Green Stormwater Infrastructure

By

MICHAEL FITCH
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Abstract

Urban stormwater management ~~as a practice~~ faces growing challenges from urbanization and climate change and is increasingly relied ~~up~~on to mitigate risks ~~caused by~~ urban stormwater runoff. Green stormwater infrastructure (GI), including green roofs, rain gardens, and permeable pavement, is becoming more acceptable ~~worldwide~~ as a cost-effective ~~supplement~~ to conventional stormwater infrastructure. An overview of GI and selected topics in the field ~~of GI~~ are provided, including computer modeling ~~research~~ and innovative financing approaches.

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1. Introduction

Municipalities in the US and stormwater ~~management authorities~~ worldwide face increasing challenges from climate change and urbanization. More intense storms are expected to increase the risk of local flooding and combined sewer overflows (CSOs). In the US, a shift in federal regulation toward water quality concerns increased demands on stormwater utilities and stormwater infrastructure. More stringent water quality regulations are expected (Casal-Campos et al. 2018, Weiss et al. 2017).

Stormwater cannot infiltrate into concrete and other impermeable surfaces, such as rooftops, roads, and sidewalks, which are plentiful in the built environment. So runoff volumes are generally much higher in developed urban areas than under pre-development conditions, which leads to higher flood risk. Impervious surfaces also accelerate post-development runoff compared to pre-development conditions. These higher velocity flows and greater runoff volumes can increase erosion and sediment loading. Post-development runoff also differs from pre-development runoff in its constituents. Sediment from erosion, heavy metals, pathogens, and nutrients are pollutants found in urban areas and transported to surface waters, degrading water quality of aquatic ecosystems (Sharma and Malaviya 2020). Modern stormwater management attempts to mitigate these risks and harms economically.

Green infrastructure (GI) is a classification of stormwater control measures (SCMs) and design approaches that attempt to mimic natural hydrological processes. GI measures are typically small-scale source controls implemented in distributed layouts. They can provide conventional runoff management benefits, reducing ~~the~~ reliance on conventional SCMs, and provide co-benefits such as treatment and climate adaptation ~~related~~ benefits.

This paper provides an overview of stormwater management in the US and the growing role of GI as runoff management and climate adaptation infrastructure, including recent computer modeling research and examples of innovative financing instruments for GI. ~~It~~ is organized into four sections: Background, Design and Benefits of Selected GI Measures, Simulation and Optimization, and Financing Needs and Innovations.

2. Background

This section provides a brief history of federal stormwater regulation in the US, which now helps drive GI adoption, followed by an introduction to GI in three sub-sections: an overview of GI as a design philosophy and set of stormwater management tools, a summary of current implementation worldwide, and a discussion of common barriers to adoption.

2.1. Stormwater infrastructure and regulation in the United States

In US urban areas, rainwater quickly becomes runoff on impervious surfaces and, in Municipal Separate Storm Sewer Systems (MS4s), drains into dedicated stormwater collection systems. In areas with combined sewer systems (CSSs), runoff and sewer water mix and are conveyed to treatment plants. During intense storms, CSSs can become overwhelmed with voluminous runoff and overflow without treatment to local water bodies. These untreated discharge events are called CSOs and pose major risks to the environment and human health. MS4s and CSSs use catch basins, gutters, storm drains, ditches, and pipelines to collect and convey runoff. These types of control structures are the framework of a centralized approach to stormwater management and are collectively referred to as “grey infrastructure.”

Modern stormwater management authorities in the US have two primary objectives: reduce local flooding risks and reduce water quality risks from pollutant-laden runoff (Malinowski et al. 2020). These two objectives have not historically received the same degree of attention. For most of the 20th century, runoff was managed with the goal of rapid conveyance and direct discharge into downstream water bodies (Roy et al. 2008).

The Clean Water Act (CWA) of 1972 provides regulatory requirements to address water quality problems and led to decades of legislation intended to prohibit polluted discharges from point and nonpoint sources (Roy et al. 2008, Porse 2014). The CWA required the development of water quality standards to bring water bodies into compliance with their designated uses (Roy et al. 2008). Another important outcome of the CWA was the development of the National Pollution Discharge Elimination System (NPDES) program by the US Environmental Protection Agency (EPA) (Roy et al. 2008). The NPDES program was initiated in 1987, requiring large MS4s to acquire permits to legally discharge stormwater (Roy et al. 2008). In 1999, US EPA extended this requirement to smaller MS4s and also required permit-holders to implement post-construction stormwater management programs which mandate the use of stormwater control measures known as Best Management Practices (BMPs) (Roy et al. 2008). This focus on “second generation” stormwater problems during the early 1990s marks the beginning of the ongoing modernization of stormwater management (Hanak et al. 2014).

2.2. Introduction to green infrastructure and overview of benefits

The terms associated with “green infrastructure” have overlapping and sometimes identical meanings. Distinguishing between these terms is useful in placing GI in the broad context of the urban environment. A brief review of nomenclature is provided.

Low Impact Development (LID) is a popular term in the US, referring to decentralized, on-site-focused stormwater management approaches made possible with GI measures. GI is one of several terms under the umbrella of “LID.” Some types of GI are used outside of a stormwater context. For example, greenway corridors (e.g., forests and floodplains) qualify as GI because they provide ecological services, yet, strictly speaking, they are unrelated to stormwater management (EPA 2012).

Stormwater GI and LID go by other names, domestically and abroad. Australia uses the term "water-sensitive urban design" (WSUD). In Europe, "nature-based solutions" is a commonly used. Other related or synonymous terms include integrated urban water management (IUWM), sustainable drainage systems (SUDS), green-blue infrastructure (GBI), and some best management practices (BMPs) (Alves et al. 2020). For simplicity, all nuances in GI-related terminology are disregarded in the remainder of this paper.

GI is a set of SCMs and practices which attempt to mimic natural hydrological processes to minimize the hydrologic and water quality harms from urban development. GI measures are typically small, decentralized stormwater control features (EPA 2005). Whereas conventional grey infrastructure is designed to quickly convey runoff away from its impervious sources, GI measures are on-site control measures which restrict, delay, or infiltrate runoff transport (Zhang and Chui 2018). For example, roof downspouts typically discharge onto driveways and subsequently into stormwater collection systems, but rainwater can instead be channeled to infiltration areas or rain gardens, a type of GI measure constructed in lieu of a traditional grass lawn, so that runoff is managed on-site (EPA 2005). Figure 1 is a conceptual diagram of runoff behavior with and without GI.

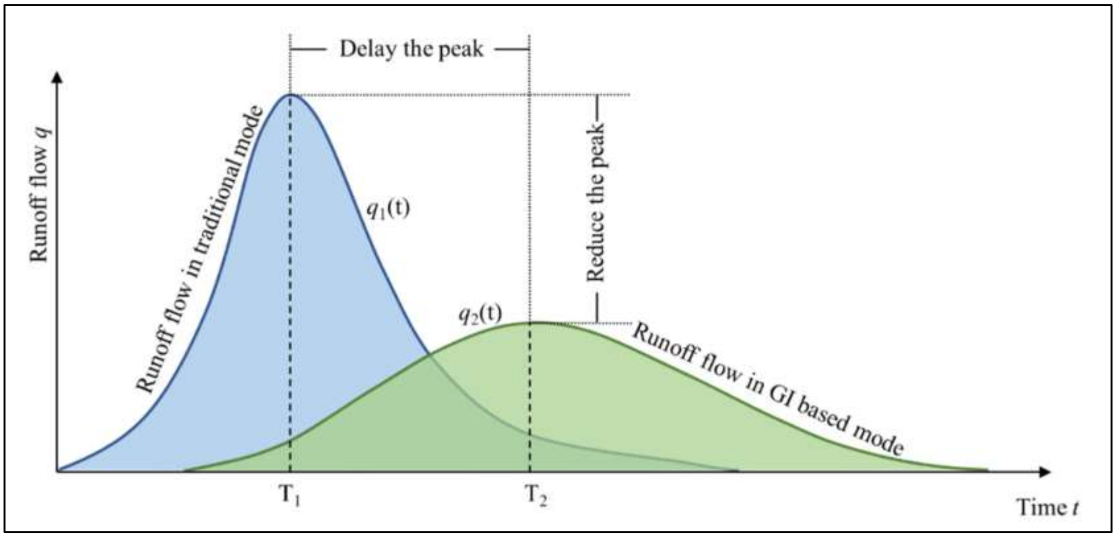


Figure 1: Runoff behavior before and after GI implementation (Source: Wang et al. 2020)

GI uses combinations of infiltration, retention, evapotranspiration, and detention (Feldman et al. 2019, Wang et al. 2020). It reduces total runoff volume, primarily by infiltration and retention, and reduces runoff peak flows, primarily using storage. GI measures typically are designed to control runoff from the first 2.54-3.81 cm of rainfall (Malinowski et al. 2020), limiting their flood risk reduction capacity of GI for large storms (Wang et al. 2020). Given the likelihood of bigger storms, GI is insufficient as a complete substitute for conventional grey infrastructure. Instead, it can supplement more traditional stormwater management, reducing the amount of runoff that enters collection systems, thereby decreasing the capacity of grey infrastructure needed (Christophers 2018).

There are many types of GI measures, including green roofs, rain gardens, permeable pavement, bioretention cells, bioretention swales, filter strips or vegetated swales, infiltration trenches, detention ponds, retention ponds, and rain barrels, and the designs of each of these measures can vary (Pour et al. 2020).

2.3. Existing green infrastructure

GI is increasingly recognized globally as effective for difficult stormwater management problems in urban areas. Many countries have adopted policies to actively promote GI implementation (Wang et al. 2020).

In China, national policy and strong organizational structure has driven GI adoption (Rodak et al. 2020). In 2005 China launched an ambitious program, the Sponge City pilot project, which involves retrofitting 30 cities with GI to meet the ambitious goal of 70% reuse of rainwater in 80% of urban areas by 2030. Sweden's GI initiatives have been driven by local priorities, public awareness, and trust in GI performance (Rodak et al. 2020). In Copenhagen, green roofs have been mandatory for most large buildings since 2010. Toronto, Canada has a mandatory downspout disconnection policy and a by-law on mandatory implementation of green roofs (Eckart et al. 2017).

GI adoption is primarily driven by regulation in the US. Many US cities, especially older cities with CSSs, are incorporating GI into their existing urban drainage systems. Such cities include Portland, OR, Seattle, WA, Philadelphia, PA, Kansas City, KS, New York, NY, Washington D.C., and Louisville, KY (Feldman et al. 2019). For example, Portland, OR requires all new City-owned buildings to be built with a green roof covering at least 70% of the roof (Vijayaraghavan et al. 2016). Portland, OR and Seattle, WA are leaders in GI adoption, in part because GI measures are better suited for the frequent, relatively low intensity rainfall profiles of these cities (Gallo et al. 2012). GI adoption in other areas with CSSs is driven in part by Long Term Control Plans (LTCPs) mandated by EPA regulation (Wise et al. 2010/Eckart et al. 2017).

2.4. Suitability and barriers to adoption

It is generally easier and less expensive to implement GI projects on new construction than by retrofitting existing buildings. This cost difference is reflected in existing regulations. However, stormwater utilities face legal limitations with regards to private property.

GI performance is more difficult to generalize and predict than for traditional grey infrastructure. GI takes advantage of processes that occur naturally, but the natural environment (soil, precipitation patterns, groundwater characteristics, native vegetation) is more variable and less easily controlled than traditional infrastructure. As such, the performance of GI projects is often uncertain, and risk-averse decision makers are likely to disfavor them.

Another related barrier to adoption is lack of expertise or design standards (Roy et al. 2008).

Financing GI projects is a significant barrier for stormwater municipalities. Innovative funding methods are discussed in further detail in a later section of this paper.

3. Design and Benefits of Selected GI Measures

Unlike conventional grey infrastructure, GI offers environmental and socioeconomic benefits not directly related to runoff volume reduction or peak flow attenuation. These diverse “co-benefits” include improved aesthetics, provision of green space and wildlife habitat, reduction in heat island effect, energy savings, air quality improvements, carbon sequestration, increased property values, reduction in potable water demand, and groundwater recharge (Alves et al. 2020, Malinowski et al. 2020, Wang et al. 2020).

Runoff volume management and most co-benefits are boons to climate adaptation, which is a growing goal of GI implementation (Cousins and Hill 2021). GI is becoming more popular worldwide, likely from clearer understanding of increasing climate change-induced risks. Increased urbanization, with its increased concentration of impervious surfaces and pollutant-rich conditions, is also a strong driver of GI adoption.

The following sub-sections describe the design and benefits of three popular GI measures: green roofs, raingardens, and permeable pavements. These particular measures are more commonly-used and collectively involve all natural processes involved in GI measures: infiltration, storage, evaporation, and transpiration. In addition, these three GI are well-represented in the literature. Figure 2 shows the number of studies done on various GI types worldwide between 2008 and 2017, most of which are related to green roofs, raingardens, and permeable pavements.

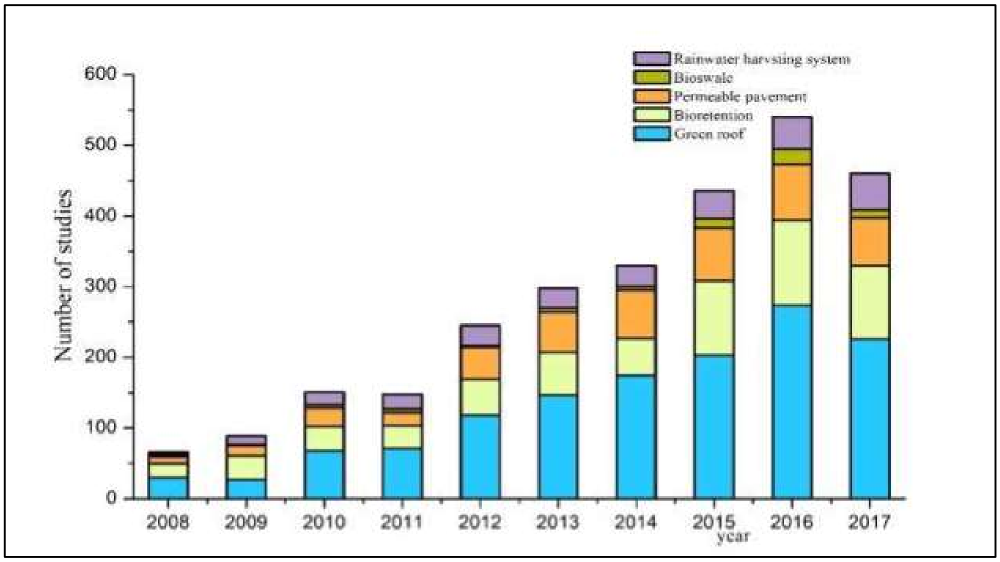


Figure 2: Number of studies on various GI measures in recent years (Source: Li et al. 2019)

3.1 *Green roofs*

Green roofs, also known as vegetative roofs, eco roofs, or living roofs, are designed to function as roofs for buildings while supporting living vegetation. They typically have a series of layers: a vegetation layer, a lightweight growing medium layer, and a storage or drainage layer placed on top of a waterproof membrane (Li et al. 2019). The design of green roofs may require and include other features, such as an irrigation system (Rodak et al. 2020). Figure 3 is a schematic of green roof components.

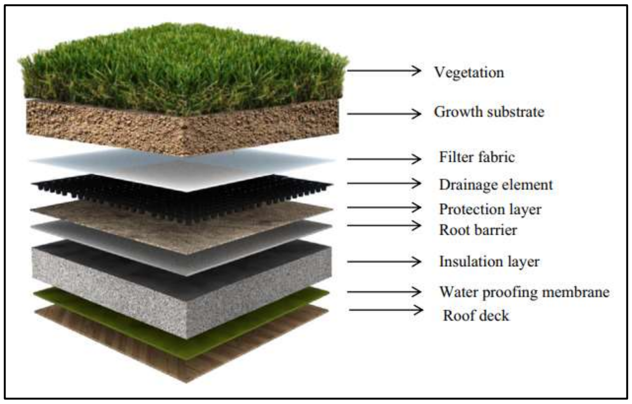


Figure 3: Green roof schematic (Source: Vijayaraghavan et al. 2016)

Green roofs are storage-based GI measures. They store and retain rainwater, with co-benefits such as urban heat island mitigation and, potentially, runoff treatment.

There are two categories of green roofs: extensive and intensive. The two types are distinguished by the thickness of growing layer. Extensive green roofs typically have growing layers of 15 cm thickness or less, and intensive green roofs typically have growing layers more than 15 cm deep (Li et al. 2019).

Substrate depth, roof slope, vegetation type, type of drainage element and its storage capacity, volume of rain event and time of previous dry period, and slope are factors that influence the performance of green roofs, and recent research finds that substrate material is the most influential factor in retention performance (Rodak et al. 2020, Vijayaraghavan et al. 2016). A higher water holding capacity of the substrate increases runoff retention (Graceson et al. 2013). The choice of plants and their corresponding root system and water use also influence retention (Rodak et al. 2020).

The conventional stormwater management benefit of green roofs is rainwater retention in the growing substrate and its voids; this retention also detains peak flows and reduces the risk of local flooding (Vijayaraghavan et al. 2016). Captured stormwater transpires through the vegetation, reducing the total volume of runoff by the amount retained. Liu and Chui (2019) measured average runoff reduction from green roofs in Hong Kong, China, Maryland, US, and New York, US, and found that green roofs could reduce runoff for smaller storms in the range of 5-10 year return periods, with performance plateauing at longer return periods (Rodak et al. 2020). An intensive green roof provided an average runoff retention of 65.7% compared to 33.6% on an adjacent paved roof (Vijayaraghavan 2016).

A prominent co-benefit of green roofs is mitigation of the urban heat island effect. The urban heat island effect is the phenomenon by which urban areas experience higher temperatures because of the high surface area of low-albedo asphalt and other temperature-raising characteristics of cityscapes. Green roofs help to mitigate the urban heat island effect by replacing surfaces that would otherwise absorb high amounts of thermal energy with their vegetation-rich surfaces.

As stormwater passes through the growing layer and other potential layers, it receives some treatment. However, it is uncertain if green roofs have a net positive or net negative effect on water quality. They may be a source or a sink of various water quality pollutants (Rodak et al. 2020) so further research is needed on this concern.

Green roofs can reduce the energy costs of buildings by providing insulation. Green roofs can provide aesthetic recreational locations for humans and wildlife. They also offer carbon sequestration via the vegetation.

Because of climate variability, the most effective design for a green roof depends on location. The optimal design in a tropical, humid environment might not be suitable in an arid part of the world, and this spatial dependency is a driving force behind numerous studies worldwide (Vijayaraghavan et al. 2016). Because they use existing rooftop space, green roofs are primarily used in highly developed urbanized areas where space is extremely limited (Rodak et al. 2020). Commercial properties, with their big buildings, make better sites for green roofs than residential homes.

3.2 Rain gardens

Rain gardens are shallow, ditch-like areas made of soil, vegetation, and mulch. Bioretention cells are similar to rain gardens but are typically larger and engineered, whereas rain gardens are smaller and require little or no engineering. Figure 4 is a diagram of a rain garden installed in a sidewalk.

Figure 4: Diagram of a curbside rain garden (Source: Partenio 2020)

Rain gardens are infiltration-based GI measures. They provide treatment by removing pathogens, nutrients, metals, and other organic substances from collected water (Sharma and Malaviya 2020).

Rain gardens are a comparatively economical solution to decrease runoff, with the advantages of low construction area, low maintenance requirements, and high standard of efficiency (Sharma and Malaviya 2020). Theoretically they can be built on any unpaved surface (Sharma and Malaviya 2020), including front yards, backyards, and commercial areas. They also can be constructed within a roadway or existing median, adjacent to those high runoff-producing areas (Partenio 2020).

3.3 Permeable pavements

Permeable pavement is distinguished from conventional pavement by its porous surface and its subsurface layers which provide runoff storage and facilitate infiltration. The design of a permeable pavement system essentially requires two designs: one for the water storage component of the system, and another to ensure its structural integrity (Weiss et al. 2017). The three common varieties of permeable pavement are asphalt, concrete, and interlocking pavers; Figure 5 is a conceptual diagram of these permeable pavement types (USGS 2018).

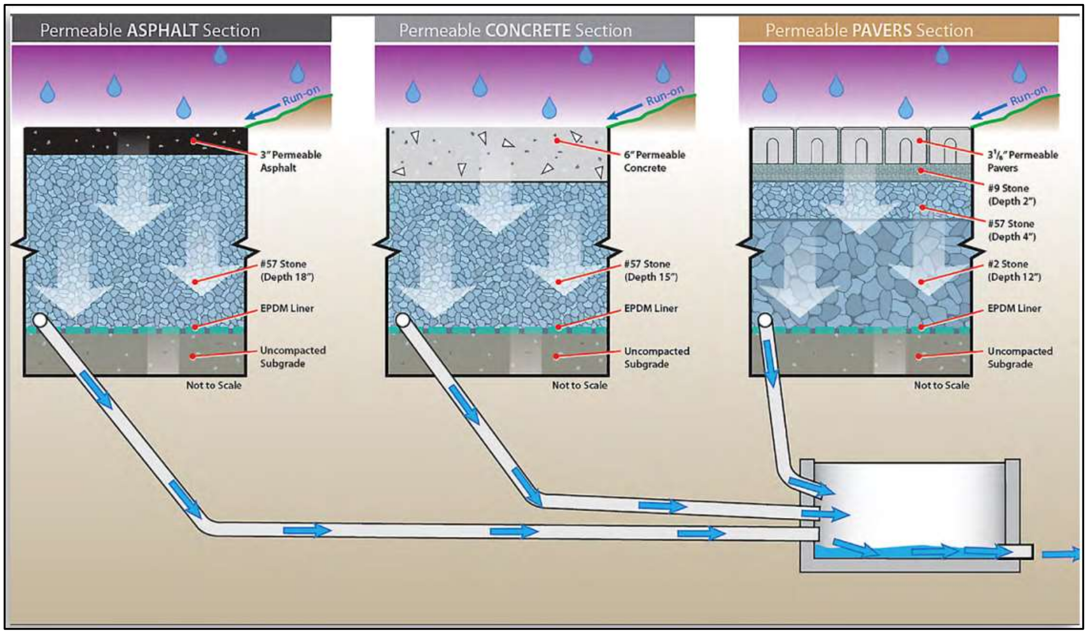


Figure 5: Diagram of three types of permeable pavement (Source: USGS 2018)

Co-benefits of permeable pavement systems include groundwater recharge, urban heat island mitigation, skid resistance, and noise reduction (Rodak et al. 2020).

4. Simulation and Optimization

Computer modeling is common~~ly used~~ in engineering practice to simulate the effect of one or more projects on a system, to estimate the project’s performance prior to construction. This helps engineers and planners design cost-effective infrastructure. Given an accurate simulation, optimization techniques can further assist in design by identifying the better of many possible alternatives. The literature of computer modeling for GI includes many attempts to overcome GI-specific challenges. This section begins with an introduction to these notable challenges, followed by an overview of three experimental solutions from the recent literature.

4.1. Introduction

The performance of GI measures is “notoriously variable” (William et al. 2018). Uncertainty in GI performance is a fundamental barrier to adoption (Roy et al. 2008). Developing accurate measurement methods and predictive simulations is key to promoting the adoption of effective GI actions. However, it is generally much more difficult to estimate the stormwater management performance for GI than the more certain performance calculations used for grey infrastructure (The Resilience Shift 2020). Field studies, SWMM, and the rational method can estimate performance (Wang et al. 2020), but site-specific conditions, which are spatially and temporally variable, strongly affect GI performance.

It is impossible to generalize the runoff reduction performance of GI measures to the same extent as with grey infrastructure. Performance, especially that of infiltration-based GI measures, depends on the unique characteristics of each project site, such as soil type, slope, depth to groundwater, and depth to bedrock (Malinowski et al. 2020).

It is important to optimize placement of GI measures to maximize their effectiveness and take full advantage of available capital. Examples of location dependences include upstream versus downstream, at-source versus end-of-pipe, and proximity to receiving waters (Zhang and Chui 2018).

In the case of new development, ideal locations for GI can be identified in the planning stage and potentially be granted a high priority (Zhang and Chui 2018). However, in already-developed areas, specifically urban areas, scarcity of available land means that surface area required for GI is expensive. Additionally, existing infrastructure in urban areas, such as underground cables and pipelines, physically limits potential GI locations or adds to its expense (Zhang and Chui 2018). Space limitation is normally the major problem in implementing GI in dense urban areas (Pour et al. 2020). Therefore, optimal selection of GI measures is key to ensuring cost-effectiveness and maximum runoff reduction.

The remainder of this section reviews three studies which develop new modeling techniques to address uncertainties in performance and provide optimization for GI implementation.

4.2. Cumulative, ex-post performance – Li et al. (2019)

GI has greater cumulative benefits than in isolation (Pour et al. 2020). However, estimating the cumulative effects of a set of GI measures is difficult. The primary metrics for evaluating GI include runoff volume, peak flow, runoff load reductions, and/or economic costs (Rodak et al. 2020). Theoretically, volume reduction and peak flow attenuation can be measured by determining a relationship between rainfall quantity and basin outflow. If rainfall events were similar to one another (and if hydrologic processes such as subsurface flow were easy to model), then this relationship could simply be measured. GI performance could be evaluated by determining the difference in pre- and post-construction hydraulic performance. However, rainfall events are unique; they occur at different times and over different areas, and vary in terms of depth, intensity, and duration (Li et al. 2019). Furthermore, the hydraulic modelling required to evaluate GI performance typically requires information such as pipe location, material, diameter, and elevations, which is not always available or easy to obtain.

In Li et al. (2020), the authors develop a method to estimate GI performance using an artificial neural network (ANN) to estimate a relationship between rainfall events and resulting flow volumes and peak flow rates. The researchers used their models to estimate GI performance. The authors modelled a 111-ha campus in Louisville, KY, which, due to frequent flash flooding, had installed a combination of infiltration basins, rain gardens, green roofs, and bio-swales within nine separate projects (Li et al. 2019). The ANNs used for the models were "trained" using pre-construction data until they accurately predicted pre-development flow volumes and peak flow rates, given historic, observed flow volume data. The researchers then ran the model (with no GI features included in the model), using post-GI construction flow volume data as inputs, and compared the predicted peak flow rates with the observed peak flow rates for the same time period. The model's peak flow rate results were expected to be higher than the observed results because the model was not accounting for the newly constructed GI projects. The model outputs matched that general expectation. Figure 6 is a plot of the Pre-Development Observed (white), Post-Development Predicted (red), and Post-Development Observed (green) peak flow rates, with the difference between the red bars and the green bars representing the estimated improvements in peak flow rates due to the GI projects on the study site.

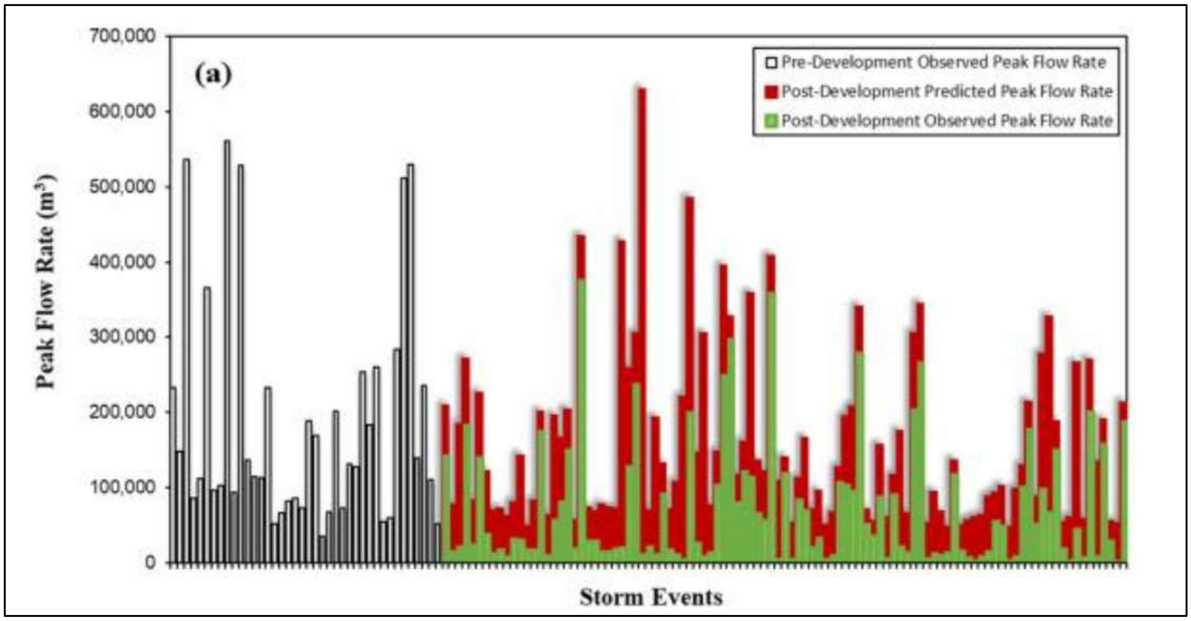


Figure 6: Peak flow rates observed (with and without GI) and predicted (without GI) (Source: Li et al. 2020)

The authors estimated the cumulative hydraulic effects of nine GI projects on a particular watershed. Because conditions vary greatly from watershed to watershed, these results have limited applicability to other watersheds. However, field-scale studies like this contribute to a larger body of knowledge about GI projects in general and guides future research. Others have identified other limitations on existing hydraulic-focused models, such as their inability to simulate infiltration under the unsaturated soil condition (Baek et al. 2019). Advances in hydrologic modelling, including groundwater modelling, will likely have cross-benefits for GI modelling efforts.

Many planners and engineers are skeptical of performance data from other regions, despite similarities in climate and soil conditions (Roy et al. 2008). Local, field-scale data may be necessary to address skepticism, but in lieu of that, performance uncertainty can be managed with probabilistic design.

4.3. Individual, ex-ante performance – Hung and Hobbs (2019)

Many stochastic optimization problems include multiple opportunities to make decisions, made in series, which affect available choices and expected outcomes during subsequent decision opportunities, i.e., they have multiple stages. Stochastic programming has been used to support decision-making under uncertainty in power systems, finance, and many engineering applications (Barah et al. 2021).

Adaptive management is a management approach that recognizes risks and opportunities to learn (Hung and Hobbs 2019). GI has promising environmental, economic, and social benefits which are uncertain, and implementation, field studies, and the resulting accumulation of experience are likely to reduce performance uncertainty. However, budgets are a major limit in stormwater management projects, which makes optimizing the selection and placement of GI measures important (Eckart et al. 2017).

In “How can learning-by-doing improve decisions in stormwater management? A Bayesian-based optimization model for planning urban green infrastructure investments” (Hung and Hobbs 2019), the authors develop a mixed integer, two-stage stochastic programming (TSP) model from an adaptive management perspective to probabilistically account for learning about GI performance. Their approach assumes a fixed budget, which can be used during two stages, to invest in individual GI measures. Figure 7 is a schematic decision tree of the two-stage decision-making process. Their approach also recognizes risk aversion to poor outcomes and uses a quantitative measure of risk aversion to simulate decision-maker preferences and examine optimization results obtained under increasing degrees of risk aversion.

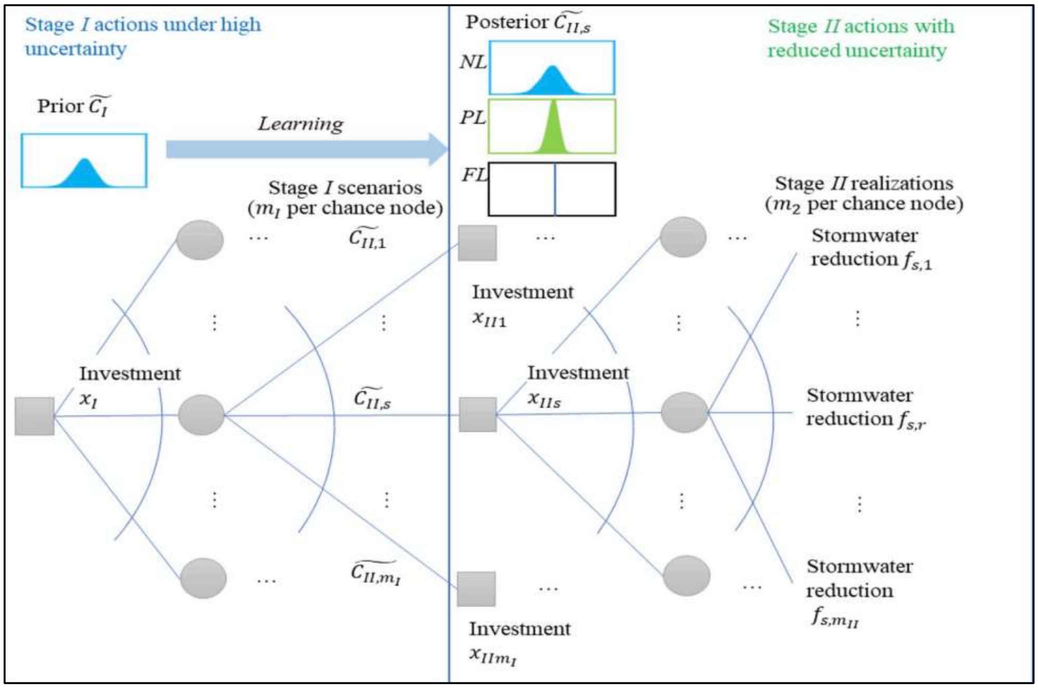


Figure 7: Schematic decision tree of two-stage decision-making (Source: Hung and Hobbs 2019)

The performance measure to be maximized is total runoff reduction. Investments made in the earlier stage earn greater expected reductions over the entire planning horizon, due to longer GI activity, and greater certainty in performance via "learning," which allows for more confident investments in the later investment stage. Their framework assumes that performance of the system is solely based on individual GI performance and does not attempt to account for cumulative effects.

An assumption in the models presented in the paper is that investment in GI measures results in learning about their performance over time. In other words, it is assumed that part of the return on investment in GI is less uncertainty in GI performance. Learning is represented in the model by changes in performance probability distributions between stages: "full learning" narrows the probability distributions, whereas "partial learning" or "no learning" mildly narrows the probability distributions or offers no change at all, respectively. Bayesian Inference is used in either model to update the probability distributions. Learning is represented by increased or decreased mean values and decreased variance values.

4.4. Optimization of selection and placement – Zeng et al. (2020)

Improving urban stormwater management is a multi-objective problem (Zhang and Chui 2018). We want to attenuate peak flows to avoid floods, manage nonpoint source pollution, and maintain ecosystems, all while minimizing costs to society. The distributed nature of GI means thousands of alternatives may be possible for a site/watershed. It would be cost prohibitive to evaluate many design alternatives using non-automated approaches. Modeling makes it possible to quickly evaluate many design alternatives.

Unlike the centralized nature of conventional grey infrastructure, GI implementation tends to be within distributed networks of components. Distributed schemes have many possible design alternatives involving many combinations of location, type, sizing, and number of GI measures. With many such decision variables, and possibly given multiple objectives, identifying optimal design alternatives is difficult. Multi-objective evolutionary algorithms (MOEAs) can help with this task.

Models can be used to identify optimal designs that maximize benefits given a fixed budget and constrained design locations. Figure 8 is an example of possible locations for GI measures in a study by Zeng et al. (2020). The recent literature on GI optimization includes many uses of multi-objective evolutionary algorithms (MOEAs). These algorithms are used to identify Pareto-optimal solutions to design problems with multiple objectives. They generally rely on SWMM models to simulate GI performance in the given watershed.

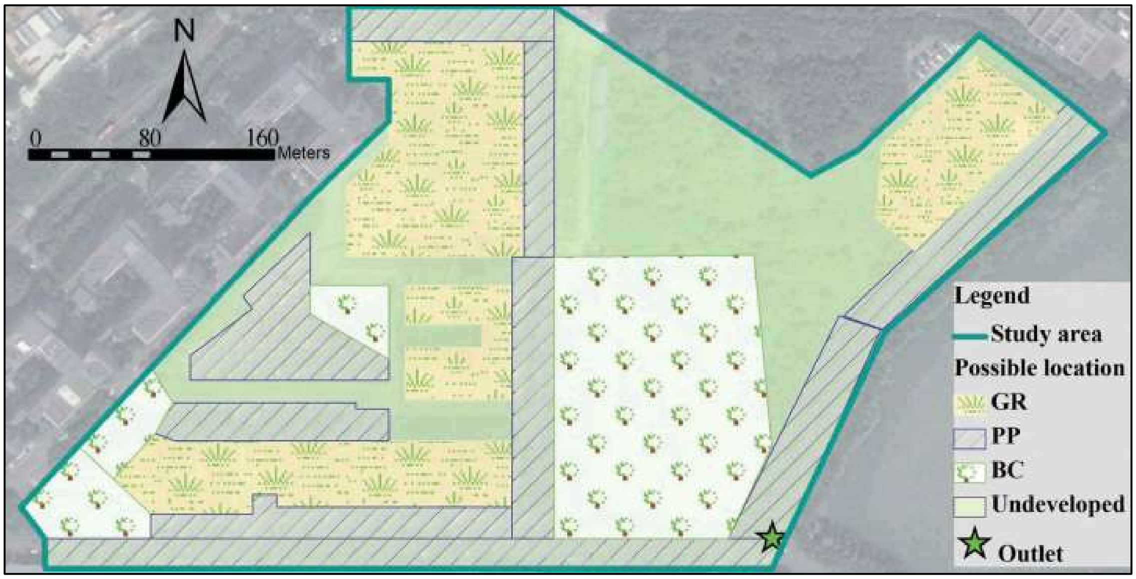


Figure 8: Example of possible locations in a study area (Source: Zeng et al. 2020)

In “Optimizing the Cost Effectiveness of Low Impact Development LID Practices Using an Analytical Probabilistic Approach” (Zeng et al. 2020), the authors used an MOEA, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Deb et al. 2002) to evaluate the performance of green roofs, bioretention cells, and permeable pavement with and without storage layers.

An important step in Zeng et al. (2020) is the development of analytical functions for the expected inflows into, and outflows from, the LID measures considered. SWMM’s LID module can be used to model such hydrologic behavior, but doing so requires data, time, and expertise that may not be available to decision makers (Zeng et al. 2020). The authors instead developed expected value functions to model inflow and outflow probabilistically. They assume storms can be adequately characterized for LID performance modeling based on three synthetic variables: rainfall event volume, rainfall duration, and interevent time (Zeng et al. 2020). This approach has been implemented in other work (Zhang and Guo 2012, 2013, 2014) and reduces the number of parameters considered at the cost of greater uncertainty in results. However, the discrepancies between using continuous simulation (SWMM) and the probabilistic method (analytical equations) are expected to be small (Zeng et al. 2020), and the primary goal in this work appears to be the formulation of an optimization framework that is practical to use for planners, especially those in China’s Sponge Cities.

Figure 9 is the expected value function for inflows into a LID measure, a function of r, the ratio between the adjacent impervious area and the LID area, ζ, a distribution parameter for rainfall event volume, and v, inflow volume. Figure 10 is the expected value function for outflow from a LID measure, a function of v_o, outflow volume, and $f(v_o)$, a probability density function (PDF) of outflow volume. The parameters and the PDF in these functions result from statistical analysis of three rainfall characteristics: rainfall volume, rainfall duration, and interevent time.

$$\boxed{E(v_i) = \int_0^\infty (r+1) v \zeta e^{-\zeta v} dv = \frac{1+r}{\zeta}}$$

Figure 9: Expected value function for inflow into a LID measure (Source: Zeng et al. 2020)

$$\boxed{E(v_o) = \int_0^\infty v_o f(v_o) dv_o}$$

Figure 10: Expected value function for outflow from a LID measure (Source: Zeng et al. 2020)

Another function, $E(v_r)$, describes the expected value of the runoff reduction of any one LID measure; it is simply the difference between $E(v_i)$ and $E(v_o)$. This function was used as the first objective function (maximize) in NSGA-II. It effectively replaces the LID module in SWMM. The authors used SWMM as a fitness function for NSGA-II, but the hydrologic behavior of the LID measures was modelled by the analytic probabilistic functions instead of by the SWMM LID module.

The second objective function is for life cycle cost (LCC) (minimize). It considers initial construction costs, annual operational and maintenance costs, and the salvage value of LID measures.

Figure 11 is a plot that compares the cost-effective curves of LID measures with and without storage (Zeng et al. 2020). This plot highlights the tradeoffs between total runoff reduction and total costs using LID measures with and without storage layers. Cases #1-3 in Figure 10 highlight specific combinations of LID measures whose details are provided in a table (not seen).

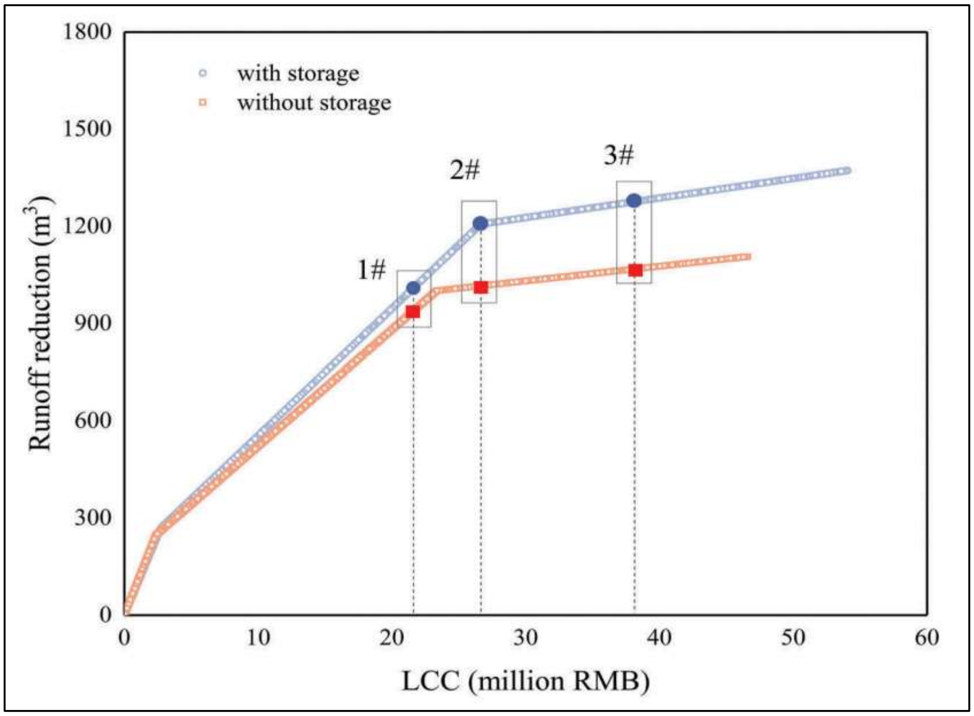


Figure 11: Pareto optimal combinations of LID measures, with and without storage layers (Source: Zeng et al. 2020)

It is generally prohibitively expensive to use these types of simulation and optimization methods to design and evaluate the performance of GI projects. Therefore, it is important to develop tools and methods which are easy to use. As Zerbe et al. (2011) note, all financial analyses involve a tradeoff between the cost of conducting the analysis and the value of the information gained from it. Therefore, there is not only a need for decision-support tools and methods which are powerful and accurate, but those which are also inexpensive and can be used easily, i.e., which do not require advanced expertise. Further research is needed to develop cost-effective methods to evaluate expected GI project benefits, both to drive regulation and to build trust in the projects.

5. Financing Needs and Innovations

GI is a cost-effective supplement to grey infrastructure, offering flexible stormwater control measures of various sizes for new development and retrofit projects. Demand for green infrastructure in the US is primarily driven by federal and state regulations.

Constitutional property rights limit the authority ~~that~~ municipalities ~~have~~ to enforce stormwater runoff quantity and quality standards from existing developed property, ~~and~~ they instead implement GI projects predominantly on public and institutional land (Fu et al. 2019, Malinowski et al. 2020). However, there are ways ~~of~~ support~~ing~~ GI adoption on private land. For example, incentive programs subsidize retrofits directly or indirectly through fee reductions. For new development and redevelopment, municipalities can implement land development policies and building codes that set GI requirements.

The costs of GI implementation, as with grey infrastructure, include design, construction, and maintenance. Much of the cost occurs early in implementation, whereas the full environmental benefits of a GI project may take years to realize (Eckart et al. 2017). Opportunity costs, i.e., the portion of property used for GI and therefore unavailable for alternative use, are an additional cost of GI (Roy et al. 2008). These can be especially high in denser and already-developed areas. GI measures also require regular maintenance. Bioretention cells, for example, suffer reduced performance without regular maintenance due to clogging. The high costs of GI implementation, especially for retrofits, demand financial innovations to generate capital within legal constraints (Cousins and Hill 2021).

This section is structured as follows. An overview of the conventional command-and-control approach to stormwater management is provided. Following that are descriptions of three innovative financing methods for GI projects being explored by researchers and stormwater municipalities in the US: user fees and credit trading programs, incentive programs, and bonds, specifically Environmental Impact Bonds (EIBs). The final section provides details about Washington, D.C.'s Clean Rivers Project, which involves each of these market-based instruments.

5.1. Command-and-control approach

The command-and-control approach to stormwater management establishes and enforces performance and technology standards to meet runoff reduction and water quality targets. This approach is possible only when a regulatory entity has authority to apply sufficient pressure to municipalities. The term “command” refers to the standards established by the authority, and “control” refers to negative sanctions from lack of compliance (Pappalardo and Rosa 2020).

The performance and technology standards set by policies in a command-and-control approach are traditionally uniform for all sources (Parikh et al. 2005). Performance standards set a target, such as a maximum runoff volume for a particular storm frequency, and such types of standards allow for flexibility in the infrastructure required to meet the target (Parikh et al. 2005). Other types of performance measurements for GI measures include peak rates, groundwater recharge, water quality, pollution loading, and erosion (Pappalardo and Rosa 2020). Technology standards specify how individuals must comply with regulations (Parikh et al. 2005). For example, a technology standard may require property owners to use rainwater harvesting facility and install green roofs (IISD 2017). Expectations for technology standards can be expressed based on a system of “green points,” which quantify the value of individual GI measures from a compliance perspective. For example, developers may be required to employ a minimum number of GI measures, selected from a menu of options that provides design details, while also meeting a minimum number of points (Pappalardo and Rosa 2020).

In the US, the CWA is the primary regulatory driver for improving stormwater management. The CWA grants the EPA authority to regulate stormwater dischargers. The EPA's NPDES program is a national program requiring stormwater dischargers to acquire and renew NPDES permits to legally discharge stormwater. Parallel to upholding standards set by NPDES permits, the EPA's CSO policy requires permit holders in CSS areas to develop Long Term CSO Control Plans (LTCPs) to address CSO problems. Consent decrees involving the municipality, the EPA, and the Department of Justice put additional pressure on municipalities to follow through with this requirement. Some examples of cities in which this is happening are Philadelphia, Pittsburgh, Washington D.C., Chicago, Los Angeles, and Boston.

The CWA requires cities to meet water quality standards per their NPDES permits but does not provide any budget allocation to do so (Tasca et al. 2017). Cities and stormwater municipalities, therefore, are responsible for financing infrastructure projects. Command-and-control approaches are feasible for new development and redevelopment, where municipalities have greater authority (Malinowski et al. 2020). However, constitutional property rights prevent municipalities from enforcing new standards on existing developments. Market-based approaches use financial instruments, specifically incentive-based programs, to promote desired activity on private property. These are likely to succeed in promoting GI on private property where command-and-control approaches cannot.

5.2. Market-based approaches

Market-based approaches to infrastructure financing seek to directly finance or encourage private investment. They rely on legal agreements and policies, distinguished from the command-and-control approach in being based on economic principles. Market-based instruments, or financial instruments, are used to raise capital for projects on publicly-owned land or incentivize desired behavior on private property. For urban stormwater management, financial instruments can be legal alternatives to raise capital for and incentivize GI projects.

In microeconomic terms, minimizing the aggregate cost to society to meet a target (e.g., runoff reduction in a watershed) is desirable for maximizing social economic surplus. However, minimizing the aggregate cost to society also imposes runoff reduction costs differently across individuals. In other words, the marginal costs of reduction are different among individuals.

Figure 12, adapted from Parikh et al. (2005), demonstrates how a runoff Abatement target of 14 units can be achieved given a uniform performance standard (dashed red line), a Pigouvian tax (solid green line), and given a quantity-based allowance market (dashed blue line, superimposed on the solid green line). In this example, two individuals, Mr. A and Ms. B, have different marginal cost (MC) curves for runoff abatement. Ms. B's property might be more developed than Mr. A's, increasing opportunity costs of installing SCMs which provide abatement. Therefore, it costs Ms. B more to provide seven units of abatement than it costs Mr. A to provide the same abatement. I have created the marginal abatement costs for demonstration.

Given the command-and-control approach represented by the uniform performance standard, marginal costs are not equalized, and so the lowest aggregate cost to society is not obtained. An aggregate cost of $875 is incurred. The uniform standards set by the command-and-control approach fail to provide economically efficient outcomes.

Figure 12 shows how a market-based instruments can shift a larger portion of runoff reduction burden onto individuals with ~~relatively~~ lower reduction costs, reducing the overall cost to society (Parikh et al. 2005).

Consider a Pigouvian tax against individuals on a per unit basis. Mr. A is encouraged to supply abatement on his property until he has provided nine units, at which point providing additional abatement would cost him more than the per unit tax (T), which he would therefore rather pay. Similarly, Ms. B will provide only five units of abatement on her property since the punitive tax is less than the cost of providing additional abatement after five units. In this scenario, marginal costs are equalized and the total abatement target of 14 units is obtained at the lowest aggregate cost of $770.

Consider a quantity-based allowance market. Under these conditions, Mr. A and Ms. B are each granted an allowance of abatement credits which they can buy and sell to one another in a private market. In this scenario, marginal costs are equalized (neglecting any transaction costs of negotiation and agreement) and the total abatement target of 14 unit is obtained at the lowest aggregate cost.

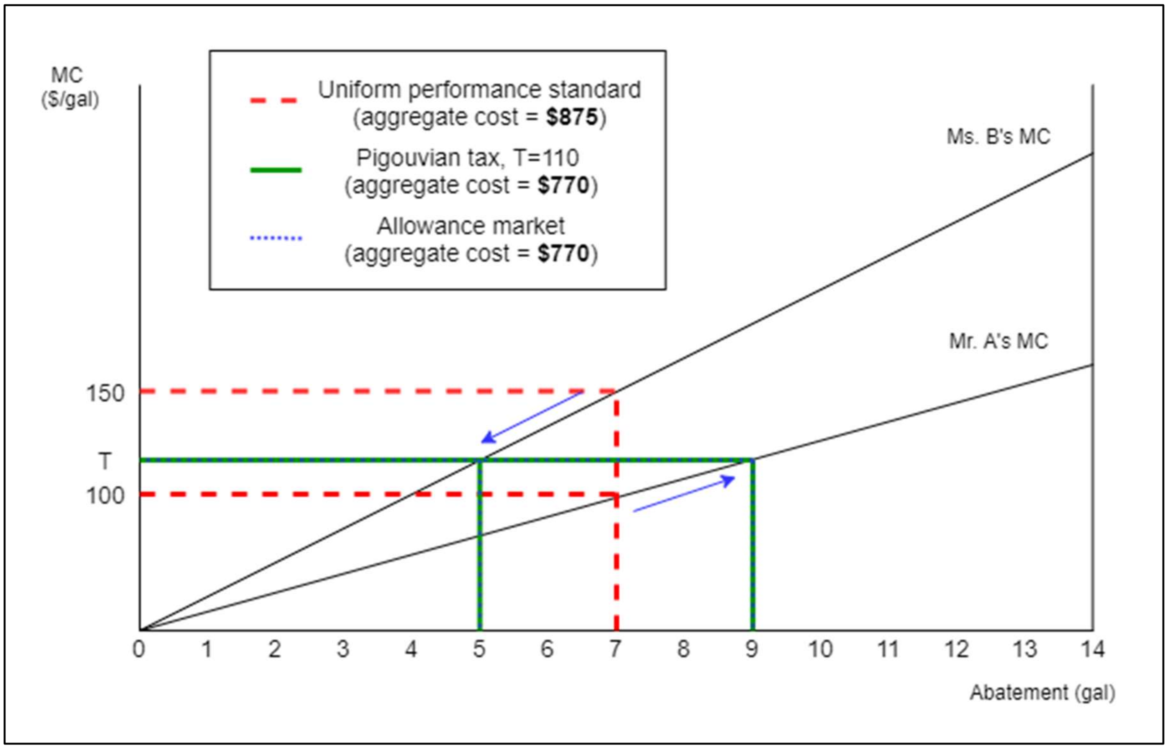


Figure 12: Cost allocations given uniform performance standards (dashed red), Pigouvian tax (solid green), and allowance market (dashed blue) (Adapted from Parikh et al. 2005)

No agreed-upon market mechanism is perfect for stormwater control. The effective use of financial instruments depends on specific hydrologic, economic, and legal needs and constraints which vary by region. It is a significant challenge to identify and implement legally sound mechanisms that successfully reduce the aggregate cost of reaching reduction targets (Parikh et al. 2005).

5.3. User fees and credit trading programs

Stormwater user fees are charged to owners of parcels with impervious surface to fund the conveyance and treatment infrastructure needed to properly manage runoff generated by the impervious area. Fee amounts for a given parcel, therefore, typically depend on the estimated quantity of runoff produced by the parcel, as well as the type of property (commercial or residential) (Malinowski et al. 2020). Fees are classified as a price-based instrument by economists, and they are the most common way stormwater municipalities finance their projects; at least 1,600 stormwater municipalities and local governments in the US rely on fees (Cousins and Hill 2021). Several methods exist for determining the size of fees, but the most popular system, used by more than 80 percent of US stormwater utilities (EPA 2009), relies on the Equivalent Residential Unit (ERU). An ERU is the impervious area on a typical single-family residential home.

The primary benefit of a stormwater fee/credit system is that it is legally acceptable in most jurisdictions (Parikh et al. 2005). Fees can be easier to establish than a local tax because municipalities have authority to charge fees for services they provide, whereas they may not have the authority to levy a local tax. Also, stormwater fees do not need public approval, although they do need political support (EPA 2010). However, generally it is not easy to justify increases in stormwater utility fees, and Malinowski et al. (2020) argue that MS4 municipalities will not need or be able to justify fee increases unless stricter requirements are put on them (Malinowski et al. 2020). Additional changes in regulation are likely required to drive fees closer to economically efficient amounts. A prominent example of legislation which inhibits fee increases is California's Proposition 218, which requires a two-thirds majority from property owners to increase fees (Cousins and Hill 2021, Hanak et al. 2014).

A stormwater user fee structure may include a credit or fee reduction system in which individuals are incentivized to reduce runoff from their parcels using GI measures (Parikh et al. 2005). Credit trading programs create a private market for stormwater "credits," which property owners can purchase in lieu of implementing GI measures sufficient to reach runoff reduction targets (Pappalardo and Rosa 2020). Trading can equalize marginal costs among individuals. It can also result in more effective GI projects by shifting their location to more optimal locations.

Although many municipalities in the US already offer fee credits, user rates are as low as 1%, primarily because of the low prices of fees (Malinowski et al. 2020). Property owners tend to simply pay the fees, not only because of low prices but also because of additional barriers, such as high transaction costs, long-term maintenance contracts, permanent easement requirements, risks related to duration and credit renewal policies, and lack of knowledge of credit programs (Malinowski et al. 2020).

5.4. Incentive programs

Also known as voluntary offset programs, incentive programs offer financial incentives to private landowners to adopt GI measures on their property to reduce runoff quantities (Parikh et al. 2005). In microeconomic terms, these programs supply a Pigouvian subsidy to mitigate negative externalities caused by runoff. Even though the private landowner may have the legal right to release stormwater, i.e., generate runoff, an incentive in the form of a fee discount or subsidy incentivizes the generation of less than legally-acceptable runoff amounts.

This approach is particularly attractive for areas with CSSs, and less so for MS4s which have less stringent regulatory obligations (Parikh et al. 2005).

5.5. Bonds

Municipal bonds are used by cities and stormwater utilities to borrow money for public projects. Bonds to raise capital for stormwater projects have been used before. In 2004, the City of Los Angeles issued a $500 million bond for stormwater projects" (Hanak et al. 2014).

An Environmental Impact Bond (EIB) is a new type of bond used by DC Water, one of the stormwater municipalities of Washington, D.C., to finance GI. It is essentially a municipal bond (Cousins and Hill 2021). Other cities which have used EIBs to fund green infrastructure include Columbia, South Carolina and Atlanta, Georgia (Cousins and Hill 2021).

5.6. Washington, D.C.'s Clean Rivers Project

Washington, D.C. is a highly urbanized US city on the Anacostia and Potomac rivers. Roughly one-third of the city is served by a CSS. The remainder of the city is served by separate stormwater infrastructure. The city's two nearby rivers are some of the most polluted in the nation. In 2011, for example, CSOs from Washington, D.C. released an estimated 1.5 billion gallons into the Anacostia river and 850 million gallons of overflow into the Potomac river (Sustainable Prosperity 2016).

Two entities are responsible for stormwater management in Washington, D.C. DC Water is responsible for addressing CSOs, and the Department of Energy and the Environment (DOEE) focuses on the MS4s in the city (Sustainable Prosperity 2016). DC Water manages an ongoing, multi-billion dollar project, the Clean Rivers Project, to reduce CSOs and improve water quality in the Anacostia and Potomac rivers.

In 1994, the EPA updated its CSO policy to require CSS NPDES permit holders to develop a Long Term CSO Control Plan (LTCP). Municipalities across the country, DC Water among them, were slow to respond to this requirement (Christophers 2018). By 2000, several local environmental and recreational groups were frustrated with DC Water's lack of progress toward CWA compliance, and they filed a suit against DC Water, which the EPA later joined (Christophers 2018). This suit led to a consent decree requiring DC Water to implement the Clean Rivers Project, designed to address CSO and water quality issues, by 2025. The project had a $2.4 billion budget, and $1.7 million, a tiny fraction of the total budget, was apportioned to GI. The project's main components were three tunnels to store millions of gallons of sewer water for conveyance to DC Water's Blue Plains wastewater treatment plant (Christophers 2018). The original consent decree locked DC Water into a predominantly grey infrastructure plan.

In 2016, however, DC Water successfully changed the consent decree to include several GI projects and a unique type of green bond, the EIB. Figure 2 is a map of the updated Clean Rivers Project. Washington D.C.'s Clean Rivers Project includes the market-based instruments introduced previously: credit trading, an incentive program, and an EIB. The following sections further discuss each of these three elements.

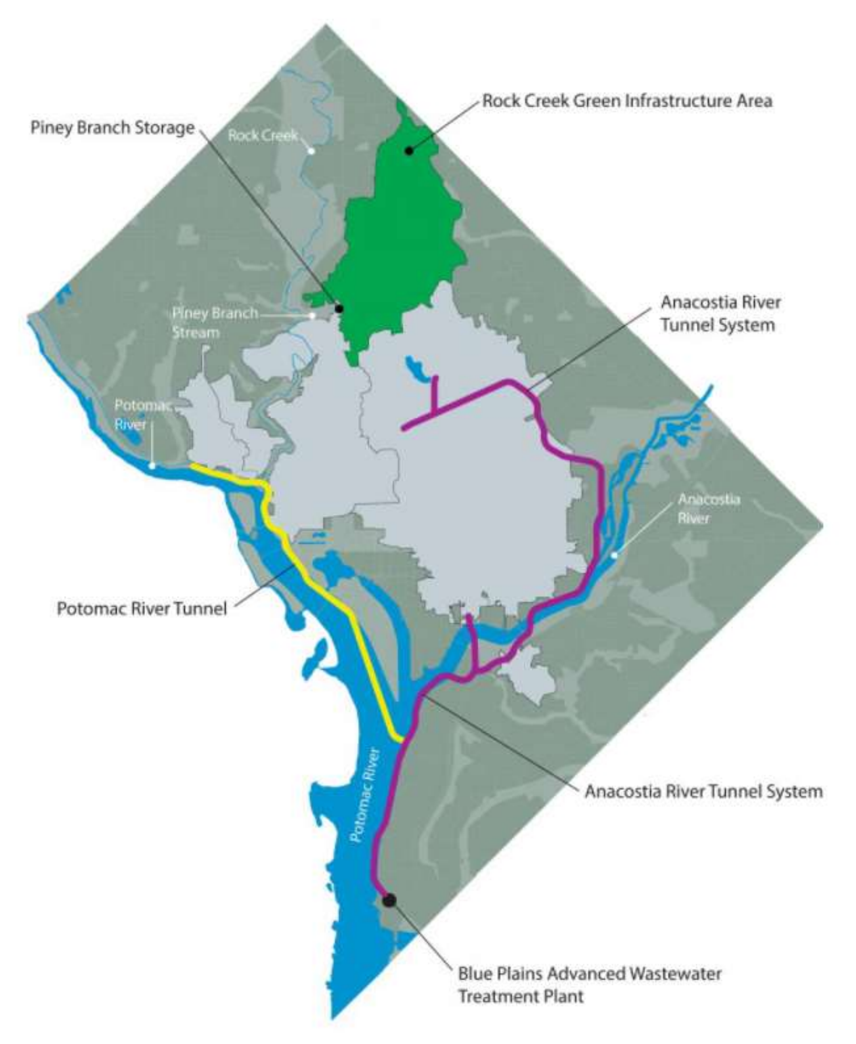


Figure 2: Clean Rivers Project map (Source: dcwater.com)

DC Water and the DOEE, the responsible entities for stormwater management in the city, collect stormwater fees from residents to fund the Clean Rivers Project and the implementation of the DOEE's MS4 NPDES permit (Sustainable Prosperity 2016). The two fees are based on an ERU of 1,000 square feet, and in 2016 the combined total of the two fee types for an average resident was approximately $23 (Sustainable Prosperity 2016).

In 2013, the city introduced on-site retention requirements for large construction projects and introduced a private market for trading stormwater retention credits. The retention-based performance standards apply to new developments and redevelopments of 5,000 square feet or more: 50% retention is required for the 1.2 or 0.8 inch storm, depending on project type (Sustainable Prosperity 2016). Stormwater Retention Credits (SRCs) are earned by individuals who exceed the standard, and these SRCs can be traded on the private market to individuals who have a deficit on their property. Alternatively, an in-lieu fee can be paid to the DOEE to compensate for sub-standard retention performance (Sustainable Prosperity 2016).

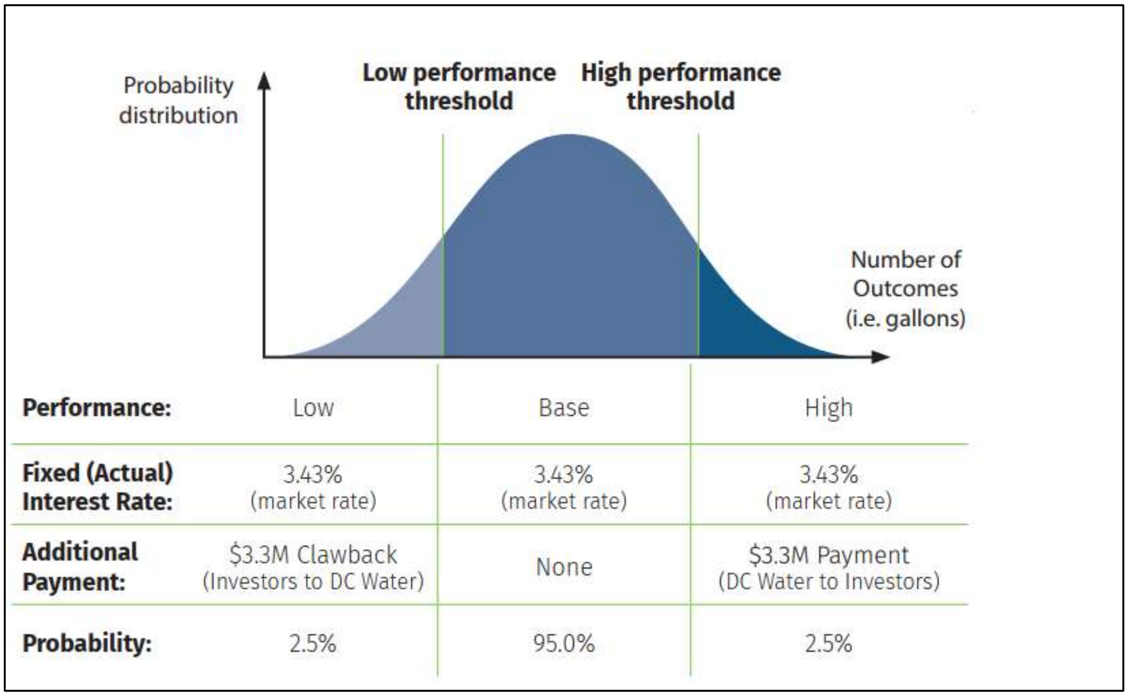
Stormwater retention credit aggregators are suppliers of SRCs who seek investment capital to construct GI projects, then sell their earned SRCs on the market. The DOEE encourages the growth of this industry by purchasing SRCs at a guaranteed, minimum price, should an aggregator be unable to sell surplus SRCs to private buyers within the market (DOEE website).

The Clean Rivers Project includes a voluntary offset program. The program incentivizes private property owners to disconnect roof downspouts and install rain barrels (Christophers 2018).

DC Water has sold several municipal bonds, classified as "green bonds" due to the inclusion of GI projects in the Clean Rivers Project. In 2014 DC Water issued the first green bond for $350 million, then another in 2015 ($100m), followed by the EIB in 2016 ($25m), and another, more standard, green bond in 2017 ($100m). The EIB is a type of green bond specifically for GI projects, whereas the other green bonds, despite their title, are used to finance the grey infrastructure portions of the Clean Rivers Project (Christophers 2018).

Washington D.C. is the first city to issue an EIB to raise funds for GI implementation (The Resilience Shift 2020). The EIB is a 30-year tax exempt bond to Goldman Sachs and the Calvert Foundation (IISD 2017). Payments depend on the performance of the project; a $3.3 million Outcome Payment will be paid to the investors by DC Water if runoff reduction exceeds 41.3%, and $3.3 million will be paid as a Risk Share Payment to DC Water from the investors if runoff reduction is less than 18.6%, with no payment being made to either party if the runoff reduction falls between the two thresholds (IISD 2017). Figure 13 is a diagram of the performance structure of the bond.

The idea of an EIB for GI projects resulted from the failure to provide sustainable financing for the original, grey infrastructure-dominated Clean Rivers Project. The monthly charge on ratepayers to finance the Clean Rivers Project was set at an unsustainably low rate at the project's year of inception, 2009, and by 2018 the rate had climbed to $25.18/month, an unsustainably high rate for churches, not-for-profits, and low-income communities (The Resilience Shift 2020). In 2010, DC Water began to consider using GI to provide potentially more cost-effective means of reducing stormwater volumes. Because of the uncertainty of GI performance, the utility sought a low risk financing method, and in 2016 DC Water issued the first EIB to finance the first phase of GI construction under the Clean Rivers Project (The Resilience Shift 2020).



Performance:	Low	Base	High
Fixed (Actual) Interest Rate:	3.43% (market rate)	3.43% (market rate)	3.43% (market rate)
Additional Payment:	$3.3M Clawback (Investors to DC Water)	None	$3.3M Payment (DC Water to Investors)
Probability:	2.5%	95.0%	2.5%

Figure 13: DC Water EIB performance structure (Source: Quantified Ventures 2021)

Command-and-control and market-based approaches have strengths and weaknesses for promoting economically efficient stormwater management solutions in legal, equitable ways. In the US, legislation has driven municipalities to rely heavily on financial tools such as user fees and bonds, and a rising demand for GI is resulting in the adoption of more innovative tools such as credit trading programs, voluntary offset programs, and green bonds and EIBs. Market-based instruments have been used effectively to manage air pollution (Parikh et al. 2005), and they may prove equally useful in managing runoff using GI.

There are many costs and risks for implementing market-based instruments for stormwater management. A difficulty tied to the larger problem of runoff quality is the lack of economic monitoring, which hinders efforts to reduce uncertainty in GI performance and increase confidence among private landowners (Parikh et al. 2005). Other barriers, specifically to the implementation of credit programs, are high transaction costs, such as administrative costs (needed to manage the program and facilitate trades) and consulting fees (needed for design) (Malinowski et al. 2020). A risk of implementing an incentive program is that the market (private landowners) will not respond to the incentives as desired or expected after the potentially costly program has been designed and implemented, leaving local governments responsible for financing infrastructure projects in other ways or increasing existing budget deficits (IISD 2017). Finally, GI as a set of source control measures provides greater benefits closer to project locations. When costs are incurred broadly among residents to provide greater benefits for a portion of the public, it becomes challenging to reconcile the conflict between broad environmental objectives and the desire for social-spatial equity.

6. Conclusion

Worldwide, there is increasing focus on stormwater management ~~from~~ water quality and treatment ~~perspectives.~~ Costs from existing and emerging pollutants are becoming better understood and quantified, and this increased awareness raises interest in improving stormwater management. Climate change will likely increase the frequency of intense storms, bringing more attention to stormwater issues. GI technology and methods help mitigate both quality and quantity problems, and further exploration and adoption of GI is a path toward optimal management of urban runoff.

Advances in GI assessment and a general increase in confidence in GI may help to form new regulation in the US to drive GI adoption further. However, new regulations must be introduced carefully. Inducing change by way of regulation (i.e., force) alone can result in a lack of enforcement, misunderstandings of ownership and maintenance responsibilities, and an overall reduction in the effectiveness of GI (Rodak et al. 2019).

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