M. Tang et al., *Toxicity Characterization of Urban Stormwater with Bioanalytical Tools*, 47 Water Research 5594, 5603 (2013) (finding "high baseline toxicity, genotoxicity after metabolic activitation[,] and oxidative stress response" in urban runoff); T. Mayer et al., *Environmental Characterization of Surface Runoff from Three Highway Sites in Southern Ontario, Canada:1. Chemistry*, 46.2 Water Quality Research J. of Canada 110, 110 (2011) ("Highway runoff is a significant source of contaminants entering many freshwater systems."); U.S. Envtl. Prot. Agency, Assessment of Water Quality of Runoff from Sealed Asphalt Surfaces 4 (2011); Nat'l Research Council, *supra* note 1, at 217; Darrin J. Greenstein et al., *Toxicity of Parking Lot Runoff After Application of Simulated Rainfall*, 47 Arch. Environ. Contm. & Toxicol. 199, 199 (2004) ("Every runoff sample tested was found to be toxic."); J. Marsalek et al., *An Exploratory Study of Urban Runoff Toxicity*, 39 Water Sci. & Technology 33, 33 (1999) (finding that "almost 20% of MLDH [multi-lane divided highway runoff] samples were severely toxic compared to 1% of urban stormwater samples"); Denny R. Buckler & Gregory E. Granato, Assessing Biological Effects from Highway-Runoff Constituents 2 (1999) (Although highway runoff "may not usually be acutely toxic," "[t]issue analysis and community assessments . . . indicate effects[—elevated concentrations of highway-runoff constituents in tissues and decreases in diversity and aquatic ecosystem productivity—]from highway-runoff sediments near discharge points (even from sites near highways with relatively low traffic volumes)."). It can also be hazardous to human health. *See, e.g.,* Barbara J. Mahler et al., *Coal-Tar-Based Pavement Sealcoat and PAHs: Implications for the Environment, Human Health, and Stormwater Management*, 46 Envtl. Sci. & Tech. 3039, 3043 (2012); Elizabeth P. Sauer et al., *Detection of the Human Specific Bacteroides Genetic Marker Provides Evidence of Widespread Sewage Contamination of Stormwater in the Urban Environment*, 45 Water Research 4081, 4081 (2011); Nat'l Research Council, *supra* note 1, at 225 (referencing studies that "provide ample evidence that stormwater runoff can serve as a vector of pathogens with potential health implications").

[8] *See* Nat'l Research Council, *supra* note 1, at 32 ("[S]tormwater treatment must address not only "pollutants" but also physically and ecologically deleterious changes in flow rate and total runoff volume."); *id.* at 34, 218 (discussing temperature).

[9] *See What is Green Infrastructure?,* U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_what.cfm (last updated June 13, 2014).

[10] *See id.*; Noah Garrison & Karen Hobbs, Natural Res. Def. Council, Rooftops to Rivers II: Green Strategies for Controlling Stormwater and Combined Sewer Overflows 13 (2011), *available at* http://www.nrdc.org/water/pollution/rooftopsII/files/rooftopstoriversII.pdf.

[11] *See* U.S. Envtl. Prot. Agency et al., Managing Wet Weather with Green Infrastructure: Action Strategy 7 (2008) [hereinafter Managing Wet Weather], *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/gi_action_strategy.pdf (describing green infrastructure as "a cost effective and . . . environmentally preferable approach to reduc[ing]stormwater and other excess flows entering combined or separate sewer systems in combination with, or in lieu of, centralized hard infrastructure solutions").

[12] *See* U.S. Envtl. Prot. Agency, Enhancing Sustainable Communities with Green Infrastructure 6 (Oct. 2014), *available at* http://www.epa.gov/smartgrowth/pdf/gi-guidebook/gi-guidebook.pdf.

[13] *See id.*

[14] *See id.*; *see also* Managing Wet Weather, *supra* note 11, at 5–6; *Why Green Infrastructure?*, U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_why.cfm (last updated July 22, 2014); Alexandra Dapolito Dunn, *Siting Green Infrastructure: Legal and Policy Solutions to Alleviate Urban Poverty and Promote Healthy Communities*, 37 Envtl. Affairs 41, 41, 46–50 (2010); Ctr. for Neighborhood Tech., The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social benefits 3 (2010), *available at* http://www.cnt.org/repository/gi-values-guide.pdf (identifying the potential benefits of green infrastructure practices).

[15] *See* Dunn, *supra* note 14, 50–51; Low Impact Dev. Ctr., Low Impact Development Manual for Southern California: Technical Guidance and Site Planning Strategies 9 (2010), *available at* https://www.casqa.org/resources/lid/socal-lid-manual; *Why Green Infrastructure?*, *supra* note 14.

[16] The EPA has been actively encouraging GSI since 2007 and maintains an extensive GSI website. *See What is EPA Doing to Support Green Infrastructure?*, U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_support.cfm (last updated July 22, 2014); *Green Infrastructure*, U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/ (last updated Oct. 27, 2014) (providing basic information about green infrastructure and what EPA is doing to support it, cost-benefit resources, policy guides, design and implementation resources, modeling tools, information about funding opportunities, etc.). The agency has a "strategic" GSI agenda. *See* U.S. Envtl. Prot. Agency, Green Infrastructure Strategic Agenda 2013, *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/2013_GI_FINAL_Agenda_101713.pdf. It issues policy memos and other documents "clarifying the relationship of its enforcement, drinking water, and water permitting programs to the implementation of green infrastructure" and enters into MOUs that "document how EPA can work with other organizations to accelerate" GSI implementation. *What is EPA Doing to Support Green Infrastructure?: Policy Memos and MOUs*, U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_support.cfm#PolicyMemos (last updated July 22, 2014); *see also, e.g.,* Memorandum from Nancy Stoner, Acting Assistant Adm'r, U.S. Envtl. Prot. Agency, to EPA Reg'l Adm'rs, OW & OECA Office & Div. Dirs., at 2 (Apr. 20, 2011), *available at* http://www.epa.gov/npdes/pubs/gi_memo_protectingwaterquality.pdf (regarding "Protecting Water Quality with Green Infrastructure in EPA Water Permitting and Enforcement Programs"); *Federal Regulatory*

Programs, U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_regulatory.cfm (last updated April 10, 2014) (providing links to policy memos and GSI-related permitting and enforcement guidance and fact sheets). EPA engages in community partnerships to highlight successful implementation and share lessons learned and provides technical assistance directly to communities. *See What is EPA Doing to Support Green Infrastructure?*, *supra*. Because EPA believes that "[r]egulatory drivers can provide an effective foundation for the consistent implementation of green infrastructure across a community, state, or region," the agency shows "how green infrastructure can be integrated into federal regulatory programs" under the Clean Water Act "for municipal separate storm sewer systems (MS4s), combined sewer overflows (CSOs), and Total Maximum Daily Loads (TMDLs)." *Federal Regulatory Programs*, *supra*. State and federal stormwater permitting authorities have included numeric post-construction GSI standards in general and/or individual MS4 permits in various states. *See infra* note 59 and accompanying text. More and more commonly, water-quality-based effluent limitations in MS4 permits are directly or indirectly driving GSI implementation. *See infra* note 60 and accompanying text. Additionally, since 2009, a number of CSO consent decrees (or decree amendments) have included GSI requirements or options. *See infra* note 48 and accompanying text. Other federal agencies, in addition to EPA, support GSI. *See A Roadmap to Green Infrastructure in the Federal Agencies*, Nat'l Ass'n Reg'l Councils, http:// http://narc.org/environment/green-infrastructure-and-landcare/roadmap/ (last visited Jan. 5, 2015). For example, on July 16, 2014, EPA announced a Green Infrastructure Collaborative between itself and the federal Departments of Housing and Urban Development, Transportation, Agriculture, Interior, and Defense. *See* Letter of Federal Agency Support for the Green Infrastructure Collaborative, *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/Federal-Support-for-Green-Infrastructure-Collaborative_508.pdf (describing agency commitments). More recently, EPA announced a broader Green Infrastructure Collaborative that includes a variety of professional, conservation, and other stakeholder organizations in a "network[]-based learning alliance" to "build capacity for green infrastructure implementation." *See* U.S. Envtl. Prot. Agency, Green Infrastructure Collaborative: Statement of Support (Oct. 8, 2014), *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/greeninfrastructure_collaborative2014.pdf.

[17] Green infrastructure is most effective when incorporated at a range of scales. *See* Ctr. for Leadership in Global Sustainability, Greening the Grey: An Institutional Analysis of Green Infrastructure for Sustainable Development in the US 13 (2013), *available at* http://cligs.vt.edu/wp-content/uploads/2014/01/CLiGS-NARC_GI2013_final.pdf (describing green infrastructure "as a multi-scale network of ecological features and systems that provide multiple functions and benefits" that "provides a systems approach to planning and development that recognizes the value of ecosystem services and strives to integrate and enhance those ecosystem services within our built environment"); *see also* Reg'l Plan Ass'n, *supra* note 1, at 3–6 (describing nested watershed, city, neighborhood, and site level strategies). At a regional scale, riparian corridors, wetlands, and other protected or restored open spaces are important components of green infrastructure. *See* U.S. Envtl. Prot. Agency, Water Quality Scorecard: Incorporating Green Infrastructure Practices at the Municipal, Neighborhood, and Site Scales 2–3 (2009) [hereinafter EPA Scorecard], *available at* http://www.epa.gov/smartgrowth/pdf/2009_1208_wq_scorecard.pdf. On a community level, green infrastructure encompasses planning and development that maximizes undeveloped areas, minimizes impervious cover, and achieves better integration of the natural and built environments. *See id.* This includes compact, mixed-use infill and redevelopment, reduced parking areas, complete/green streets, and urban forestry initiatives. *See id.* at 3. Finally, at a particular site, green infrastructure "mimics natural systems by absorbing stormwater back into the ground (infiltration), using trees and other natural vegetation to convert it to water vapor (evapotranspiration), and using rain barrels or cisterns to capture and []use stormwater." *See id.* at 2. Infiltration- and evapotranspiration-oriented green infrastructure facilities include bioretention systems (rain gardens), vegetated swales and median strips, permeable pavements, and green roofs. *See* Managing Wet Weather, *supra* note 11, at 3. **This site-scale green infrastructure is what this report calls "GSI."**

[18] *See* EPA Scorecard, *supra* note 17, at 2–3; *See* Managing Wet Weather, *supra* note 11, at 4–5. The EPA uses the term green infrastructure to broadly encompass "systems and practices that use or mimic natural processes to . . . support the principles of" low impact development (LID). *Low Impact Development (LID)*, U.S. Envtl. Prot. Agency, http://water.epa.gov/polwaste/green/ (last updated Oct. 3, 2014) [hereinafter *EPA LID*].

[19] LID is an approach to development and redevelopment that "manage[s] stormwater as close to its source as possible" by "preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and appealing site drainage that treat[s] stormwater as a resource rather than a waste product." *EPA LID, supra* note 18; *see also Low Impact Development (LID) and Other Green Design Strategies*, U.S. Envtl. Prot. Agency, http://water.epa.gov/polwaste/npdes/swbmp/Low-Impact-Development-LID-and-Other-Green-Design-Strategies.cfm (last updated July 2, 2014); Prince George's County, Maryland, Low-Impact Development Design Strategies: An Integrated Design Approach 1-1 (1999), *available at* http://water.epa.gov/polwaste/nps/upload/lidnatl.pdf ("The low-impact development (LID) approach combines a hydrologically functional site design with pollution prevention measures to compensate for land development impacts on hydrology and water quality."). Note that the terms "green infrastructure" or "green stormwater infrastructure" and "LID" are sometimes used interchangeably. *See, e.g.*, Arthur L. Storey et al., Harris County Low Impact Development & Green Infrastructure Design Criteria for Storm Water Management 2 (2011), *available at* http://www.hcfcd.org/downloads/manuals/2011-FINAL_LID_GIDC.pdf ("The term Green Infrastructure (GI) is synonymous with LID."); *LID vs. Green Infrastructure*, CLEAR News (Dec. 10, 2013), http://blog.clear.uconn.edu/2013/12/10/lid-vs-green-infrastructure/.

[20] *See infra* note 107 and associated text.

[21] Depending on site conditions and objectives, a bioretention system may or may not include an underdrain. *See Minnesota Stormwater Manual: Bioretention Terminology,* Minn. Pollution Control Agency, http://stormwater.pca.state.mn.us/index.php/Bioretention_terminology (last modified Apr. 4, 2014). While bioinfiltration systems filter and exfiltrate stormwater into surrounding soils, some treated stormwater leaves biofiltration systems through an underdrain that feeds into the storm sewer system. *See id.* Where stormwater is highly contaminated or groundwater recharge would be problematic, biofiltration systems include an impervious liner intended to eliminate exfiltration into surrounding soils. *See id*. These lined systems reduce flow to the storm sewer system through evapotranspiration only. *See id.*

[22] *See* Univ. of Fla., Florida Field Guide to Low Impact Development: Bioretention Basins/Rain Gardens 1 (2008) [hereinafter Univ. of Fla. - Bioretention], *available at* http://buildgreen.ufl.edu/Fact_sheet_Bioretention_Basins_Rain_Gardens.pdf. In addition, detention basins can be built as, or retrofitted to become, "vegetated water quality basins" that further LID principles. *See* Pa. Envtl.

Council, Improving Stormwater Detention Basins for Better Stormwater Management 2 (2006), *available at* http://www.lowimpactdevelopment.org/raingarden_design/downloads/PADetentionBasinFactsheetFINAL.pdf ("A vegetated water quality basin or an extended detention basin is a BMP designed to (1) maximize the flow path through the basin, (2) slow the flow of stormwater through the basin, (3) improve how plants use stormwater to increase absorption and evapotranspiration, (4) filter and trap common runoff pollutants, (5) promote soil saturation/groundwater recharge, and (6) increase evaporation of stormwater."). Bioretention retrofits can improve the stormwater retention and pollution-reduction potential of conventional detention basins that were originally designed for the limited purpose of flood control. *See, e.g.,* Michael Haberland et al., Green Infrastructure: Converting Dry Detention Basins to Natural Ecosystems – Cooperative Extension Fact Sheet FS1195 (Nov. 2012), *available at* http://njaes.rutgers.edu/pubs/fs1195/green-infrastructure.asp; Univ. of Fla., Florida Field Guide to Low Impact Development: Enhanced Stormwater Basins 1–2 (2008), *available at* http://buildgreen.ufl.edu/Fact_sheet_Enhanced_Stormwater_Basins.pdf; Pa. Envtl. Council, *supra*, at 2.

[23] *See* Univ. of Fla. - Bioretention, *supra* note 22, at 1.

[24] *See* Univ. of Fla., Florida Field Guide to Low Impact Development: Bioswales/Vegetated Swales 1 (2008), *available at* http://buildgreen.ufl.edu/Fact_sheet_Bioswales_Vegetated_Swales.pdf; Nat'l Res. Conservation Serv., U.S. Dep't of Agric., Bioswales (2007), *available at* ftp://ftp-fc.sc.egov.usda.gov/MT/www/technical/water/Bioswale.pdf.

[25] *See Vegetated Filter Strip*, U.S. Envtl. Prot. Agency, http://water.epa.gov/polwaste/npdes/swbmp/Vegetated-Filter-Strip.cfm (last updated July 3, 2014); *see also Vegetated Filter: The Reinvention of the Filter Strip*, Chesapeake Stormwater Network, http://chesapeakestormwater.net/training-library/stormwater-bmps/non-structural-bmps/vegetated-filter/ (last visited Jan. 7, 2015) (describing some of the potential pitfalls of improperly installed or maintained filter strips).

[26] *See* Maria Cahill et al., Vegetated Filter Strips 1 (2011), *available at* http://extension.oregonstate.edu/stormwater/sites/default/files/VegetatedFilterStrips.pdf ("Generally, vegetated filter strips minimize flow velocities, filter pollutants, and collect sediment before passing the remaining runoff volume to a secondary facility, such as a swale or bioretention practice, but they can also be designed like rain gardens with amended soils to store and infiltrate runoff volumes."); *see also Vegetated Filter Strip*, 3 Rivers Wet Weather, http://www.3riverswetweather.org/green/green-solution-vegetated-filter-strip (last visited Jan. 7, 2015) ("Vegetated filter strips are effective for treating low-intensity storms and are commonly used as first-in-line pretreatment for sequential treatment train BMPs.").

[27] *See Pervious Concrete Pavement,* U.S. Envtl. Prot. Agency, http://water.epa.gov/polwaste/npdes/swbmp/Pervious-Concrete-Pavement.cfm (last updated July 2, 2014); *Porous Asphalt Pavement,* U.S. Envtl. Prot. Agency, http://water.epa.gov/polwaste/npdes/swbmp/Porous-Asphalt-Pavement.cfm (last updated July 3, 2014); Univ. of Fla., Florida Field Guide to Low Impact Development: Permeable Surfaces 1 (2008), *available at* http://buildgreen.ufl.edu/Fact_sheet_Permeable_Surfaces.pdf.

[28] *See Permeable Interlocking Concrete Pavement*, U.S. Envtl. Prot. Agency, http://water.epa.gov/polwaste/npdes/swbmp/Permeable-Interlocking-Concrete-Pavement.cfm (last updated July 2, 2014).

[29] *See Infiltration Trench,* U.S. Envtl. Prot. Agency, http://water.epa.gov/polwaste/npdes/swbmp/Infiltration-Trench.cfm (last updated July 2, 2014); *see also* Univ. of Fla., Florida Field Guide to Low Impact Development: Exfiltration Tanks/Trenches 1 (2008) [hereinafter Exfiltration Tanks/Trenches], *available at* http://buildgreen.ufl.edu/Fact_sheet_Exfiltration_Tanks_Trenches.pdf.

[30] *See* Exfiltration Tanks/Trenches, *supra* note 29, at 1–2. Infiltration trenches and exfiltration trenches and tanks generally provide little in the way of stormwater treatment. *See* U.S. Envtl. Prot. Agency, Green Infrastructure Opportunities and Barriers in the Greater Los Angeles Region: An Evaluation of State and Regional Regulatory Drivers that Influence the Costs and Benefits of Green Infrastructure 3 tbl.1 n.c (2012) [hereinafter Opportunities and Barriers], *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/Council_Watershed_Health_GI_Report.pdf ("USEPA generally does not consider dry wells a green infrastructure practice. Dry wells are not intended as treatment systems; they reduce stormwater flow rate and volume and help recharge groundwater only."). These types of infrastructure are generally regulated as Class V injection wells under the Safe Drinking Water Act. *See id.* 3 tbl.1; 40 C.F.R. 144.80(e); U.S. Envtl. Prot. Agency, Underground Injection Control (UIC) Program Class V Well Identification Guide 4 (June 11, 2008), *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/memo_gi_classvwells.pdf ("These devices are generally considered Class V wells if stormwater is directed to any bored, drilled, driven shaft, or dug hole that is deeper than its widest surface dimension, or has a subsurface fluid distribution system."); *see also* Mary Tiemann, Cong. Research Serv., Safe Drinking Water Act (SDWA): A Summary of the Act and Its Major Requirements 8–9 (2014). EPA urges "UIC Program managers [to] consider the proximity to sensitive ground water areas when looking at the suitability of stormwater infiltration practices," noting that, "[d]epending on local conditions, infiltration without pretreatment may not be appropriate in areas where ground waters are a source of drinking water or other areas identified by federal, state, or local governments as sensitive ground water areas, such as aquifers overlain with thin, porous soils." Memorandum from Linda Bornazian, Director, Water Permits Division, & Steve Heare, Director, Drinking Water Protection Division, U.S. Envtl. Prot. Agency, to Water Division Directors, Regions 1–10 (June 13, 2008), at 2, *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/memo_gi_classvwells.pdf (addressing the subject of "Clarification on which stormwater infiltration practices/technologies have the potential to be regulated as "Class V" wells by the Underground Injection Control Program").

[31] *See* Univ. of Fla., Florida Field Guide to Low Impact Development: Green Roofs/Eco-roofs 1, 2 (2008), *available at* http://buildgreen.ufl.edu/Fact_sheet_Green_Roofs_Eco_roofs.pdf.

[32] *See* Univ. of Fla., Florida Field Guide to Low Impact Development: Cisterns/Rain Barrels 1 (2008), *available at* http://buildgreen.ufl.edu/Fact_%20sheet_Cisterns_Rain_Barrels.pdf.

[33] **Figure 1** is based on William F. Hunt et al., *Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design*, 139 J. Envtl. Eng'g 698, 699 fig.1, 705 fig.2 (2012). The bioretention cell is depicted with an underdrain, internal water storage created by an upturned elbow in the underdrain exit pipe, and a raked bottom to enhance exfiltration potential. Including an internal water storage layer in a bioretention facility can provide "water quality, hydrologic, and thermal benefits." Robert A. Brown et al., N.C. State Univ. Coop. Extension, Urban

Waterways: Designing Bioretention with an Internal Water Storage (IWS) Layer 1 (2009), *available at* http://www.bae.ncsu.edu/stormwater/PublicationFiles/IWS.BRC.2009.pdf. Raking "can reduce soil compaction and enhance exfiltration from bioretention cells and permeable pavement." Robert A. Brown & William F. Hunt, N.C. State Univ. Coop. Extension, Urban Waterways: Improving Exfiltration from BMPs: Research and Recommendations 1, 6 fig. 7 (2009), *available at* http://www.bae.ncsu.edu/stormwater/PublicationFiles/ConstructionLID.2009.pdf.

[34] *See* Brown et al., *supra* note 33, at 2 (defining "exfiltration," "infiltration," "drainage," and "overflow").

[35] *See, e.g.*, *How Can I Overcome the Barriers to Green Infrastructure?* U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_barrier.cfm (last updated Jun. 13, 2014) (identifying unknown performance, higher costs, resistance within the regulatory community, conflict with smart growth principles, conflict with water rights law, unfamiliarity with maintenance requirements and costs, conflicting codes and ordinances, lack of government staff capacity and resources, skepticism about long-term performance, and design challenges—including brownfield sites, clay-rich soils, high sediment volumes, cold weather, limited water supply for irrigation of GSI plantings, and space constraints—as potential barriers and offering potential solutions).

[36] *See, e.g.*, U.S. Envtl. Prot. Agency, Green Infrastructure Barriers and Opportunities in Camden, New Jersey (2013), *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/Camden_GI_Evaluation.pdf (explaining that "[l]ocal codes and ordinances can include inflexible standards or incorporate outdated requirements that result in excess impervious cover and reduce the functionality of landscapes" and reviewing Camden's regulations and standards "to identify opportunities to minimize impervious cover and promote environmentally sensitive site design during development and redevelopment activities and to identify potential barriers to the implementation of structural green infrastructure practices" as part of EPA's Green Infrastructure Technical Assistance Program).

[37] *See, e.g.*, *Year in Review: 2014 Under the Stormwater Lens*, Water Envt. Fed'n, Jan. 7, 2015, http://stormwater.wef.org/2015/01/stormwater-year-review-2014/ [hereinafter *Year in Review*] (reporting that "[a]ttendees at the EPA Innovation Blueprint session . . . call[ed] lack of workforce training and turnover a barrier to green infrastructure implementation as well as a must-have for success").

[38] Funding multi-benefit projects, like GSI, can be challenging where many potential funding sources (with inflexible purpose-of-use limitations) are directed at just one, or a few, project benefits. For example, to execute its Sustainable Streets program, which combines "complete streets" with "green streets," the City of San Mateo hopes to tap multiple funding sources. *See* City of San Mateo, Sustainable Streets – Public Draft 1-2, K-1(Oct. 2014), *available at* http://sustainablestreetssanmateo.com/downloads/. One potential funding source is the Highway Safety Improvement Program (HSIP); although "[n]on-safety related items . . . may be included in an HSIP project, . . . they are considered incidental . . . and shall not exceed 10% of a project's construction costs." *Id.* at K-8. Curb extensions promote pedestrian safety, but the funds necessary to incorporate stormwater controls (like bioretention) into curb extensions might be considered "incidental," and would likely require an additional funding source directed at improving stormwater quality.

[39] *See, e.g.*, *Year in Review, supra* note 37 (describing stormwater funding issues, including "opposition to stormwater fees" in many communities); Ellen Hanak et al., Pub. Policy Inst. of Cal., Paying for Water in California 51 (2014), *available at* http://www.ppic.org/content/pubs/report/R_314EHR.pdf (decribing a large funding gap for flood protection, stormwater management, and aquatic ecosystem management in California as "in part owing to the voter approval requirements of Propositions 218 and 26" for property-related fees and regulatory fees).

[40] *See* U.S. Envtl. Prot. Agency, Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs 22 (2013), *available at* http://water.epa.gov/polwaste/green/upload/lid-gi-programs_report_8-6-13_combined.pdf.

[41] For example, the July/August 2014 issue of the journal Stormwater contains articles on "Making Rain Gardens Work," "The Challenges of Keeping the 'Low' in LID," "Test Case for Improving a Highly Urbanized Watershed," and "Green Infrastructure Sizing Criteria Development." All of these articles highlight the developing nature of GSI technology and the importance of paying attention to site-specific details. *See* Janice Kaspersen, *Editor's Comments: Getting Green Infrastructure Right*, Stormwater, July–Aug. 2014, at 10, *available at* http://www.stormh2o.com/SW/Articles/Getting_Green_Infrastructure_Right_26319.aspx (contrasting Portland, Oregon's, Green Streets program, that has "a more-than-10-year track record and about 1,400 GI facilities," with "those of us in other parts of the country who have less experience, perhaps, with rain gardens and other green infrastructure elements, but who nevertheless want to incorporate them into a stormwater management strategy? Where do we start? And how do we know we're doing it right?"); Jim Nabong, *A Test Case for Improving a Highly Urbanized Watershed: Designing and Testing BMPs in San Diego*, Stormwater, July–Aug. 2014, at 48, 49, *available at* http://www.stormh2o.com/SW/Articles/Test_Case_for_Improving_a_Highly_Urbanized_Watersh_26323.aspx ("Each pilot project is a test to see if engineering and operations personnel can approve a design that breaks convention with decades-old practices for designing improvements in the street right of way. It is also a test of the city's ability to gain community acceptance of streetscapes that look different from what people are used to seeing."); *see also, e.g., Pilot Projects*, Think Blue San Diego, http://www.sandiego.gov/thinkblue/pilot-projects/index.shtml (last visited Jan. 7, 2015) (providing links to a stormwater filtration project, a rain barrel downspout disconnect project, and a parking lot infiltration project); *North Coast Stormwater Coalition's Low Impact Development (LID) Pilot Project*, Natural Res. Servs., http://www.naturalresourcesservices.org/projects/north-coast-stormwater-coalition%E2%80%99s-low-impact-development-lid-pilot-project (last visited Jan. 7, 2015) (describing a 2013 to 2015 "project to promote the understanding and use of LID along the Northcoast" of California).

[42] *See* Haifeng Jia et al., *Development of a Multi-Criteria Index Ranking System for Urban Runoff Best Management Practices (BMPs) Selection*, 185 Envtl. Monitoring & Assessment 7915, 7917–18, 7917 fig.1, 7918 fig.2 (2013) (enumerating site suitability considerations for GSI, including land use type, pollutant loading, regulatory requirements, soil characteristics, groundwater characteristics, topography, catchment properties, and space requirements); *see also infra* **Parts III.A**, **B**.

[43] *See* Claudia Copeland, Cong. Research Serv., R43131, Green Infrastructure and Issues in Managing Urban Stormwater 6, 9 (2014), *available at* http://nationalaglawcenter.org/wp-content/uploads/assets/crs/R43131.pdf (stating that "green infrastructure is often located on private properties"; discussing stormwater fee discounts or credits intended to encourage "private businesses, institutions, and homeowners . . . to support on-site green infrastructure"; and describing incentives for developers to use GSI).

[44] *See id.*; discussion *infra* **Part V.B.**

[45] *See infra* notes 177–181 and accompanying text.

[46] *See* 33 U.S.C. § 1342(q) ("Each permit, order, or decree issued pursuant to this chapter after December 21, 2000 for a discharge from a municipal combined storm and sanitary sewer shall conform to the Combined Sewer Overflow Control Policy . . . ."); Combined Sewer Overflow (CSO) Control Policy, 59 Fed. Reg. 18688, 18688 (Apr. 11, 1994) (asking "CSO permittees [to] immediately . . . develop long-term CSO control plans which evaluate alternatives for attaining compliance with the CWA, including . . . water quality standards and protection of designated uses" and "to implement the plans' recommendations as soon as practicable"); *see also* U.S. Envtl. Prot. Agency, Greening CSO Plans: Planning and Modeling Green Infrastructure for Combined Sewer Overflow (CSO) Control 5–6 (2014) [hereinafter Greening CSO Plans], *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/Greening_CSO_Plans.PDF ("Under their NPDES permits, communities are required to implement nine minimum controls (NMC) and to develop and implement Long Term Control Plans (LTCPs). Many communities are still searching for cost effective ways to implement their LTCPs.").

[47] *See* Peter Kenyon, *Green Surge Threatens CSO Storage Solution*, TunnelTalk (Jun. 19, 2013), http://tunneltalk.com/Discussion-Forum-19June2013-Investigating-the-future-of-deep-storage-tunnels-in-the-USA.php; Greening CSO Plans, *supra* note 46, at 7, 12 (noting that "[m]any communities are still searching for cost effective ways to implement their [Long Term Control Plans]" and stating that green infrastructure "may be able to reduce the size of more capital-intensive, "downstream" gray infrastructure control measures" like off-line storage tunnels).

[48] GSI is becoming a common component of CSO consent decrees—negotiated settlements between enforcing agencies and permittees. *See generally Enforcement: Settled EPA Clean Water Act Enforcement Matters with Green Infrastructure Components*, U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/enforcement.cfm (last updated Mar. 7, 2014) (describing GSI components in decrees for Chicago, Illinois; Chattanooga, Tennessee; Kansas City, Kansas; Seattle and King County, Washington; Washington, D.C.; Philadelphia and Scranton, Pennsylvania; Boston, Massachusetts; and St. Louis, Missouri); U.S. Envtl. Prot. Agency, Consent Decrees that Include Green Infrastructure Provisions (2012), *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/EPA-Green-Infrastructure-Supplement-1-061212-PJ.pdf (describing GSI components in decrees for Dallas, Texas; Washington, D.C.; the Washington Suburban Sanitary Commission, Maryland; the Cincinnati and Cleveland areas in Ohio; Louisville and Jefferson County in Kentucky; and Kansas City, Missouri); Greening CSO Plans, *supra* note 46, at 12.

[49] *See Green City, Clean Waters*, Philadelphia Water Department, http://phillywatersheds.org/what_were_doing/documents_and_data/cso_long_term_control_plan (last visited Jan. 7, 2015) ("Green City, Clean Waters is Philadelphia's 25-year plan to protect and enhance our watersheds by managing stormwater with innovative green infrastructure."). The city will "achieve the elimination of the mass of pollutants that would otherwise be removed by the capture of 85% by volume of the combined sewage collected in the combined sewer system during precipitation events on a system-wide annual average basis" by the year 2036. Philadelphia Water Department, Green City, Clean Waters: Comprehensive Monitoring Plan 1-2 (revised 2014), *available at* http://www.phillywatersheds.org/doc/Revised_CMP_1_10_2014_Finalv2.pdf.

[50] *See* Greening CSO Plans, *supra* note 46, at 7.

[51] *See id.* at 5 (describing the environmental and public health impacts of CSOs).

[52] *See* discussion *infra* **Part V.B.**

[53] MS4 operators are experiencing both direct and indirect pressure to adopt GSI. Direct pressure comes from stormwater permit requirements that specifically encourage or require GSI. *See, e.g.,* Cal. State Water Res. Control Bd., Water Quality Order No. 2013-0001-DWQ, National Pollutant Discharge Elimination System (NPDES) General Permit No. CAS000004, Waste Discharge Requirements (WDRs) for Storm Water Discharges from Small Municipal Separate Storm Sewer Systems (MS4s) (General Permit), at pt. E.12 (adopted Feb. 5, 2013, effective July 1, 2013) [hereinafter CA General Permit], *available at* http://www.swrcb.ca.gov/water_issues/programs/stormwater/docs/phsii2012_5th/order_final.pdf (requiring small MS4s "to implement standards to effectively reduce runoff and pollutants associated with runoff" and to mandate GSI/LID site design measures for projects that create or replace more than a certain threshold of impervious surface); *see also* Jeffrey Odefey, Am. Rivers, Permitting Green Infrastructure: A Guide to Improving Municipal Stormwater Permits and Protecting Water Quality 3 (2013), *available at* http://www.americanrivers.org/assets/pdfs/reports-and-publications/permitting-green-infrastructure.pdf. (explaining that, although "many of the initial MS4 permits simply required the permittees to implement stormwater management plans (or SWMPs), subsequent generations of permits, especially in California and other more progressive jurisdictions, have become far more specific and detailed[,] . . . incorporating provisions specifically designed to reduce stormwater discharges from new and re-development projects by imposing standards that require on-site management of precipitation"). Additionally increasingly stringent receiving water and effluent limitations are leading MS4 operators to consider GSI where conventional methods have so far failed to achieve water quality goals. *See, e.g.*, Ellen Hanak et al., Pub. Policy Inst. Cal., Paying for Water in California 43 (2014), *available at* http://www.ppic.org/content/pubs/report/R_314EHR.pdf (describing "increasingly stringent" MS4 requirements leading to rising costs); Kelly Lennon & Everett Gupton, *Tidal Back River Greening Projects: A Case Study in BMP Placement, Performance & Practice*, *in* World Envtl. & Water Res. Cong. 2014, at 22, 24 (2014) ("One of the main goals of the project," which involves multiple "green infrastructure and restoration sites in eastern Baltimore County[,] . . . is . . . to retrofit portions of the watershed developed prior to passage of the current stormwater management regulations" in "partial fulfillment of the County's MS4 permit and [to] help the County meet the required pollutant load reductions associated with the Chesapeake Bay TMDL for Nitrogen and Phosphorus."); U.S. Envtl. Prot. Agency, Total Maximum Daily Loads 4 (2012), *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/EPA-Green-Infrastructure-Factsheet-5-061212-PJ.pdf (describing TMDL implementation plans, like the Machado Lake Toxics TMDL, that identify GSI as an effective means of controlling pollutant loads to impaired waters); *see also* sources cited *infra* note 135.

[54] For example, the MS4 permit for the California Department of Transportation requires projects within the Department's right of way to comply with "standard project planning and design requirements" that reflect LID principles and to include GSI post-construction stormwater

treatment controls. Cal. State Water Res. Control Bd., Order No. 2012-0011-DWQ, NPDES No. CAS000003, National Pollution Discharge Elimination System (NPDES) Statewide Storm Water Permit Waste Discharge Requirements (WDRS) for State of California Department of Transportation, at pt. E.2.d (eff. Jul. 1, 2013), *available at* http://www.swrcb.ca.gov/board_decisions/adopted_orders/water_quality/2012/wqo2012_0011_dwq.pdf. Caltrans must also comply with 84 TMDLs for pollutants around the state. *See* Cal. State Water Res. Control Bd., Order No. 2014-0077-DWQ Amending National Pollutant Discharge Elimination System (NPDES) Statewide Storm Water Permit for State of California Department of Transportation Order 2012-0011-DWQ, NPDES No. CAS000003, at amended finding 36, *available at* http://www.swrcb.ca.gov/board_decisions/adopted_orders/water_quality/2014/wqo2014_0077_dwq.pdf.

[55] For example, the new California general industrial stormwater permit encourages GSI by requiring that dischargers, "to the extent feasible, implement and maintain" BMPs "necessary to reduce or prevent discharges of pollutants," like those "that infiltrate or []use storm water" or "treatment control" practices that meet volume- and flow-based design-storm standards. Cal. State Water Res. Control Bd., Order No. 2014-0057-DWQ, General Permit for Storm Water Discharges Associated with Industrial Activities, at pts. X.H.2.a, b.ii–iii, 6 (adopted Apr. 1, 2014; effective July 1, 2015), *available at* http://www.waterboards.ca.gov/board_decisions/adopted_orders/water_quality/2014/wqo2014_0057_dwq.pdf.

[56] For example, the California general construction stormwater permit requires discharges in areas not covered by an MS4 permit to "replicate the pre-project water balance" through GSI practices. Cal. State Water Res. Control Bd., Order No. 2009-0009-DWQ [As Amended by Order Nos. 2010-0014-DWQ and 2012-0006-DWQ] National Pollutant Discharge Elimination System General Permit No. CAS000002, Waste Discharge Requirements for Discharges of Storm Water Runoff Associated with Construction and Land Disturbance Activities, at pt. XIII, app. 2, *available at* http://www.waterboards.ca.gov/water_issues/programs/stormwater/docs/constpermits/wqo_2009_0009_complete.pdf.

[57] *See* 33 U.SC. § 1342(p)(3)(B)(iii); 40 C.F.R. § 122.26 (d)(2)(iv); 40 C.F.R. § 122.34(a) (explaining to regulated small MS4 operators: "[y]our NPDES MS4 permit will require at a minimum that you develop, implement, and enforce a storm water management program designed to reduce the discharge of pollutants from your MS4 to the maximum extent practicable (MEP), to protect water quality, and to satisfy the appropriate water quality requirements of the Clean Water Act."); *see also* Odefey, *supra* note 53, at 2 ("Like other point sources, where discharges that are subject to these technology-based standards [(i.e., for stormwater: reducing the discharge of pollutants to the maximum extent practicable)] exceed local water standards, MS4 operators are also obliged to implement more stringent water quality based permit controls that are tailored to achieve compliance.").

[58] MS4s are subject to the following general requirements:

- Public education and outreach on stormwater impacts. 40 C.F.R. § 122.26(d)(2)(iv)(A)(6); 40 C.F.R. 122.34(b)(1); *see also* 40 C.F.R. § 122.26(d)(2)(iv)(B)(5). Permittees can hold educational events about (and post explanatory signage near) GSI installations and provide GSI guidance for developers and private citizens.
- Public involvement / participation. 40 C.F.R. § 122.26(d)(2)(iv); 40 C.F.R. 122.34(b)(2). Permittees can encourage community residents and businesses to implement GSI on private property.
- Illicit discharge elimination. 40 C.F.R. § 122.26(d)(2)(iv)(B)(1); 40 C.F.R. 122.34(b)(3). GSI can capture non-stormwater runoff, such as sprinkler runoff, in addition to stormwater runoff.
- Construction site stormwater runoff control. 40 C.F.R. § 122.26(d)(2)(iv)(D); 40 C.F.R. 122.34(b)(4). GSI can capture construction-site runoff, and incorporating LID principles into design and construction planning can reduce the area disturbed during construction.
- Post-construction stormwater management in new development and redevelopment. 40 C.F.R. § 122.26(d)(2)(iv)(A)(2); 40 C.F.R. § 122.34(b)(5). Permittees can pass ordinances and develop standards that encourage or require GSI to be incorporated into development, redevelopment, and retrofit projects, including public works projects.
- Pollution prevention / good housekeeping for municipal operations. 40 C.F.R. § 122.26(d)(2)(iv)(A)(1), (3); 40 C.F.R. § 122.34(b)(5). Permittees that use native plants in GSI will reduce the need for irrigation, fertilizers, and pesticides, decreasing MS4 pollutant load.

[59] State and federal stormwater permitting authorities have included numeric post-construction GSI standards in general and/or individual MS4 permits in Alaska, California, Connecticut, Delaware, Kentucky, Maryland, Minnesota, Montana, New Jersey, New Mexico, New York, Oregon, Tennessee, Vermont, Washington, West Virginia, Wisconsin, and Washington, D.C. *See* U.S. Envtl. Prot. Agency, Municipal Separate Storm Sewer System Permits – Post-Construction Performance Standards & Water Quality-Based Requirements: A Compendium of Permitting Approaches 3–12 (2014) [hereinafter Compendium], *available at* http://www.epa.gov/npdes/pubs/sw_ms4_compendium.pdf; *see also supra* note 53 and accompanying text; *infra* note 185 and accompanying text.

[60] More and more commonly, increasingly stringent water-quality-based effluent limitations in MS4 permits are directly or indirectly driving GSI implementation. *See* Compendium, *supra* note 59, at 15–20 (describing numeric water-quality-based effluent limitations in general or individual MS4 permits in California, Virginia, Maryland, Hawaii, and Washington, D.C.); Jonathan E. Jones et al., *BMP Effectiveness for Nutrients, Bacteria, Solids, Metals, and Runoff Volume: International Stormwater BMP Database reaches the 500-BMP Milestone*, Stormwater, Mar./Apr. 2012, *available at* http://www.stormh2o.com/SW/Articles/16214.aspx ("[C]urrent regulatory drivers [for understanding BMP effectiveness] include (1) the USEPA urging states to adopt numeric nutrient criteria, (2) steadily increasing use of numeric action levels and numeric effluent limits for stormwater municipal and industrial discharges, (3) new initiatives for reducing bacteria levels in waterbodies used by the public for recreation, (4) total maximum daily loads (TMDLs) that identify waste load allocations for stormwater discharges . . . ."). *See also supra* note 53 and accompanying text; *infra* note 183 and accompanying text.

[61] For example, The Los Angeles Regional MS4 permit allows certain permittees to satisfy compliance with interim water-quality-requirements in part by conducting a "Reasonable Assurance Analysis" that demonstrates the permittee's "activities and control measures . . . will achieve applicable water quality based effluent limitations and/or receiving water limitations." Los Angeles Regional Water Quality Control Board, Order No. R4-2012-0175, NPDES Permit No. CAS004001, Waste Discharge Requirements for Municipal Separate Storm Sewer System (MS4) Discharges within the Coastal Watersheds of Los Angeles County, Except those Discharges Originating from the City of Long Beach MS4, at pt. VI.C.5.b.iv.5. (adopted Nov. 8, 2012) [hereinafter LA Regional Permit], *available at* http://www.waterboards.ca.gov/rwqcb4/water_issues/programs/stormwater/municipal/la_ms4/2012/Order%20R4-2012-0175%20-%20A%20Final%20Order%20revised.pdf. This quantitative

analysis involves modeling the effectiveness of stormwater control measures using a combination of local data ("including land use and pollutant loading data") and control-measure performance data drawn from peer-reviewed sources. *See id*. Permittees must also develop and implement a monitoring program to "assess progress toward achieving the water quality-based effluent limitations and/or receiving water limitations per the compliance schedules" and use adaptive management to improve their effectiveness in achieving water-quality requirements. *Id.* at pts. VI.C.2, 7, 8. Therefore, if the assumptions about GSI performance encompassed in the Reasonable Assurance Analysis turn out to be inaccurate, the permittee must change course, making improvements as necessary.

[62] The Los Angeles Regional MS4 permit allows certain permittees to satisfy compliance with final water-quality-based effluent limitations and related receiving-water limitations by retaining "(i) all non-storm water and (ii) all storm water runoff up to and including the volume equivalent to the 85th percentile, 24-hour event . . . for the drainage area tributary to the applicable receiving water." LA Regional Permit, *supra* note 61, at pt. VI.E.2.e.i(4); *see also id.* at pt. VI.E.2.d.i(3) (stating that, if "[t]here is no direct or indirect discharge from [a] Permittee's MS4 to the receiving water," the permittee will "be considered in compliance with an applicable interim water quality-based effluent limitation and interim receiving water limitation for a pollutant associated with a specific TMDL").

[63] *See, e.g.*, Andrew Fahlund et al., *Water in the West*, 6 Cal. J. Pol'y 61, 81–82 (2014) (describing "stormwater capture and storage in groundwater aquifers to augment water supplies" as "[a]n important secondary goal of Los Angeles's green infrastructure efforts"); Opportunities and Barriers, *supra* note 30, at 1–2 (describing the potential groundwater recharge benefits of GSI).

[64] *See* Daniel B. Stephens et al., *Decentralized Groundwater Recharge Systems Using Roofwater and Stormwater Runoff*, 48 J. Am. Water Res. Ass'n 134, 138, 142 (2012) (contrasting "rain barrels, green (vegetated) roofs, rain gardens, contained planters, vegetated swales, and flow-through planters" that "primarily capture runoff for use by on-site vegetation" with GSI "focused more on infiltration, including permeable pavers/pavement, turf blocks, vegetated infiltration basins, infiltration planters, surface and subsurface infiltration basins, and trenches").

[65] *See* Stephens et al., *supra* note 64, at 144 ("Stormwater capture for groundwater recharge at the lot, subdivision, or commercial site deserves consideration from groundwater managers as a means to replenish aquifers. . . ."). *But see id.* at 140–43 (describing some of the "potential challenges to implementing a decentralized recharge program using stormwater," including water-quality concerns, low "infiltrability of local soils, impacts of excess local water on geotechnical stability, . . . flushing natural salts from the soil profiles," and state surface water rights); Opportunities and Barriers, *supra* note 30, at 1, 2 (explaining that groundwater adjudications in the Los Angeles area prevent "parties who infiltrate stormwater through green infrastructure practices" from receiving the "[legal] benefit of increased groundwater supply," dampening the incentives for GSI implementation). Some areas already employ centralized groundwater recharge facilities. For example, in California, centralized groundwater recharge using "imported surface water, local recycled wastewater, or stormwater . . . has been used successfully for some decades by the Orange County Water District, the Water Replenishment District of Southern California, the Pajaro Valley Water Management Agency, and the Santa Clara Valley Water District" which have "special legislative authority to manage groundwater supplies on behalf of their communities." Ellen Hanak et al., *supra* note 53, at 31–32.

[66] *See* 2013 California Senate Bill Nos. 1168 and 1319, Assembly Bill No. 1739, California 2013-2014 Regular Session; *see also* Nell Green Nylen, *California's New Groundwater Law: An Interactive Timeline*, Legal Planet, Oct. 8, 2014, http://legal-planet.org/2014/10/08/californias-new-groundwater-law-an-interactive-timeline/.

[67] *See Municipal Separate Storm Sewer System (MS4) Main Page*, U.S. Envtl. Prot. Agency, http://water.epa.gov/polwaste/npdes/stormwater/Municipal-Separate-Storm-Sewer-System-MS4-Main-Page.cfm (last updated Nov. 26, 2014).

[68] *See Combined Sewer Overflows (CSO) Home*, U.S. Envtl. Prot. Agency, http://water.epa.gov/polwaste/npdes/cso/index.cfm (last updated Dec. 15, 2014); *Combined Sewer Overflows Demographics*, U.S. Envtl. Prot. Agency, http://cfpub.epa.gov/npdes/cso/demo.cfm?program_id=5 (last updated Oct. 15, 2008). Combined sewer systems are legacy systems created before the availability of sewage treatment, when sewer systems simply collected waste and stormwater to direct it to local waters. *See San Francisco Combined Sewers*, Oakland Museum of California, http://www.museumca.org/creeks/1690-OBSFSewers.html (last visited Jan. 7, 2015).

[69] *See Combined Sewer Overflows*, *supra* note 68.

[70] *See id.*; *Combined Sewer Overflows Demographics*, *supra* note 68.

[71] *See* Osman A. Akan, Urban Stormwater Hydrology: A Guide to Engineering Calculations 53 (1993) (differentiating overland flow from channel flow).

[72] The Safe Drinking Water Act applies to both surface water and groundwater supplies used for drinking water. *See supra* note 30 (describing some aspects of underground injection control under the Safe Drinking Water Act). It authorizes the EPA to set national health-based standards for drinking water contaminants. *See* 42 U.S.C. § 300g-1. Although it initially focused on treatment, 1996 amendments added source water protection requirements. *See* 42 U.S.C. §§ 300h–300h-8, 300j-13.

[73] *See* Greening CSO Plans, *supra* note 46, at 32 ("Although it is relatively straightforward to model gray infrastructure solutions because of the limited number of feasible alternatives and locations, analyzing the opportunities afforded by green infrastructure requires additional modeling considerations.").

[74] See William D. Shuster et al., *Front-Loading Urban Stormwater Management for Success—A Perspective Incorporating Current Studies on the Implementation of Retrofit Low-Impact Development*, Cities & the Env't, vol. 1, iss. 2, art. 8, at 5 (2008).

[75] See Jia et al., *supra* note 42, at 7917–18; Greening CSO Plans, *supra* note 46, at 7 ("Green infrastructure opportunities within a catchment largely depend on soil characteristics, topography and land use."); Allen P. Davis et al., *Improving Urban Stormwater Quality: Applying Fundamental Principles*, 146 J. Contemporary Water Research & Educ. 3 (2010) ("The performance of a specific technology will depend on the facility configuration and makeup, climate, surrounding soil characteristics, topography, and the site hydrology."); Mahesh R. Gautam

et al., *Best Management Practices for Stormwater Management in the Desert Southwest*, 146 J. Contemporary Water Research & Educ. 39, 40 (2010) ("The natural drivers of [the] movement [of sediment, nutrients, pollutants, or debris from land to surface or ground waters] are highly dependent on the interaction among entities such as soil, vegetation, land use, storm and runoff characteristics, and processes such as runoff formation, infiltration, erosion, and sediment transport. The natural factors that guide these processes are dependent on topography, geology, soil-geomorphology, and the hydrometeorology of the region."); Gautam et al., *supra*, at 47 ("[S]oil type and the level of pollution in the soil determine the feasibility of infiltration BMPs."); *see also* Low Impact dev. Ctr., *supra* note 15, at 16–37 (explaining that "[a] comprehensive site assessment is a fundamental starting point in the development of an LID site design" and explaining important components of a site assessment); Prince George's County, *supra* note 19, at 4-4.

[76] GSI involves "creatively designing hydrologic functions into the site design with the intent of replicating the predevelopment hydrology." Prince George's County, *supra* note 19, at 1-5; *see also* Cal. Water & Land Use P'ship, How Urbanization Affects the Water Cycle, at 2 fig.2 (2006), *available at* http://www.coastal.ca.gov/nps/watercyclefacts.pdf ("With natural groundcover, 25% of rain infiltrates into the aquifer and only 10% ends up as runoff. As imperviousness increases, less water infiltrates and more . . . runs off. In highly urbanized areas, over one-half of all rain becomes surface runoff, and deep infiltration is only a fraction of what it was naturally.").

[77] *See* Allen P. Davis et al., *Hydrologic Performance of Bioretention Storm-Water Control Measures*, 17 J. Hydrologic Eng'g 604, 605–06 (2012) (describing bioretention system design parameters, media conductivity and moisture, the conductivity of surrounding soils, and precipitation intensity and patterns as influencing hydrologic performance); Shuster et al., *supra* note 74, at 5 ("[I]mplementation of effective LID in great part relies upon specific knowledge of soil hydrology and soil physical properties, and it follows that assessment of these properties will largely dictate the type of LID practice used in a given situation and its capacity for retaining and infiltrating stormwater runoff."). Texture, density, structure, and water content all influence a soil's infiltration capacity. *See* Shirley E. Clark & Robert Pitt, *Influencing Factors and a Proposed Evaluation Methodology for Predicting Groundwater Contamination Potential from Stormwater Infiltration Activities*, 79 Water Env't Research 29, 32 (2007).

[78] *See* Douglas Beyerlein, *Regional Differences in the Effectiveness of Low-Impact-Development Facilities: Understanding the Mechanisms of LID*, Stormwater, May 2012, at 32, 35, 35 tbl.1, *available at* http://www.stormh2o.com/SW/Articles/Regional_Differences_in_the_Effectiveness_of_LowIm_16764.aspx (modeling a 22% annual runoff volume reduction for a green roof in Seattle, compared to an approximately 40% reduction in Atlanta, Los Angeles, and Philadelphia).

[79] *See* Beyerlein, *supra* note 78, at 32 (noting that Philadelphia's alluvial soils "have higher infiltration rates than the glacier-compacted till soils found in Seattle or the clay soils of Los Angeles and Atlanta"); Nicole David et al., *Removal Efficiencies of a Bioretention System for Trace Metals, PCBs, PAHs, and Dioxins in a Semiarid Environment*, J. Envtl. Eng'g 04014092-1, 04014092-2 (published online, ahead of print, Dec. 2, 2014) ("In the [San Francisco] Bay Area, the prevalence of clay soils with poor infiltration properties necessitates the use of subdrains" in bioretention facilities.").

[80] *See* Gautam et al., *supra* note 75, at 43, 44 ("[S]oils in arid regions are typically comprised of the erosion products of the underlying rock and do not have an overlying layer of organic matter marking the absence of O or A Horizons. The relative absence of organic matter, litter, and vegetation on the surface has implications for hydrological processes and flow pathways. . . . In some parts of the arid West, the desert soils consist of the silty low permeable vesicular A (Av) horizon. The discontinuous porosity in such soil, aided with their platy structure, leads to low infiltration rates, which have implications for aquifer recharge capacity and stormwater management BMPs." (Citation omitted)).

[81] In arid and semi-arid regions, rainfall can occur in brief, intense bursts that overwhelm the infiltration capacity of poorly developed soils. *See* Gautam et al., *supra* note 75, at 40, 41, 41 fig.1 ("Although the average and annual total precipitation in the Desert Southwest is much lower than in other regions, the extreme value of rainfall depth and intensity can be significant.").

[82] *See, e.g.,* Laurent M. Ahiablame et al., *Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research*, 223 Water Air Soil Pollution 4253, 4256, 4258, 4259–60 (2012).

[83] *See id.* at 4256; *see also* Int'l Stormwater BMP Database, Addendum 1 to Volume Reduction Technical Summary (January 2011): Expanded Analysis of Volume Reduction in Bioretention BMPs 18 (2012) [hereinafter Expanded Analysis of Volume Reduction in Bioretention BMPs], *available at* http://www.bmpdatabase.org/Docs/Bioretention%20Volume%20Reduction%20Addendum%205%2031%2012.pdf ("Volume-related data for bioretention BMPs in the BMP Database show that bioretention can be an effective approach for reducing runoff frequencies, peak flow rates and volumes during frequently occurring storm events.").

[84] *See* Expanded Analysis of Volume Reduction in Bioretention BMPs, *supra* note 83, at 7 exhibit 3, 18. The report notes that "the reliability of categorical analysis results is still limited by the number of available studies," that "[m]any of the studies have been concentrated in a few areas of the country," and that "some studies are understood to have been conducted on systems with somewhat atypical design conditions (i.e., very large footprints; very high infiltration rates)," so care should be taken "when extrapolating [the] results[ ]of categorical and study-level analyses." *Id.* at 18.

[85] Alicia N. Gilbreath et al., S.F. Estuary Inst., Monitoring and Results for El Cerrito Rain Gardens 13–14 (2012), *available at* http://www.sfei.org/sites/default/files/El%20Cerrito%20Rain%20Garden_FINALReport.pdf.

[86] Davis et al., *supra* note 77, at 605 ("Although volume/flow management itself is important as an urban runoff goal to reduce erosion potential and sediment transport, volume is also critical in managing pollutant loadings, which are defined as the product of concentration and total volume.").

[87] *See, e.g.*, Houng Li & Allen P. Davis, *Water Quality Improvements Through Reductions of Pollutant Loads Using Bioretention*, 135 J. Envtl. Eng'g 567, 575 (2009) (concluding that "[b]ioretention has varying capacity to manage different pollutants; field data indicate that it can effectively reduce TSS, chromium, lead, and zinc concentrations in runoff. Slight organic matter and nutrient leaks may occur from the bioretention media.").

[88] *See* Clark & Pitt, *supra* note 77, at 30.

[89] *See* Davis et al., *supra* note 75, at 8 (GSI "operations and treatments occur via specific flow and environmental process pathways that are known to engineers and scientists in other applications," however, "[t]he stormwater application is unique because of its high variability of input, operating, and design conditions.").

[90] For example, the fate of some forms of nutrients in bioretention systems is not well understood. *See, e.g.*, Liqing Li & Allen P. Davis, *Urban Stormwater Runoff Nitrogen Composition and Fate in Bioretention Systems*, 48 Envtl. Sci. & Tech. 3403, 3403 (2014) ("Nitrogen behavior in bioretention systems is . . . complex because of the biogeochemical complexity of the nitrogen species [which varies with land use and hydrologic conditions] and the numerous treatment mechanisms inherent to bioretention, including sedimentation/filtration, adsorption, mineralization, and biological transformations."); Audrey Roy-Poirier et al., *Bioretention Processes for Phosphorus Pollution Control*, 18 Envtl. Rev. 159, 160, (2010); *see also* Gregory H. LeFevre et al., *Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells*, 141 J. Envtl. Eng'g 04014050-1, -17, (2015) (proposing "[seven] areas of research that will be critical to understanding bioretention function for dissolved pollutant removal, system sustainability, and water resource protection").

[91] *See* Davis et al., *supra* note 75, at 8.

[92] The information in this table derives from the following sources unless otherwise specified: Erickson et al., *supra* note 7, at 23–51 (describing stormwater treatment processes); Davis et al., *supra* note 75, 5–8; Clark & Pitt, *supra* note 77, at 30–33; Jennifer Read et al., *Variation Among Plant Species in Pollutant Removal from Stormwater in Biofiltration Systems*, 42 Water Research 893, 894, 901 (2008) (explaining that plants can contribute directly to GSI treatment efficiency through "degradation of organic pollutants, uptake of macronutrients [nitrogen and phosphorus] and heavy metals and maintenance of longer-term soil porosity" and finding "marked variation in pollutant removal . . . among plant species" (citations omitted)); LeFevre et al., *supra* note 90, at 04014050-2–3 (discussing hydrocarbon removal by plant uptake).

[93] Particle-associated pollutants may settle out of stormwater when its flow slows during detention or retention in GSI. Therefore, properly designed, installed, and maintained GSI that includes sedimentation and filtration processes will generally result in good suspended solids removal. *See* Int'l Stormwater BMP Database, Advanced Analysis: Influence of Design Parameters on Achievable Effluent Concentrations 72 (2013), *available at* http://www.bmpdatabase.org/Docs/BMPDB_AdvancedAnalysis_Final_2013.pdf [hereinafter Influence of Design Parameters]; *see also* Int'l Stormwater BMP Database, Pollutant Category Summary: Statistical Addendum: TSS, Bacteria, Nutrients, and Metals 5 fig.2, tbl.2 (2012) [hereinafter Pollutant Category Summary], *available at* http://www.bmpdatabase.org/performance-summaries.html (showing boxplots and table of median influent/effluent TSS concentrations that demonstrate statistically significant TSS removal for GSI categories). However, settling does not remove all particle-associated pollutants at the same rate. Instead, different pollutants may be associated with different particle size fractions, and smaller particles generally take longer to drop out of suspension. For example, although both PCBs and mercury—two legacy pollutants of significant concern in the San Francisco Bay area—are associated with sediment particles, settling is more effective at removing PCBs, which "appear to be associated with slightly coarser f[r]actions in flowing stormwater" than mercury. *See* Lester McKee et al., S.F. Estuary Inst., A BMP Tool Box for Reducing Polychlorinated Biphenyls (PCBs) and Mercury (Hg) in Municipal Stormwater 23–27, 44–45, A-13 (2010). The majority of metals and PAHs may be associated with small particles that are less susceptible to removal by physical filtration. *See* Simon Toft Ingvertsen et al., *A Minimum Data Set of Water Quality Parameters to Assess and Compare Treatment Efficiency of Stormwater Facilities*, 40 J. Envtl. Qual. 1488, 1491 tbl.2 (citing studies finding the majority of cadmium, copper, lead, zinc, and PAHs associated with particles smaller than about 63 μm).

[94] *See, e.g.,* Ahiablame et al., *supra* note 82, at 4256, 4260, 4261. Sediment mobilized by stormwater acts as a physical pollutant. *See* Edwin D. Ongley, Food & Agric. Org. of the United Nations, Control of Water Pollution from Agriculture, ch. 2 (1996), *available at* http://www.fao.org/docrep/w2598e/w2598e05.htm#chapter%202:%20pollution%20by%20sediments (describing "[p]ollution by sediments"). Not only can sediment clog storm drains and reduce the effective volume of other flood control structures, it alters natural stream channel characteristics and fills in lakes, ponds, and wetlands, with repercussions for ecosystem function and navigability. *See id.* A sediment imbalance can negatively impact aquatic ecosystems in many ways. Suspended sediment interferes with photosynthesis and growth in aquatic plants and algae, and sediment-laden water can scour algae, plants, and animals from stream bottoms. *See* Walter Berry & Brian Hill, U.S. Envtl. Prot. Agency, The Biological Effects of Suspended and Bedded Sediment (SABS) in Aquatic Systems: A Review 7–8 (2003), *available at* http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/sediment/upload/2004_08_17_criteria_sediment_appendix1.pdf. These impacts on plants and algae in turn affect other organisms' abilities to find food, grow, and reproduce. *See id.* High sedimentation rates can overwhelm filter-feeders, bury bottom-dwelling organisms, and impair salmonid reproduction and migration. *See id.* at 8 (noting that "[i]ncreased sedimentation can limit the amount of oxygen in the spawning beds which can reduce hatching success, or trap the fry in the sediment after hatching"); C.P. Newcombe & D.D. MacDonald, *Effects of Suspended Sediments on Aquatic Ecosystems*, 11 N. Am. J. Fisheries Mgmt. 72, 73 (1991). Particles of sediment in stormwater can also carry chemical pollutants and pathogens. *See* Kevin G. Taylor, *Urban Environments, in* Environmental Sedimentology, at 190, 192 (Chris Perry & Kevin Taylor eds. 2007); Ongley, *supra*. In fact, "sediments act as the major vector for the transport of contaminants in most aquatic systems." Taylor, *supra*, at 192; *see also* Newcombe & MacDonald, *supra*, at 73 ("[I]ncreases in nutrients or toxic compounds, or both, adsorbed on suspended sediments can alter growth rates and biomass of algae."). In particular, silt- and clay-sized organic and inorganic particles are significant reservoirs of nutrients, metals, and organic pollutants. *See* J.M. Zanders, *Road Sediment: Characterization and Implications for the Performance of Vegetated Strips for Treating Road Run-Off*, 339 Sci. Total Env't 41, 42 (2005); Stanley B. Grant et al., Caltrans, A Review of the Contaminants and Toxicity Associated with Particles in Stormwater Runoff 1-4, 2-1, 5-1 (2003); Ongley, *supra*. As Ongley explains:

> Phosphorus and metals tend to be highly attracted to ionic exchange sites that are associated with clay particles and with the iron and manganese coatings that commonly occur on these small particles. Many of the persistent, bioaccumulating and toxic organic contaminants, especially chlorinated compounds including many pesticides, are strongly associated with sediment and especially with the organic carbon that is transported as part of the sediment load in rivers.

Ongley, *supra*. Sediment deposits can temporarily store contaminants that are later remobilized. Taylor, *supra*, at 192.

[95] *See* Ahiablame et al., *supra* note 82, at 4256, 4259, 4260, 4261; LeFevre et al., *supra* note 90, at 04014050-8 to 04014050-12 (discussing

dissolved-metal removal performance of bioretention systems).

[96] The data depicted in the chart come from the following source: Pollutant Category Summary, *supra* note 93 at 5–30 tbls. 2–27. The amount of data available for different pollutant types in different categories of GSI varies significantly. For example, from 0 to 5 installations were monitored for E. coli in each category, while between 2 and 63 were monitored for TSS. *See id.* at 5 tbl.2, 7 tbl.4. Some of the categories in the BMP database may include examples of both conventional stormwater infrastructure and GSI. For instance, conventional detention basins are widely used to slow stormwater flow by temporarily detaining it. *See Dry Detention Ponds*, U.S. Envtl. Prot. Agency, http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=67. However, detention basins can be built as, or retrofitted to become vegetated water quality basins that further LID principles. *See supra* note 22. The detention basin category in the International BMP Database includes 33 "grass-lined" basins and 6 "concrete lined basins or underground concrete vaults," however, water quality performance was only analyzed for a subset of the grass-lined basins. Int'l Stormwater BMP Database, Narrative Overview of BMP Database Study Characteristics 6 (2012) [hereinafter Narrative Overview], *available at* http://www.bmpdatabase.org/Docs/Simple%20Summary%20BMP%20Database%20July%202012%20Final.pdf.

[97] Separate results are shown for disinfection-, filtration-, and physical-settling-based devices.

[98] *See* Ahiablame et al., *supra* note 82, at 4256, 4258–59, 4260, 4261; LeFevre et al., *supra* note 90, at 04014050-3 to 04014050-8 (discussing dissolved nutrient removal performance of bioretention systems).

[99] *See* Janel E. Grebel et al., *Engineered Infiltration Systems for Urban Stormwater Reclamation*, 30 Envtl. Eng'g Sci. 437, 441 (2013) ("Removal of pathogens from stormwater by engineered infiltration systems . . . requires further study and improvement."); Ahiablame et al., *supra* note 82, at 4265 ("The influence of LID practices on pathogens should continue to be investigated . . . .").

[100] *See* LeFevre et al., *supra* note 90, at 04014050-12 to 04014050-17 (summarizing studies examining organic pollutant removal by bioretention systems and stating that "little is known about [the fate of] more polar organic pollutants" in bioretention systems); Grebel et al., *supra* note 99, at 440–41 ("Further research is particularly necessary to ensure adequate removal of hydrophilic organic stormwater contaminants that pose the greatest risks for groundwater contamination."); Gregory H. LeFevre et al., *The Role of Biodegradation in Limiting the Accumulation of Petroleum Hydrocarbons in Raingarden Soils*, 46 Water Research 6753, 6754 (2012); *see also* Gregory H. LeFevre et al., *Quantification of Petroleum Hydrocarbon Residual and Biodegradation Function Genes in Rain Garden Field Sites*, *in* Low Impact Development 2010: Redefining Water in the City, at 1379, 1380 (2010) ("Few studies have explicitly examined petroleum hydrocarbon removal in raingardens. . . . Based on the available evidence, bioretention appears to be successful in removing hydrocarbons from infiltrated stormwater. Nonetheless, we are unaware of any research performed to investigate the ultimate fate of hydrocarbons in raingardens. Removal is presumed to be a combination of sorption and biodegradation, but these two mechanisms and their relative importance in raingardens have not been adequately explored.").

[101] *See* LeFevre et al., *supra* note 90, at 04014050-17 ("Road salt is a major source of dissolved chloride in some portions of the world, but little research has focused on its impact on bioretention function including pollutant removal.").

[102] *See San Francisco Bay Mercury TMDL*, S.F. Bay Reg'l Water Quality Control Bd., http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/sfbaymercurytmdl.shtml (last visited Jan. 7, 2015); *San Francisco Bay PCBs TMDLProject*, S.F. Bay Reg'l Water Quality Control Bd., http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/sfbaypcbstmdl.shtml (last visited Jan. 7, 2015); *Diazinon and Pesticide-Related Toxicity in Urban Creeks TMDL*, S.F. Bay Reg'l Water Quality Control Bd., http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/urbancrksdiazinontmdl.shtml (last visited Jan. 7, 2015); *see also* David et al., *supra* note 79, at 04014092-2 (noting that "[t]here are few published studies exploring LID performance for a suite of toxicants, including . . . dioxins . . . , polychlorinated biphenyl (PCB) congeners, and mercury").

[103] *See Lake Stressors: Toxic Chemicals*, Great Lakes Envtl. Assessment & Mapping Project, http://www.greatlakesmapping.org/great_lake_stressors/1 (last visited Jan. 7, 2014).

[104] Although "[d]issolved pollutants are more bioavailable, impacting the receiving water and its biota more quickly," and "[m]any important storm-water pollutants are present partially or primarily in the dissolved phase, including some PCBs, copper, petroleum hydrocarbons, phosphorus, zinc, nickel, nonylphenols, and low molecular weight PAHs," "much of the storm-water literature has not differentiated between dissolved and particle-associated pollutants and has often not addressed fundamental physical, chemical, and biological storm-water pollutant removal mechanisms." LeFevre et al., *supra* note 90, at 04014050-2 to 04014050-3.

[105] While percent reduction (also known as removal efficiency) is commonly reported, it does not paint a complete picture of GSI effectiveness. *See generally* Int'l Stormwater BMP Database, Why Does the International Stormwater BMP Database Project Omit Percent Removal as a Measure of BMP Performance? (2007), *available at* http://www.bmpdatabase.org/Docs/FAQPercentRemoval.pdf (summarizing "some key shortcomings associated with percent removal as a tool to assess BMP performance). In fact, percent reduction can be misleading absent greater context. For example, for the same GSI facility, larger percent reductions generally accompany larger influent pollutant loads but convey nothing about the actual effluent quality achieved. *See id.* at 1. Additionally, because "[m]ethods for calculating percent removal are inconsistent (e.g., event by event, mean of event percent removals, inflow median to outflow median, inflow load to outflow load, slope of regression of loads, slope of regression of concentrations)," "[v]ery different percent removals can be reported from the same data set." *Id.* at 2. "In some percent removal calculation methods, volume reductions are partially taken into account, but not in others." *Id.* at 3. Furthermore, standard percent removal reporting "carries non of the statistical support needed to assesss uncertainty in the reported value." *Id*. at 2.

[106] *See also, e.g.*, Wash. Dep't of Ecology, Focus on Bioretention Monitoring: Ecology Begins Review of Bioretention Monitoring Data (Mar. 2013), *available at* https://fortress.wa.gov/ecy/publications/publications/1310017.pdf (noting that preliminary data from bioretention sites in three Washington cities revealed that "[p]hosphorus and dissolved copper increase[d] significantly" and "[s]hort-term significant increases in nitrate [are] also possible" in effluent, leading the agency to potentially "consider additional restrictions to prevent cumulative impacts where bioretention system effluents could eventually comprise a significant source of groundwater recharge").

[107] *See* Hunt et al., *supra* note 33, at 705 ("It is possible for bioretention to accomplish many, if not most, regulatory needs associated with urban stormwater treatement. Bioretention facilities are versatile practices, but do need to be carefully constructed.").

[108] *See supra* note 7.

[109] For many pollutants, "surface percolation devices (i.e., grass swales and percolation ponds), which have a substantial depth of underlying organic-rich soils above the groundwater, are preferable to using subsurface infiltration devices (i.e., dry wells, trenches or French drains, and especially injection wells)." Clark & Pitt, *supra* note 77, at 35. Soil characteristics that affect pollutant capture and mobility include texture, permeability, saturation, pH, mineral composition, and organic content. *See id.* at 32–33.

[110] *See* Clark & Pitt, *supra* note 77, at 32, tbl.4 and tbl.4 note, 35.

[111] *See supra* note 109; Li & Davis, *supra* note 87, at 575. *But see* Michio Murakami et al., *Sorption Behavior of Heavy Metal Species by Soakaway Sediment Receiving Urban Road Runoff from Residential and Heavily Trafficked Areas*, 164 J. Hazardous Materials 707, 707 (2009) (suggesting that dissolved organic matter in road runoff may enhance the release of zinc from sediments in infiltration facilities, contributing to groundwater contamination).

[112] *See* Hunt et al., *supra* note 33, at 703, 704; Shirley Clark & Robert Pitt, *Storm-Water Filter Media Pollutant Retention under Aerobic versus Anaerobic Conditions*, 135 J. Envtl. Eng'g 367, 367 (2009).

[113] *See, e.g.*, Eric T. Palmer et al., *Nitrate and Phosphate Removal through Enhanced Bioretention Media: Mesocosm Study*, 85 Water Env't Research 823, 831 (2013).

[114] *See, e.g.*, Grebel et al., *supra* note 99, at 447 (Although "the combination of techniques to optimize treatment of one type of contaminant may not be suitable for another, making the design of broad spectrum treatment a challenge[,] . . . a systems-level approach, with proper ordering of treatment methodologies [can be] chosen to optimize synergies and reduce antagonism between various techniques." For example, "[m]aterials could be layered to create reactive barriers that target specific types of contaminants for removal in a logical progression."); Li & Davis, *supra* note 90 , at 3403 (suggesting that "[a] specific filter media for adsorbing DON [dissolved organic nitrogen], and the incorporation of an anaerobic zone in the lower filter media [to address nitrate], may both be necessary for enhanced nitrogen removal" in bioretention systems, and noting that "biological pathways, including plant uptake and conversion to gaseous form via denitrification" may be required for sustainable nitrogen management); Palmer et al., *supra* note 113, at 831 (suggesting that adding aluminum water treatment residuals to bioretention soil media can enhance phosphate removal); Joel G. Morgan et al., Sorption and Release of Dissolved Pollutants Via Bioretention Media 32 (2011) (suggesting a top layer of compost-amended sand to capture organic compounds and toxic metals over an "iron-enhanced sand layer" to capture phosphorous).

[115] *See, e.g.,* Grebel et al., *supra* note 99, at 447 (describing three primary options and areas of research "for improving contaminant removal in infiltration systems": (1) "the choice of infiltration media," (2) "control of media saturation," and "control of . . . redox conditions within infiltration media"); Jia Liu et al., *Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater*, 6 Water 1069, 1083 (2014) ("Amendment of media to improve bioretention performance is an active area of research.").

[116] *See, e.g.*, *Low Impact Development Program*, Wash. Stormwater Ctr., http://www.wastormwatercenter.org/low-impact/ (last visited Jan. 7, 2014) ("While the decentralized LID approach shows promise to better manage stormwater, significant gaps remain in our understanding of the water quality treatment and flow control capabilities of bioretention, permeable paving, green roofs, and other LID practices. Additionally, data is needed to evaluate the performance of LID practices" under different site conditions.).

[117] Data derive from peer-reviewed field studies cited in several recent review articles. *See* Liu et al., *supra* note 115, at 1075–76 tbl.1, 1079–80 tbl.2; Ahiablame et al., *supra* note 82, at 4257 tbl.1; *see also* Audrey Roy-Poirier et al., *Review of Bioretention System Research and Design: Past, Present, and Future*, 136 J. Envtl. Eng'g 878 (2010); Allen P. Davis et al., *Bioretention Technology: Overview of Current Practice and Future Needs*, 135 J. Envtl. Eng'g 109 (2009). The data shown in **Figure 2** derives from monitoring of 24 bioretention cells in 7 states. It includes volume information for 15 cells—in North Carolina (10), Maryland (2), Connecticut (1), Virginia (1), and Washington (1)—and pollutant information for 21 cells—in North Carolina (11), Maryland (5), Connecticut (1), Kansas (1), New Hampshire (1), Virginia (1), and Washington (1). The following articles are the original sources of the data: Jennifer Olszewski & Allen P. Davis, *Comparing the Hydrologic Performance of a Bioretention Cell with Predevelopment Values*, 139 J. Irrigation & Drainage Eng'g 124, 129 tbl.3 (2013); Xiaolu Chen et al., *Nitrogen Removal and Nitrifying and Denitrifying Bacteria Quantification in a Stormwater Bioretention System*, 47 Water Research 1691, 1695 (2013); R. A. Brown & W. F. Hunt, *Improving Bioretention/Biofiltration Performance with Restorative Maintenance*, 65 Water Sci. Tech. 361, 364 fig.2, 365 tbl.2 tbl.3 (2012*);* J. M. Hathaway et al., *Field Evaluation of Bioretention Indicator Bacteria Sequestration in Wilmington, North Carolina*, 137 J. Envtl. Eng'g 1103, 1108, 1112 (2011); K. M. DeBusk & T. M. Wynn, *Storm-Water Bioretention for Runoff Quality and Quantity Mitigation*, 137 J. Envtl. Eng'g, 800, 803, 807 (2011); R. A. Brown & W. F. Hunt, *Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads*, 137 J. Envtl. Eng'g 1082, 1087 fig.7, 1089 tbl.8 (2011); Cameron Chapman & Richard R. Horner, *Performance Assessment of a Street-Drainage Bioretention System*, 82 Water Env't Research 109, 115 tbl.4, 118 (2010); Elodie Passeport et al., *Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution*, 135 J. Irrigation & Drainage Eng'g 505, 508 tbl.2 (2009); Houng Li et al., *Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland*, 14 J. Hydrol. Eng. 407, 412 tbl.5, 413 tbl.6 (2009); Li & Davis, *supra* note 87, at 570 tbl.2; W. F. Hunt et al., *Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, NC*, 134 J. Envtl. Eng'g 403, 405 tbl.3 (2008); Allen P. Davis, *Field Performance of Bioretention: Hydrology Impacts*, 13 J. Hydrologic Eng'g 90, 93 (2008); Allen P. Davis, *Field Performance of Bioretention: Water Quality*, 24 Envtl. Eng'g Sci. 1048, 1057 tbl.2, 1061 tbl.3 (2007); Robert M. Roseen et al., *Stormwater Low-Impact Development, Conventional Structural, and Manufactured Treatment Strategies for Parking Lot Runoff*, 1984 Transp. Research Record 135, 145 fig.7 (2006); W.F. Hunt et al., *Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina*, 132 J. Irrigation & Drainage Eng'g 600, 603, 605 tbl.4 note (2006); Michael E. Dietz & John C. Clausen, *Saturation to Improve Pollutant Retention in a Rain Garden*, 40 Envtl. Sci. & Tech. 1335, 1336 tbl.1, 1337 tbl.3 (2006); Allen P. Davis et al., *Water Quality Improvement Through Bioretention Media: Nitrogen and Phosphorus Removal*, 78 Water Env't

Research 284, 290 (2006).

[118] *See, e.g.*, David et al., *supra* note 79, at 04014092-2 ("[M]anagers need more quantitative [performance] data to establish minimum performance targets and estimate efficacy" for many toxicants. "For example, it is difficult to speculate about the efficiency of LID in the removal of . . . rarely studied toxicants in relation to the characteristics of a given bioretention design."); Li & Davis, *supra* note 90, at 3403 (Bioretention "[n]itrogen removal performance . . . has been highly variable, with reported results ranging from as high as 60% removal to net nitrogen export. . . . More information on nitrogen species concentrations in bioretention systems is needed to provide better fundamental understanding of N behavior and fate. This information can lead to enhanced N removal through improved bioretention design."); Ahiablame et al., *supra* note 82, at 4265 ("Scientific data for continuing in-depth understanding of the effectiveness of LID practices, such as swale systems, green roof, rain barrel/cistern, infiltration wetland, and porous pavement, at various temporal and spatial scales, as well as in different geographic regions are needed. Emphasis should be given to inputs, specific transformations and accumulations, and export of pollutants from the systems."); Li & Davis, *supra* note 87, at 567 ("Previous studies have indicated that bioretention effectively improves both water quality and drainage area hydrology[,] . . . [n]onetheless, water quality performance information is still lacking for many pollutants and detailed pollutant fate and transport characteristics have not yet been fully documented. Therefore opportunities exist to improve field bioretention design and maintenance procedures.").

[119] *See, e.g.*, David et al., *supra* note 79, at 04014092-1 to 04014092-2 (explaining that "[f]ield studies in semiarid environments [where the use of bioretention is complicated by pronounced wet and dry seasons] are currently lacking"); Equilibrium Cmtys. Initiative, Green Infrastructure and Low-Impact Development 15 (2013), *available at* http://www.cmhc-schl.gc.ca/odpub/pdf/67819.pdf ("[M]ore information is needed on the performance and maintenance of bioretention and permeable pavers in locations with freeze/thaw cycles and significant snow fall."); Gautam et al., *supra* note 75, at 46 ("There is a conspicuous lack of scientific research and pilot projects related to BMP design in arid desert environments despite some efforts of implementation in semi-arid environments (Northern Nevada, Southern California, Colorado, etc.). The project information, success stories, and lessons learned are thus not widely known."); Allen P. Davis et al., *Hydrologic Performance of Bioretention Storm-Water Control Measures,* 17 J. Hydrologic Eng'g 604, 604–05, (2012) ("[C]urrent bioretention design is highly empirical, and it ignores the facts that different designs in different geologic and climatic locations produce different performance results."); Allen P. Davis et al., *Improving Urban Stormwater Quality: Applying Fundamental Principles*, 146 J. Contemporary Water Research & Educ. 3 (2010) ("While implementation continues at an increasing rate, our fundamental understanding of the performance of these facilities is still forthcoming. Designs are highly empirical and performance results are broadly applied across different situations. Performance is [wrongly] assumed to be independent of many highly dynamic conditions to which these facilities are constructed and exposed, including different land uses, climates, rainfall patterns, geometry, sizes, and soil and vegetation characteristics."); Davis et al., *supra* note 117, at 109 ("Despite the rapid acceptance of" bioretention "throughout the United States, detailed performance information and related design guidance are not currently available for many regions. Several state and local governments have adopted bioretention guidelines published by another state agency, often without modifying the guidelines for local conditions, using out-of-date information, or without a good understanding of the range or limitations of these BMPs. . . .").

[120] *See, e.g.*, Grebel et al., *supra* note 99, at 437 ("Although engineered infiltration systems also have the capacity to remove contaminants from stormwater, . . . [it] has not yet been fully exploited or optimized."); *id.* at 440 ("[D]ata [for metals and nutrients] suggest that good treatment efficiencies are achievable . . . , but that improvements in overall reliability will require more careful engineering."); *id.* at 441 ("Removal of pathogens from stormwater by engineered infiltration systems also requires further study and improvement."); *see also* William J. Taylor & Cardno TEC, Stormwater Management Program Effectiveness Literature Review: Low Impact Development Techniques 39 (2013), *available at* http://www.ecy.wa.gov/programs/wq/psmonitoring/ps_monitoring_docs/SWworkgroupDOCS/LIDWhitePaperFinalApril2013.pdf (""Researchers should "[c]onduct soil media composition and leaching studies together with nutrient sorption amendments and identification of a plant pallet most appropriate for growth success. Media studies should be conducted especially related to phosphorus and copper content and their leaching potential. Results of this effectiveness study will narrow the range of appropriate media composition and viable amendments for use in bioretention and green roof facilities to prevent high concentrations of phosphorus in the runoff while encouraging success of low maintenance planting plans.").

[121] *See, e.g.*, Hunt et al., *supra* note 33, at 698 ("Bioretention is one of the most commonly used stormwater control measures (SCMs) in North America and Australasia. However, current design is not targeted to regulatory need, often reflecting an outdated understanding of how and why bioretention works." "Bioretention cells designed to meet a prioritized subset of . . . [hydrologic and/or water quality needs] would be substantially different than cells that are designed for a different subset of needs.").

[122] *See, e.g.*, Liu et al., *supra* note 117, at1082 ("Since the mechanisms and maintenance practices of bioretention systems are still evolving, long-term performance and life-cycle cost relationships are still being documented. As these relationships become better understood, simulations can better predict lifecycle costs and maintenance intervals."); Taylor & Cardno TEC, *supra* note 120, at 38 ("The long term tracking of maintenance and performance of LIDs by local agencies and institutions, and the management of those LIDs will clearly be an important component in the use and success of these systems."); Equilibrium Cmtys. Initiative, *supra* note 119, at 15 ("Another information gap is the quantification of long-term cost savings of LID practices, for example through the reduced need for conventional infrastructure."); Nicole David et al., San Francisco Estuary Institute, Bioretention Monitoring at the Daly City Library 46 (2011) ("What is lacking presently is a thorough analysis comparing the costs of application and maintenance versus efficiency of LID with a similar analysis of conventional structural and non-structural municipal BMPs.").

[123] *See* Ahiablame et al., *supra* note 82, at 4266 (stating that monitoring efforts are generally "limited to short-term evaluation . . . due to high monitoring costs"); Ahmed Mohammed Al-Rubael et al., *Long-term Hydraulic Performance of Stormwater Infiltration Systems*, Urban Water J. (published online, ahead of print, Sept. 15, 2014); Taylor & Cardno TEC, *supra* note 120, at 36 ("Long term monitoring of the performance of bioretention facility performance (more than seven to eight years) is largely unrepresented in the literature simply due to the recent advent of these systems.").

[124] *See* Ahiablame et al., *supra* note 82, at 4266 (describing most GSI monitoring as occuring at the scale of individual installations); Aaron Poresky et al., *Site-level LID Monitoring and Data Interpretation: New Guidance for International BMP Database Studies (Part 2)*, *in* Low Impact Development 2010: Redefining Water in the City, at 1387 (2010) (stating that "Low Impact Development (LID) performance

monitoring and reporting is currently in its infancy and continues to evolve as LID practices and site designs are implemented in more communities"); Martin Jaffe et al., The Illinois Green Infrastructure Study 101, 102 (2010), *available at* http://www.epa.state.il.us/green-infrastructure/docs/draft-final-report.pdf (stating that "little information is available about the use of multiple [GSI] infrastructure in combination in treatment trains or across watersheds").

[125] Taylor & Cardno TEC, *supra* note 120, at 40 (noting that the scale of implementation "and spatial/temporal effects will likely play a significant role in the performance of, and ecological benefits of, a basin-wide application of [GSI]"); *see also id.* at ES-1 (stating that, "based on modeling," "[b]asin scale performance of the use of LIDs appears to depend on a high level of basin development and a high density of LID to affect a difference in receiving waters," but that "no basin scale studies have been conducted to document improvements in receiving waters as a result of the use of LIDs"); *id.* at 33 (stating that "[i]ndications suggest there are break points for level of development and level of LID implementation where benefits should be observable, but these break points will require empirical observation rather than results from modeling").

[126] *See* Andrew J. Erickson et al., *Maintenance for Stormwater Treatment Practices*, 146 J. Contemporary Water Research & Educ. 75, 78 (2010).

[127] *See* Puget Sound Action Team, Maintenance of Low Impact Development Facilities 5, 8 (2007), *available at* http://www.psparchives.com/publications/our_work/stormwater/lid/D_RevisedMaintenanceofLIDFacilities.pdf; James J. Houle et al., *Comparison of Maintenance Cost, Labor Demands, and System Performance for LID and Conventional Stormater Management*, 139 J. Envtl. Eng'g 932, 936 (2013).

[128] *See* Grebel et al., *supra* note 99, at 447 (noting that media or media amendments can clog (with fine sediment), become saturated with pollutants, or may be "highly biodegradable," potentially requiring period replacement to maintain system performance).

[129] *See, e.g.*, Houle et al., *supra* note 127, at 932 (explaining that "there is little documentation in terms of the frequency, intensity, and costs associated with LID maintenance operations required to meet system design objectives" and noting that more long-term cost information on maintenance would make "cost estimations" for LID alternatives "easier to accomplish and more precise"); *see also* sources cited *supra* note 122.

[130] *See* Houle et al., *supra* note 127, at 932 (finding that, "generally, LID systems, as compared to conventional systems, have lower marginal maintenance burdens (as measured by cost and personnel hours) and higher water quality treatment capabilities as a function of pollutant removal performance").

[131] *See Cost-Benefit Resources*, U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_costbenefits.cfm (last updated July 22, 2014).

[132] *See* U.S. Envtl. Prot. Agency, Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs 2 (2013), *available at* http://water.epa.gov/polwaste/green/upload/lid-gi-programs_report_8-6-13_combined.pdf [hereinafter Case Studies] ("Although many entities have begun to implement LID and GSI approaches for stormwater management, research shows that a relatively small percentage of jurisdictions have conducted economic analyses of their existing or proposed programs. This lack of program analysis is due to many factors including uncertainties surrounding costs, operation and maintenance (O&M) requirements, budgetary constraints, and difficulties associated with quantifying the benefits provided by [GSI].")

[133] *See, e.g.*, U.S. Envtl. Prot. Agency, The Economic Benefits of Green Infrastructure: A Case Study of Lancaster, PA 1 (2014), *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/CNT-Lancaster-Report-508.pdf; N.Y. Dep't Envtl. Prot., NYC Green Infrastructure Plan: A Sustainable Strategy for Clean Waterways 8–10 (2010), *available at* http://www.nyc.gov/html/dep/pdf/green_infrastructure/NYCGreenInfrastructurePlan_LowRes.pdf; Stratus Consulting Inc., A Triple Bottom Line Assessment of Traditional and Green Infrastructure Options for Controlling CSO Events in Philadelphia's Watersheds (2009), *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/gi_philadelphia_bottomline.pdf; American Rivers et al., Banking on Green: A Look at How Green Infrastructure Can Save Municipalities Money and Provide Economic Benefits Community-Wide 10–12 (2012), *available at* http://www.americanrivers.org/assets/pdfs/reports-and-publications/banking-on-green-report.pdf (describing GSI's cost-effectiveness for stormwater volume control, mostly in the context of CSO reduction). *But see, e.g.,* Opportunities and Barriers, *supra* note 30, at 1–2; Case Studies, *supra* note 132, at 5 exhibit 2 (2013) (including case studies of 13 cities, counties, and districts with a variety of goals, e.g., CSO reduction (5 cases), flood control (7), meeting MS4 permit requirements (4), recharging groundwater (2), etc.).

[134] *See infra* note 183 and accompanying text.

[135] *See* Ctr. for Leadership in Global Sustainability, *supra* note 17, at 17 ("Under the Clean Water Act, municipalities are facing increasingly rigorous standards with regards to water pollutant discharge, either as part of Total Maximum Daily Load (TMDL) implementation plans or as part of National Pollutant Discharge Elimination System (NPDES) permitting programs. . . . Rather than investing in all grey infrastructure upgrades to expand capacity, an increasing number of cities and regions are looking to green infrastructure as a viable way to meet their stormwater reduction goals while also benefiting from the other functions and values green infrastructure provides."); Nabong, *supra* note 41, at 48 ("The compliance criteria in the new permit are so stringent that source control measures alone are not expected to be enough to reach success. In fact, the city has determined that an extensive program of treatment control practices in combination with source controls appears to be the only way to get close to the concentration-based load reduction requirements found within the new permit.").

[136] As reported in Liu et al., *supra* note 117, at 1083, 1075–76 tbl.1, 1079–80 tbl.2; Ahiablame et al., *supra* note 82, at 4257 tbl.1.

[137] *See* Narrative Overview, *supra* note 96, at 5; *see also BMP Map Tool*, Int'l Stormwater BMP Database, http://www.bmpdatabase.org/map.html (studies available by selecting "Bioretention" radio button). The ISBMPD contains entries for only 30 studies, representing 28 different installations. See Narrative Overview, *supra* note 96, at 5. There are no studies from arid climates, semi-arid climates, or the plains states. *Id.*

[138] The stormwater volume reduction data in **Figure 2** come from 17 sites in 5 states, while the pollutant-reduction data come from between 5 and 17 sites in 2 to 5 states, depending on the pollutant. Most studied installations are located in North Carolina (14), a few are in Maryland (6), and one each is in Connecticut, Kansas, New Hampshire, Virginia, and Washington. The ISBMPD contains data for 12 of the same North Carolina sites and the New Hampshire site analyzed in the peer-reviewed literature and adds at least some data from 15 additional sites in Wisconsin (4), New Hampshire (2), Virginia (3), and Colorado (1), Delaware (1), Massachusetts (1), Oregon (1), and Washington (1).

[139] In this situation there are significant information gaps that monitoring GSI implementation can fill, enabling adjustments in current and future implementation. *See* Holly Doremus, *Adaptive Management as an Information Problem*, 89 N. Carolina L. Rev. 1455, 1466 (2011) (describing when adaptive management makes sense). The extra cost and effort now will save money and improve the chances of meeting or making significant headway toward meeting stormwater management goals in the coming decades. *See id.* at 1479 (explaining that adaptive management, and the additional monitoring it requires, "should be used only if the tradeoffs appear to offer a net benefit, measured in terms of improved likelihood of meeting management goals"); Eric Biber, *Adaptive Management and the Future of Environmental Law*, 46 Akron L. Rev. 933, 946 (2013).

[140] *See* Shuster et al., *supra* note 74, at 10 ("Due to a lack of structured monitoring of many management actions, many LID approaches are assumed to impart long lists of anticipated benefits. . . . It is a false-economy to provide no scientific backing for benefits claimed at the inception of an LID management action.").

[141] *See* Greening CSO Plans, *supra* note 46, at 23.

[142] Greening CSO Plans, *supra* note 46, at 23; *see also* Shuster et al., *supra* note 74, at 10 ("Monitoring programs can impart a science-based assessment of environmental management practices and document their effectiveness for promotion to the public and local stormwater managers. In addition, monitoring can alert managers to conditions under which failure may result, and provide evidence for adaptation of the practices and needed maintenance following implementation."). A blend of active and passive adaptive management taking place at multiple scales is at play here, with local implementers contributing experiments and data to the broader stormwater management pool and gleaning lessons and feedback from there own and others' implementation experiences. *See* Biber, *supra* note 139, at 934 (describing active and passive adaptive management).

[143] *See e.g.*, Allen P. Davis et al., *Laboratory Study of Biological Retention for Urban Stormwater Management*, 73 Water Envt. Research 4 (2001).

[144] *See, e.g.*, R.A. Brown & W. F. Hunt, *Impacts of Media Depth on Effluent Water Quality and hydrologic performance of Undersized Bioretention Cells*, 137 J. Irrigation & Drainage Eng'g 132, 122 (2011) (analyzing the performance of monitored side-by-side bioretention cells with different media depths); J. M. Hathaway et al., *Field Evaluation of Bioretention Indicator Bacteria Sequestration in Wilmington, North Carolina*, 137 J. Envtl. Eng'g 1103, 1104 (2011) (monitoring two adjacent bioretention areas with different media depths).

[145] *See generally* McKinsey Global Institute, Big Data: The Next Frontier for Innovation, Competition, and Productivity 1 (2011) ("'Big data' refers to datasets whose size is beyond the ability of typical database software tools to capture, store, manage, and analyze.").

[146] *Cf.* Ctr. for Leadership in Global Sustainability, *supra* note 17, at 13 ("In some situations, the lack of design standards for green infrastructure precludes [it] from implementation. In other situations, it presents a perceived risk and liability for engineers to go outside of the industry standard."); Clean Water Am. Alliance, Barriers and Gateways to Green Infrastructure 14–15 (2011) ("Many respondents indicated that the lack of complete local, state and federal design standards that take into account differences in regional and local soil, climate and topography variances has limited the ability of communities to implement green infrastructure projects. Without design standards, local design professionals and engineers are less likely to deviate from the familiar measures of pipes, basins, and ditches."). General design drawings (and related standards and specifications) are currently available for some types of GSI; however, these are often very general, lacking sufficient guidance to achieve water quality goals under different site-specific conditions. *See, e.g., Drainage-Bioretention Specification*, Low Impact Development Ctr., http://www.lowimpactdevelopment.org/epa03/biospec.htm (copyright 2003). *But see* S.F. Pub. Utils. Comm'n, Green Stormwater Infrastructure Typical Details (Jul. 2014), *available at* http://sfwater.org/modules/showdocument.aspx?documentid=6009 (including fairly detailed design and specification guidance, drawings, etc.); S.F. Pub. Utils. Comm'n, Green Stormwater Infrastructure Typical Details Informational Memorandum (Aug. 2014), *available at http://sfwater.org/modules/showdocument.aspx?documentid=6008*.

[147] *See, e.g.*, Int'l Stormwater BMP Database, Advanced Analysis: Influence of Design Parameters on Achievable Effluent Concentrations 72 (2013), *available at* http://www.bmpdatabase.org/Docs/BMPDB_AdvancedAnalysis_Final_2013.pdf ("[T]here is a significant need for more complete and consistent reporting of the meta data requested for each BMP type with submissions . . . ."); Expanded Analysis of Volume Reduction in Bioretention BMPs, *supra* note 83, at 19 ("As new studies are added to the BMP Database, the benefit of these studies will be the greatest when facility design and watershed characteristics are included with the data submission.").

[148] Monitoring and quantifying the multiple benefits GSI brings and estimating the costs it avoids (like maintaining and replacing gray infrastructure) will help paint a more accurate picture of its true costs.

[149] *See* generally Ellen Hanak et al., Paying for Water in California (2014), *available at* http://www.ppic.org/content/pubs/report/R_314EHR.pdf.

[150] "Software maintenance is done to correct faults, improve performance, or adapt a software system to a new environment"; it can be corrective, adaptive, perfective, or preventative. Software Engineering: Maintenance, Openseminar, http://openseminar.org/se/modules/22/index/screen.do (last updated Aug. 14, 2008).

[151] *See, e.g.*, Geosyntec Consultants & Wright Water Engineers, Urban Stormwater BMP Performance Monitoring 1-5, ES-3 (2009) [hereinafter BMP Performance Monitoring], *available at* http://www.bmpdatabase.org/monitoring-guidance.html#MonitoringGuidance ("A strong data management and reporting system helps to ensure that studies are documented in a manner that enables long-term use of the data and transferability to the local, regional, national, and international state of the practice."); Martin Jaffe et

al., Using Green Infrastructure to Manage Urban Stormwater Quality: A Review of Selected Practices and State Programs 107 (2010), *available at* http://www.epa.state.il.us/green-infrastructure/docs/public-act-recommendations.pdf ("There is . . . a need for more consistent reporting of green infrastructure performance. . . . The usefulness and accuracy of the [International] BMP [D]atabase depends on the standardization of methodologies and the rigor of its data entries."); Ahiablame et al., *supra* note 82, at 4266 ("[I]mproved metrics are needed to improve and standardize evaluation of LID practices.").

[152] Information "is not useful for management efforts unless it reaches the people who must make management decisions and reaches them in a form they can use." Doremus, *supra* note 139, at 1490. Improving "data architecture and information flow" can be a crucial step in making this happen. *Id.* (title capitalization omitted).

[153] *See, e.g.,* Liu et al., *supra* note 117, at 1075–76 tbl.1, 1079–80 tbl.2; Ahiablame et al., *supra* note 82, at 4257 tbl.1; Roy-Poirier et al., *supra* note 117, at 878; Davis et al., *supra* note 117, at 109.

[154] *See* BMP Performance Monitoring, *supra* note 151, at 1-5 to 1-6 (prepared with the support of EPA, other government agencies, and organizations).

[155] *See id.* (summarizing sources of monitoring complexity, including stormwater's temporal and spatial variability).

[156] *See id.* (distinguishing 5 general categories of stormwater control measures, including those "with well-defined inlets and outlets" (like detention basins and vegetated swales), those "with well-defined inlets, but not outlets" (like infiltration basins, infiltration trenches, and bioretention cells), etc.).

[157] Dennis M. King & Luke W. Herbert, *The Fungibility of Wetlands*, Nat'l Wetlands Newsletter, Sept.–Oct. 1997, at 10.

[158] *See* BMP Performance Monitoring, *supra* note 151, at 1-7.

[159] *See, e.g.*, BMP Performance Monitoring, *supra* note 151, at 8-7, 8-8 (describing the importance of monitoring "the ways in which overall [development-level] site design and implementation impact hydrology and water quality"); *see also id.* at 8-9 (identifying additional challenges for larger-scale monitoring, including a "multitude of discharge locations and distributed nature of the controls [that] often does not present an opportunity to select a single monitoring point sufficient to assess site hydrology and water quality").

[160] *Cf.* Holly Doremus, *Data Gaps in Natural Resource Mangement: Sniffing for Leaks Along the Information Pipeline*, 83 Ind. L.J. 407, 429 (2008) ("Monitoring drains scarce agency resources without providing the political benefits of action. It may even threaten to scuttle delicate political compromises if it highlights problems with existing management efforts. As a result, post-decision monitoring of management steps is the exception rather than the rule, and opportunities for learning are regularly squandered.").

[161] King & Herbert, *supra* note 157, at 10; *see also* Robert Bloomfield, What Counts & What Gets Counted 51 (2014).

[162] *See supra* note 16.

[163] Stakeholder groups that have embraced GSI include the California Storwater Quality Association, the Sustainable Business Network of Greater Philadelphia, the Natural Resources Defense Council, and American Rivers. *See SoCal LID Manual*, Cal. Stormwater Quality Ass'n, https://www.casqa.org/resources/lid/socal-lid-manual (last visited Feb. 11, 2015); *Green Stormwater Infrastructure Partners*, Sustainable Bus. Network, http://www.sbnphiladelphia.org/initiatives/GSI_Partners/ (last visited Feb. 11, 2015); *Rooftops to Rivers II: Green Strategies for Controlling Stormwater and Combined Sewer Overflows*, Natural Res. Defense Council, http://www.nrdc.org/water/pollution/rooftopsii/ (last revised Oct. 29, 2013); *Green Water Infrastructure*, Am. Rivers, http://www.americanrivers.org/initiatives/pollution/green-infrastructure/ (last visited Feb. 11, 2015).

[164] *See supra* note 49 and accompanying text (describing Philadelphia's commitment to GSI); Jeff Guderson et al., *Economical CSO Management: Progressive Cities Are Incorporating Green Infrastructure Strategies with Grey Infrastructure Investments to Achieve Cost-Effective CSO Reductions*, Stormwater, May 2011, *available at* http://www.stormh2o.com/SW/Articles/14216.aspx (describing the costs and benefits of GSI initiatives in Portland, Oregon; Kansas City, Missouri; Chicago, Illinois; and New York City, New York).

[165] *See How Can I Overcome the Barriers to Green Infrastructure?* U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_barrier.cfm (last updated June 13, 2014) ("As planners, researchers, and engineers become more aware of the many benefits of green infrastructure, interest is growing in adding sustainable green practices to existing gray systems. Many communities have adopted performance standards or incentives promoting green infrastructure and many more have built demonstration projects but single-purpose gray systems remain the norm."). This is particularly true in the arid and semi-arid west and other areas where the main drivers for GSI implementation are non-CSO water quality concerns or groundwater recharge, and financial incentives for widespread implementation are less straightforward. *See supra* notes 133–135 and accompanying text.

[166] *See* Ctr. for Neighborhood Tech. & Hey & Associates, Monitoring and Documenting the Performance of Stormwater Best Management Practices viii (2012), *available at* http://www.istc.illinois.edu/info/library_docs/TR/TR048.pdf ("More widespread utilization of green infrastructure . . . is impeded by a lack of data concerning how well these BMPs perform immediately after installation, how they perform over time, and how frequently maintenance may be required."); Nabong, *supra* note 41, at 57 ("Once the [pollutant] load reduction performance is quantified, the city can refine estimates of how many treatment control BMPs such as this are needed to meet the [TMDL] load reduction mandate. . . . Ideally, new design concepts such as the ones featured here would be tested for 20 years or more before investment is made in broader implementation, but regulatory timelines don't allow that. Concurrent with testing and evaluating the featured project, additional capital improvement projects are coming online to support additional pilot testing and to make a dent in the required load reductions.").

[167] *See supra* notes 47–48, 53–56, 135, and accompanying text; *see also, e.g.*, Andrew Fahlund et al., 6 *Water in the West*, Calif. J. Pol. & Pol'y

61, 81 (2014) (describing Los Angeles's "comprehensive effort to integrate green infrastructure throughout the basin" as motivated by "water quality requirements set by the Regional Water Resources Control Board" under the Clean Water Act).

[168] *See* Water Env't Fed'n, Investigation into the Feasibility of a National Testing and Evaluation Program for Stormwater Products and Practices 4 (2014), *available at* http://www.wef.org/uploadedFiles/Access_Water_Knowledge/Stormwater_and_Wet_Weather/Stormwater_PDFs/WEF-STEPP-White%20Paper_Final_02-06-14%282%29.pdf.

[169] *See* BMP Performance Monitoring, *supra* note 151, at 1-5, ES-2–3 ("A well-thought out and systematically designed monitoring program is essential to a cost-effective study design that yields meaningful results. . . . In order to obtain high-quality data in BMP monitoring studies, it is necessary to select the proper precipitation, flow, and water quality sample collection and monitoring equipment and procedures. . . . In order for well designed monitoring programs to result in high quality data, personnel must be properly trained, equipment properly installed, calibrated and maintained, samples correctly collected and analyzed, and data properly reported. Failures at this stage of the monitoring program can result in data that cannot be used to draw valid conclusions regarding BMP performance. . . . Once data have been collected from a monitoring program, the data need to be compiled and managed in a manner that reduces introduction of errors and enables ready access for future reference . . . ."); *see also* G. Fred Lee & Anne Jones-Lee, *Issues in Monitoring Hazardous Chemicals in Stormwater Runoff/Discharges from Superfund and Other Hazardous Chemical Sites*, 20 Remediation J. 115, 115 (2010) ("Two pervasive problems are the use of analytical methods that are inadequate . . . , and the application of 'criteria/standards' that are inappropriate for evaluating . . . impacts . . . .").

[170] *See supra* notes 46–51 and associated text.

[171] For example, the city of Philadelphia's "comprehensive" monitoring plan explains that "[t]he monitoring and assessment of green stormwater infrastructure performance, sewer system response to precipitation, receiving water quality, meteorological conditions, and groundwater are integral parts of the program's implementation and adaptive management approach." Phila. Water Dep't, Green City, Clean Waters: Comprehensive Monitoring Plan 2-1 (revised 2014), *available at* http://www.phillywatersheds.org/doc/Revised_CMP_1_10_2014_Finalv2.pdf; *see also id.* at 4-13–4-14 tbl.4-2 (describing post-construction monitoring subjects, associated research questions, and potential tasks related to each). The city's view of GSI performance encompasses hydrologically-oriented "functional components," like "stormwater inflow, soil moisture storage, storage, evapotranspiration, surface infiltration, subsurface infiltration, underdrain return flow, and bypass flow"—but no direct pollutant-reduction performance monitoring. *Id.* at 4-3.

[172] *See supra* **Table 2**, notes 95–106 and associated text, and **Figure 2**; *see also, e.g.,* Mary Jane Clark & Youbin Zheng, *Fertilizer Rate and Type Affect Sedum-Vegetated Green Roof Mat Plant Performance and Leachate Nutrient Content*, 49 HortScience 328, 328 (2014) (describing leaching of nutrients from green roofs).

[173] Contamination has generally occurred in situations where stormwater is especially polluted, pretreatment (e.g., sediment settling) before infiltration is insufficient, the groundwater table is shallow, and/or infiltration occurs very rapidly (e.g., through highly permeable soils). *See* Peter T. Weiss et al., Contamination of Soil and Groundwater Due to Stormwater Infiltration Practices: A Literature Review 15–16 (2008); Clark & Pitt, *supra* note 77, at 30–31, 35 (describing reported instances of groundwater contamination and noting that "[i]Infiltration of stormwater from residential areas is . . . safer than from more contaminated areas, unless suitable pretreatment is used"); Shirley E. Clark et al., *Groundwater Contamination Potential from Infiltration of Urban Stormwater Runoff, in* Effects of Urbanization on Groundwater (2010), at 119, 121, 123, 154–55 (identifying salts and nutrients as potentially problematic); Suzanne Dallman & Martin Spongberg, *Expanding Local Water Supplies: Assessing the Impacts of Stormwater Infiltration on Groundwater Quality*, 64 Prof'l Geographer 232, 234, 247 (2012) (recapping reviews as "conclud[ing] that groundwater contamination potential from surface infiltration is low to moderate without pretreatment and low for infiltration with simple pretreatment . . . for most consituents of environmental concern," and finding "little evidence indicating that stormwater infiltration has negatively impacted groundwater at [Los Angeles Basin Water Augmentation Study] monitoring sites"); *see also Groundwater Impacts*, U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_gwimpacts.cfm (last updated June 13, 2014).

[174] *See* Joan F. Kenny et al., Estimated Use of Water in the United States in 2005 17 tbl.5, 20 tbl.6 (2009), *available at* http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf; *see also* Mary Tiemann, Cong. Research Serv., Safe Drinking Water Act (SDWA): A Summary of the Act and Its Major Requirements 8, 8 n.4 (2014), *available at* http://fas.org/sgp/crs/misc/RL31243.pdf ("Most public water systems rely on ground water as a source of drinking water.").

[175] *See, e.g.*, Richard G. Taylor et al., *Ground Water and Climate Change*, 3 Nature Climate Change 322, 326 (2013) ("Ground water can enhance the resilience of domestic, agricultural and industrial uses of fresh water in the face of climate variability and change. . . . Comprehensive management approaches to water resources that integrate ground water and surface water may greatly reduce human vulnerability to climate extremes and change, and promote global water and food security. Conjunctive uses of ground water and surface water that use surface water for irrigation and water supply during wet periods, and ground water during drought, are likely to prove essential." (Internal citation omitted)).

[176] *See* sources cited *supra* notes 16, 47–48, 53–56.

[177] 33 U.S.C. § 1251(a). The 1972 Act revised the 1948 Federal Water Pollution Control Act to achieve "a stronger regulatory, water chemistry-focused basis to deal with acute industrial and municipal effluents that existed in the 1970s." Nat'l Research Council, *supra* note 1, at 47.

[178] *See* 33 U.S.C. § 1311(a) ("Except as in compliance with this section and sections 1312, 1316, 1317, 1328, 1342, and 1344 of this title, the discharge of any pollutant by any person shall be unlawful."); 33 U.S.C. § 1362(12) (defining "discharge of a pollutant" as "any addition of any pollutant to navigable waters from any point source"). A "pollutant" is "dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt and industrial, municipal, and agricultural waste discharged into water." 33 U.S.C. § 1362(6). "Navigable waters" are "the waters of the United States, including the territorial seas." 33 U.S.C. § 1362(7). A "point source" is "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged." 33 U.S.C. § 1362(14). It "does not include agricultural stormwater

discharges and return flows from irrigated agriculture." Id. All other discharges (including agricultural discharges) are considered nonpoint sources.

[179] 33 U.S.C. § 1251(a)(3).

[180] *See* 33 U.S.C. § 1251(a)(1). Although Congress originally envisioned meeting this goal by 1985, actual results have fallen well short of even the interim target of achieving surface waters that are universally swimmable and fishable. *See* 33 U.S.C. § 1251(a)(1), (2) (describing the interim goal of "water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water").

[181] *See* 33 U.S.C. § 1342(a)(1), (b).

[182] *See supra* note 57 and associated text; *see also* 33 U.SC. § 1342(p)(3)(B); National Pollutant Discharge Elimination System—Regulations for Revision of the Water Pollution Control Program Addressing Storm Water Discharges, 64 Fed. Reg. 68,722, 68,737 (Dec. 8, 1999) (stating that "[p]ermit conditions developed to address concerns and conditions of a specific watershed . . . must provide for attainment of applicable water quality standards (including designated uses)"); *Defenders of Wildlife v. Browner*, 191 F.3d 1159, 1166 (9th Cir. 1999) ("Although Congress did not require municipal storm-sewer discharges to comply strictly with § 1311(b)(1)(C), § 1342(p)(3)(B)(iii) states that '[p]ermits for discharges from municipal storm sewers . . . shall require . . . *such other provisions as the Administrator . . . determines appropriate for the control of such pollutants.*'" These provisions may include "strict compliance with state water-quality standards" or "less than strict compliance with state water-quality standards"—for example, "us[ing] best management practices (BMPs) . . . to provide for the attainment of water quality standards.").

[183] *See* National Pollutant Discharge Elimination System—Regulations for Revision of the Water Pollution Control Program Addressing Storm Water Discharges, 64 Fed. Reg. at 68,737 (stating that "[p]ermit conditions developed to address concerns and conditions of a specific watershed . . . must provide for . . . allocations of pollutant loads established by a TMDL, and timing requirements for implementation of a TMDL"); *Overview of TMDL Program Results Analysis*, U.S. Envtl. Protection Agency, http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/results_overview.cfm (last updated Sept. 11, 2013). The Clean Water Act requires states to adopt and update water quality standards that include the designated beneficial uses of particular water bodies and water quality criteria sufficient to protect those designated uses. *See* 33 U.S.C. § 1313(c)(1), (c)(2)(A); 40 C.F.R. §§ 131.2, 131.4–131.6, 131.10–131.11, 131.12(a)(1). Designating the beneficial uses of a portion of a water body is like zoning it. *See* Nat'l Research Council, *supra* note 1, at 53. Potential beneficial uses include "public water supplies, propagation of fish and wildlife, recreational purposes, . . . agricultural, industrial, and other purposes, and . . . navigation." 33 U.S.C. § 1313(c)(2)(A). Each state must adopt water quality criteria for toxic pollutants for which the U.S. EPA has published recommended criteria that support the state's designated uses. 33 U.S.C. § 1313(c)(2)(B). Ideally, water quality criteria should be numeric, but narrative criteria (descriptive criteria "based on biological monitoring or assessment methods") are acceptable when numeric criteria are unavailable. 33 U.S.C. § 1313(c)(2)(B); *see also* 33 U.S.C. § 1362(15) (defining biological monitoring). States must identify waters within their boundaries that fail to meet applicable water quality standards and develop TMDLs, accounting for all pollution sources—including nonpoint sources—to correct exceedences of particular pollutants. *See* 33 U.S.C. § 1313(d). A TMDL is "the sum of the individual [wasteload allocations] for point sources and [load allocations] for nonpoint sources and natural background" plus a margin of safety. 40 C.F.R. §§ 130.2(i), 130.7. The TMDL process involves assessing and listing waters, developing TMDLs and source wasteload and load allocations, then implementing TMDLs by modifying NPDES permit requirements and encouraging nonpoint sources to adopt BMPs that reduce their pollutant discharges. *See Overview of TMDL Program Results Analysis*, U.S. Envtl. Prot. Agency, http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/results_overview.cfm (last updated Sept. 11, 2013).

[184] 40 C.F.R. § 130.2.

[185] *See, e.g.*, Compendium, *supra* note 59, at 3 ("Many states have developed performance and/or design standards to control post-construction stormwater discharges from newly developed and redeveloped sites. MS4 permits in 33 states have conditions implementing numeric [retention-based] performance standards."). Federal regulations require small MS4's to "develop, implement, and enforce a program to address storm water runoff from new development and redevelopment projects that disturb" at least an acre of land the MS4 "that would prevent or minimize water quality impacts." 40 C.F.R. § 122.34(b)(5)(i). More generally, they must "A) Develop and implement strategies which include a combination of structural and/or non-structural best management practices (BMPs) appropriate for [the] community; (B) Use an ordinance or other regulatory mechanism to address post-construction runoff from new development and redevelopment projects to the extent allowable under State, Tribal or local law; and (C) Ensure adequate long-term operation and maintenance of BMPs." 40 C.F.R. § 122.34(b)(5)(ii). EPA guidance urges permittees to select BMPs that "minimize water quality impacts[] and attempt to maintain pre-development runoff conditions," like GSI and the policies and ordinances required to implement it. 40 C.F.R. § 122.34(b)(5)(iii). The agency suggests that permittees ensure structural BMPs are implemented appropriately using some combination of "pre-construction review of BMP designs; inspections during construction to verify BMPs are built as designed; post-construction inspection and maintenance of BMPs; and penalty provisions for the noncompliance with design, construction or operation and maintenance." 40 C.F.R. § 122.34(b)(5)(iii). EPA emphasizes that requirements should be responsive to frequent "changes, developments or improvements in control technologies." 40 C.F.R. § 122.34(b)(5)(iii). Although EPA had been developing a national "post-construction rule" that would have included a "stormwater retention performance standard and provide[d] regulated entities with several suggested compliance options, including green infrastructure techniques, . . . [a]fter nearly four years of work," in March 2014, EPA announced it would shelve the rulemaking in favor of "incentives, technical assistance, and . . . leverage[ing] existing requirements to strengthen" MS4 permits. Copeland, *supra* note 43, at 15–16.

[186] Two such examples are the San Francisco Bay and Los Angeles municipal regional stormwater permits. The San Francisco Bay municipal regional stormwater permit requires MS4 operators to "use their planning authorities to include appropriate source control, site design, and stormwater treatment measures in new development and redevelopment projects to address both soluble and insoluble stormwater runoff pollutant discharges and prevent increases in runoff flows from new development and redevelopment projects . . . primarily through the implementation of low impact development (LID) techniques." San Francisco Bay Regional Water Quality Control Board, San Francisco Bay Region Municipal Regional Stormwater NPDES Permit, Order R2-2009-0074, at pt. C.3 (adopted Oct. 14, 2009, revised Nov. 28, 2011) [hereinafter SFB Regional Permit], *available at* http://www.swrcb.ca.gov/sanfranciscobay/board_decisions/adopted_orders/2009/R2-2009-0074.pdf; *see also id.* at pts. C.3.c, C.3.d (describing specific requirements, including LID sizing criteria). Stormwater treatment systems must be sized to accommodate a

design storm (defined either by volume or flow rate). *See id.* at pt. C.3.d.i; *see also* Compendium, *supra* note 59, at 10. Additionally, the permit requires permittees to complete "pilot green street projects that incorporate LID techniques . . . ." *See* SFB Regional Permit, *supra*, at pt. C.3.b.iii. The Los Angeles municipal regional stormwater permit requires permittees to require new development and redevelopment projects "to control pollutants, pollutant loads, and runoff volume emanating from the project site by: (1) minimizing the impervious surface area and (2) controlling runoff from impervious surfaces through infiltration, bioretention and/or rainfall harvest and use" by on-site retention of the greater of "[t]he 0.75-inch, 24-hour rain event or . . . [t]he 85th percentile, 24-hour rain event . . . ." LA Regional Permit, *supra* note 61, at pt. VI.D.7.c.i; *see also id.* at pt. VI.D.7.c.iv (requiring new development and redevelopment projects "within natural drainage systems . . . to prevent accelerated downstream erosion and to protect stream habitat . . . by maintaining the project's pre-project storm water runoff flow rates and durations"); *see also* Compendium, *supra* note 59, at 17–18. The permit prioritizes "on-site infiltration, bioretention and/or rainfall harvest and use" over "on-site biofiltration"—in other words, bioretention facilities without an underdrain are preferred to those with an underdrain. LA Regional Permit, *supra* note 61, at pt. VI.D.7.a.7. For both permits, the requirements apply to projects that exceed specific thresholds for land disturbance / size. *See* SFB Regional Permit, *supra*, at pts. C.3.b.i, ii; LA Regional Permit, *supra* note 61, at pt. VI.D.7.b. Additionally, both include alternative compliance measures (generally off-site treatment or in-lieu fees) where on-site treatment is infeasible. *See* SFB Regional Permit, *supra*, pt. C.3.e; LA Regional Permit, *supra* note 61, at pt. VI.D.7.c.ii–iii (also allowing for alternative compliance where there is "an opportunity to replenish regional ground water supplies at an offsite location").

[187] *See* 33 U.S.C. §§ 1318(a), 1342(a); 40 C.F.R. § 122.44(i); 40 C.F.R. § 122.48.

[188] 33 U.S.C. § 1342(a)(2); *see also* 40 C.F.R. § 122.44(i)(1); *Natural Res. Def. Council, Inc. v. Cnty. of L.A.*, 725 F.3d 1194, 1207 (9th Cir. 2013), *cert. denied*, (U.S., May 5, 2014, 13-901) 2014 WL 318437.

[189] 40 C.F.R. § 122.48 provides that "[a]ll permits shall specify: (a) Requirements concerning the proper use, maintenance, and installation, when appropriate, of monitoring equipment or methods (including biological monitoring methods when appropriate). (b) Required monitoring including type, intervals, and frequency sufficient to yield data which are representative of the monitored activity including, when appropriate, continuous monitoring; (c) Applicable reporting requirements based upon the impact of the regulated activity and as specified in § 122.44. . . ."

[190] *See* 40 C.F.R. §§ 122.26(d)(2)(v), 122.34(g).

[191] Alternative compliance mechanisms in the Los Angeles municipal regional stormwater permit illustrate this point. For example, the standard compliance path would require permittees to demonstrate compliance with water-quality-based effluent limitations through direct measurement of specific pollutant concentrations at MS4 outfalls. *See* LA Regional Permit, *supra* note 61, at pt. VI.E.2.d.i.1, VI.E.2.e.i.1. By contrast, a permittee who chooses to develop a Watershed Management Programs (WMP) or Enhanced Watershed Management Programs (EWMP) can demonstrate compliance with interim water-quality-based effluent limitations by fully implementing that program, including by making sure that structural BMPs are "designed and maintained to treat storm water runoff from the 85th percentile, 24-hour storm" and that up-to-date maintenance records are available for inspection. *See id.* at pt. VI.E.2.d.i.4. Permittees who develop EWMPs can demonstrate compliance with final water-quality-based effluent limitations by retaining "(i) all non-storm water and (ii) all storm water runoff up to and including the volume equivalent to the 85th percentile, 24-hour event . . . for the drainage area tributary to the applicable receiving water." *See id.* at pt. VI.E.2.e.i.4. This option requires no water-quality monitoring at all, although it would require monitoring of stormwater volume. In a 2013 factsheet, the EPA suggested that "[p]re- and post-implementation water resources monitoring and assessment," "[a]ssessment of erosion rates in receiving waters," "[a]ttainment of water quality standards for specific pollutants," [p]ercent stormwater volume capture in a combined sewer area," or "[p]ercent reduction in CSO volume as a result of [GSI]" are potential metrics for gauging GSI effectiveness. U.S. Envtl. Prot. Agency, General Accountability Considerations for Green Infrastructure 3–5 (2012) [hereinafter General Accountability Fact Sheet], *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/EPA-Green-Infrastructure-Factsheet-1-061212-PJ-2.pdf.

[192] Stoner, *supra* note 16, at 2; *see also* General Accountability Fact Sheet, *supra* note 191, at 5 ("It is important to carefully select a set of metrics and incorporate them into evaluation requirements to ensure that desired outcomes are being approached and/or achieved. . . . There should also be clear expectations for corrective action when observed values and progress do not meet established standards or thresholds. . . . In addition, for long-term compliance schedules, performance data should be fed back into an adaptive management framework so that performance can be continuously improved over time.").

[193] SFB Regional Permit, *supra* note 186, at pt. C.3.b.iii, iii.5. The permit also requires 10 pilot projects for "removal of mercury by on-site treatment systems [like detention basins, bioretention units, sand filters, infiltration basins, and treatment wetlands] via retrofit of such systems into existing storm drain systems." *Id.* at pt. C.11.e. Similarly, the permit requires 10 pilot projects (which may be the same as for mercury) for on-site retrofits to remove PCBs. *Id.* at pt. C.12.e.

[194] SFB Regional Permit, *supra* note 186, at pt. C.3.b.iii.5.

[195] *See* discussion *supra* **Part III.**

[196] *See* SFB Regional Permit, *supra* note 186, at pt. C.3.b.v.2. For the mercury and PCBs on-site removal retrofit pilot programs (mentioned in note 193, above), permittees must report "status, results, mercury[/PCBs]-removal effectiveness, and lessons learned from the ten pilot studies and their plan for implementing this type of treatment on an expanded basis throughout their jurisdictions during the next permit term." *Id.* at pts. C.11.e.iv, C.12.e.iv.

[197] SFB Regional Permit, *supra* note 186, at pt. C.8.d.ii (noting that the BMP effectiveness investigation may be done on a green streets pilot project (pt. C.3.b.iii), a mercury-removal on-site treatment retrofit pilot project (pt. C.11.e), or a PCBs-removal on-site treatment retrofit pilot project (pt. C.12.e)).

[198] SFB Regional Permit, *supra* note 186, at pt. C.8.d.ii.

[199] *See* LA Regional Permit, *supra* note 61, at pt. VI.D.7.d.iv (requiring permittees to implement electronic tracking, certification, inspection, and enforcement for GSI and related BMPs).

[200] LA Regional Permit, *supra* note 61, at pt. VI.D.7.d.iii(1). The requirements for single family residences are different, and include keeping GSI maintenance records on site. *See id.*

[201] LA Regional Permit, *supra* note 61, at pt. VI.D.7.d.iv.1.c (for those BMPs "operated by the permittee); *see also id.* at pt. VI.D.7.d.iv.1.d (requiring permittees to "require the other parties to document proper maintenance and operations" for BMPs that are "operated and maintained by parties other than the Permittee").

[202] *See* L.A. Reg'l Water Quality Control Bd., Monitoring and Reporting Program for Order R4-2012-0175, NPDES Permit No. CAS004001, Waste Discharge Requirements for Municipal Separate Storm Sewer System (MS4) Discharges Within the Coastal Watersheds of Los Angeles County, Except Those Discharges Originating from the City of Long Beach MS4, Nov. 8, 2012, at pt. X.

[203] *History*, Int'l Stormwater BMP Database, http://www.bmpdatabase.org/history.html (last visited Jan. 7, 2014).

[204] *See BMP Monitoring and Performance Evaluation Guidance*, Int'l Stormwater BMP Database, http://www.bmpdatabase.org/monitoring-guidance.html ("Since the BMP Database project's inception in 1996, a key purpose of project has been to provide better guidance on urban stormwater BMP monitoring, reporting protocols and performance analysis methods."). This includes a manual that contains "a recommended set of protocols and standards for collecting, storing, analyzing, and reporting . . . monitoring data that will lead to better understanding of the function, efficiency, and design of urban stormwater BMPs." BMP Performance Monitoring, *supra* note 151, at ES-1. The manual covers: designing a monitoring and reporting program; methods and equipment for BMP monitoring; monitoring program implementation; data management, evaluation, and reporting; BMP performance analysis; and cumulative monitoring and performance evaluation of distributed GSI.

[205] Narrative Overview, *supra* note 96, at 1, 14.

[206] *See* Narrative Overview, *supra* note 96, at 1. As of July 2012, this included at least some water quality data for 30 bioretention systems, 13 green roofs, 86 grass swales or strips, 2 infiltration basins, 37 media filters, 12 percolation trenches or wells, and 35 porous pavements. *See id.*

[207] *See Performance Summaries*, Int'l Stormwater BMP Database, http://www.bmpdatabase.org/performance-summaries.html (last visited Jan. 5, 2015) (providing links to more than 17 documents, including volume reduction analyses and summaries of performance data on nutrients, metals, bacteria, and solids).

[208] *See National Stormwater Quality Database*, Int'l Stormwater BMP Database, http://www.bmpdatabase.org/nsqd.html (last visited Jan. 7, 2015).

[209] *See id.*; *see also* Alex Maestre & Robert Pitt, The National Stormwater Quality Database, Version 1.1, at ii (2005), *available at* http://rpitt.eng.ua.edu/Publications/Stormwater%20Characteristics/NSQD%20EPA.pdf.

[210] Given the difficulties of collecting ambient environmental data on an ongoing basis, it would be wise to put this environmentally relevant data to full use. *See generally* Eric Biber, *The Problem of Environmental Monitoring*, 83 U. Colo. L. Rev. 1 (2011).

[211] Models have been developed to help predict the performance and cost of GSI and to help with watershed-wide siting decisions. *See generally* U.S. Envtl. Prot. Agency, Green Infrastructure Models and Calculators (2012), *available at* http://water.epa.gov/infrastructure/greeninfrastructure/upload/EPA-Green-Infrastructure-Supplement-3-061212-1-PJ-2.pdf; *Modeling Tools*, U.S. Envtl. Prot. Agency, http://water.epa.gov/infrastructure/greeninfrastructure/gi_modelingtools.cfm (last updated June 13, 2014). The quality and utility of model results will improve as the data that drives them improves.

[212] Influence of Design Parameters, *supra* note 93, at 1. The review focused on 6 BMP categories (bioretention systems with underdrains, detention basins, grass strips, grass swales, media filters, and retention ponds), for which there was potentially enough design data to support meaningful analysis. *See id.* at 2, 70.

[213] *See id.* at 71.

[214] *See id.* at 3–4. The pollutants were total phosphorus, dissolved phosphorus, nitrate, total suspended solids, total copper, and dissolved copper. *See id.* at 2. The design parameters were (1) the ratio of system footprint to drainage area, (2) the depth of soil media above the underdrain, and (3) whether or not the system included internal water storage below the underdrain outlet. *See id.* at 3.

[215] *Id.* at 3.

[216] *See id.* at 3–4.

[217] *See id.* at 3–4, 4 tbl.2.

[218] *See*, e.g., Eric W. Strecker et al., *Determining Urban Storm Water BMP Effectiveness*, J. Water Res. Planning & Management, May/June 2001, at 144, (describing BMP monitoring study inconsistencies and proposing protocols for future analyses). **Table 2** includes parameters deemed important to report with water quality data for different types of BMPs. *See id.* at 146.

[219] GSI "studies without well designed and implemented hydrologic and hydraulic monitoring components are of little value to the technical community." *See* BMP Performance Monitoring, *supra* note 151, at 3-1. The Urban Stormwater BMP Performance Monitoring Manual describes meteorological data collection and flow measurement methods, discusses cost considerations, and directs readers to more detailed references. *See id.* ch. 3.

[220] *See e.g.*, BMP Performance Monitoring, *supra* note 151, at 4-1 (describing how to select water quality parameters for a monitoring location); *see also* Ingvertsen et al., *supra* note 93, at 1490 fig.1 (suggesting a mimimum data set of the concentration of suspended solids less than 63 μm in size, total copper, total zinc, several PAHs, total phosphorus, and total nitrogen as well as potential additional parameters where possible

or locally important (pesticides, phenols, molybdate reactive phosphorus, chemical oxygen demand, biological oxygen demand, *E. coli*, and *Enterococci*)).

[221] *See also* Martin Jaffe et al., The Illinois Green Infrastructure Study 36, 103 (2010)*, available at* http://www.epa.state.il.us/green-infrastructure/docs/draft-final-report.pdf (recommending "implementation of a systematic monitoring and reporting program requiring submission of standardized data to the [ISBMPD] . . . in the format required by this database").

[222] *See Terms of Use and Disclaimer for the International Stormwater BMP Database*, Int'l Stormwater BMP Database, http://www.bmpdatabase.org/Docs/Terms%20Of%20Use.pdf (last updated Jun. 25, 2008) (allowing "[u]se of database structure and/or data entry spreadsheets to track performance data for regional, state, watershed or local purposes or for subsequent upload to the International Stormwater BMP Database").

[223] *See NPDES Electronic Reporting Rule*, U.S. Envtl. Prot. Agency, http://yosemite.epa.gov/opei/RuleGate.nsf/byRIN/2020-AA47 (last updated Jan. 5, 2015) (projecting adoption of the final rule in August 2015). The proposed rule requires NPDES permittees to submit permit reports and compliance monitoring information electronically instead of on paper. NPDES Electronic Reporting Rule, 78 Fed. Reg. 46,007 (proposed July 30, 2013) (to be codified at 40 C.F.R. pts. 122, 123, and 127). It would also require regulators to electronically submit "facility information from NPDES permit applications, permit information including outfalls, limits, and permit conditions, compliance determination information including that from inspections, and enforcement response information" and would make this data publically available. *Id.*

[224] According to the EPA:

> The Integrated Compliance Information System for the National Pollutant Discharge Elimination System program (ICIS-NPDES) is one of EPA's two existing NPDES national data systems, designed as an effort to modernize and eventually replace its predecessor system, the Permit Compliance System (PCS). The ICIS-NPDES system is currently operational and, as of December 2012, contains NPDES information for all 50 states, 10 EPA regions, 19 territories, and 2 tribes. All States have had their NPDES data migrated from PCS into ICIS-NPDES. EPA plans to decommission PCS by the third quarter of the federal fiscal year 2013 (April-June 2013).

NPDES Electronic Reporting Rule, 78 Fed. Reg. 46,010 (proposed July 30, 2013) (to be codified at 40 C.F.R. pts. 122, 123, and 127).