

UC Santa Barbara

UC Santa Barbara Previously Published Works

Title

Stormwater Control Measures for Runoff and Water Quality Management in Urban Landscapes

Permalink

<https://escholarship.org/uc/item/3cm720mk>

Journal

JAWRA Journal of the American Water Resources Association, 54(1)

ISSN

1093-474X

Authors

Sadeghi, K Majid

Loáiciga, Hugo A

Kharaghani, Shahram

Publication Date

2018-02-01

DOI

10.1111/1752-1688.12547

Peer reviewed

STORMWATER CONTROL MEASURES FOR RUNOFF AND WATER QUALITY MANAGEMENT IN URBAN LANDSCAPES¹

K. Majid Sadeghi, Hugo A. Loáiciga , and Shahram Kharaghani²

ABSTRACT: This study develops and tests a novel optimization method for optimally selecting and sizing stormwater control measures (SCMs) in urban landscapes for selected design storms. The developed methodology yields SCMs that capture and retain stormwater via onsite percolation, remove stormwater pollutants, and minimize stormwater control expenditures. The resulting environmental optimization problem involves integer and real variables imbedded in an objective function that is subjected to multiple constraints. This study's methodology aims at practicality and ease of implementation in the solution of the SCM sizing and selection optimization problem while taking into account the main factors that govern stormwater management in urban landscapes. The near-optimal global solution of the SCM selection and design problem is obtained with nonlinear programming and verified with the average of multiple solutions calculated with multiple runs of an optimization evolutionary algorithm. The developed methodology is illustrated with one stormwater project in the City of Los Angeles, California.

(KEY TERMS: stormwater; percolation; urban flooding; water quality; optimization.)

Sadeghi, K. Majid, Hugo A. Loáiciga, and Shahram Kharaghani, 2018. Stormwater Control Measures for Runoff and Water Quality Management in Urban Landscapes. *Journal of the American Water Resources Association* (JAWRA) 54(1): 124-133. <https://doi.org/10.1111/1752-1688.12547>

INTRODUCTION

The relative impervious nature of the urban landscape with its propensity for high pollutants' loading by multiple human activities is the cause of large runoff generation with poor water quality in urban areas. Flooding and discharge of polluted stormwater to rivers, lakes, wetlands, and seas within and neighboring to cities are endemic to many urban areas across the United States (U.S.) and elsewhere (City of Los Angeles, 2011; Loáiciga *et al.*, 2015).

The term stormwater control measures (SCMs) describes relatively small structures (small compared with conventional facilities such as flood control reservoirs) that are installed within urban areas to capture, retain, and improve the quality of storm runoff. It has replaced the term "best management practice" (or BMP) to some extent, which has a generic connotation that goes beyond stormwater control (USEPA, 1993; Loáiciga *et al.*, 2015; Liu *et al.*, 2016). The focus of this work is on SCMs with the capacity to retain stormwater by percolation in the underlying soils, such as dry wells (DWs), infiltration trenches (IT), detention/infiltration basins, vegetated swales,

¹Paper No. JAWRA-16-0184-P of the *Journal of the American Water Resources Association* (JAWRA). Received September 23, 2016; accepted April 26, 2017. © 2017 American Water Resources Association. **Discussions are open until six months from issue publication.**

²Environmental Engineer (Sadeghi) and Program Manager (Kharaghani), LA Sanitation, Los Angeles, California 90015; and Professor (Loáiciga), Department of Geography, University of California, 1832 Ellison Way, Santa Barbara, California 93106 (E-Mail/Loáiciga: hloaiciga@ucsb.edu).

planter boxes, and porous pavement. Onsite stormwater retention is a function of SCMs that reduces stormwater impacts in accordance with low-impact development (LID) principles for green infrastructure (Davis, 2005; City of Los Angeles, 2011; Beyerlein, 2012; Houle *et al.*, 2013). Stormwater capture in semiarid areas has the esthetic benefit of increasing soil moisture that supports urban vegetation and increases percolation to recharge aquifers, thus becoming a tool for improved surface water-groundwater management given appropriate geologic conditions.

The investment in SCMs has been shown to have a significant economic benefit. In the City of Los Angeles, for example, an investment of 8 billion dollars in SCMs has been estimated to produce benefits ranging from 46 to 170 billion dollars over a 30-year period (Currier *et al.*, 2004). The 50,000 or so SCMs installed within an area of 1,225 km² with 24,000 km of streets in the City of Los Angeles are testimony to the services and benefits of SCMs. Other cost- and benefit-related topics concerning SCM deployment have been addressed by the Water Environment Research Federation (2009), McGarity (2012), and Kurkalova (2015), among other authors. Strecker *et al.* (2001) evaluated the effectiveness of stormwater BMPs. Zhen and Yu (2004) introduced an approach for the optimal location and sizing of stormwater basins at the watershed scale employing a heuristic optimization technique coupled with the agricultural nonpoint source pollution (AnnAGNPS) model. The U.S. Environmental Protection Agency's (USEPA's) stormwater management model provides stormwater simulation and SCM evaluation capabilities (USEPA, 2008), which were expanded by the USEPA's (2009) SUSTAIN framework for placement of best management practices in urban watersheds for the protection of water quality. Maringanti *et al.* (2009) reported multiobjective optimization of the selection and placement of SCMs for nonpoint source pollution control. Lee *et al.* (2012) developed a watershed-scale design optimization model for stormwater best management practices. Limbrunner *et al.* (2013) applied classic optimization techniques applied to stormwater and nonpoint source pollution management at the watershed scale. McGarity (2013) employed system analysis to meet total maximum daily loads (TMDLs) in urban watersheds. Liu *et al.* (2016) reported a decision support system for optimally implementing BMPs and LIDs in watersheds. Sebt *et al.* (2016) assessed climate-change-related impacts on SCM performance and for their selection and placement in a combined sewer.

This article presents a new nonlinear programming (NLP) method to optimally select and size SCMs in urban areas. The method takes into account the

factors that govern the allocation of resources for urban stormwater management, namely, cost minimization, runoff retention, improvement of stormwater quality, and the physical characteristics of SCMs. In addition, this study applies an evolutionary algorithm (EA) to the selection and sizing of SCMs, which serves as validation of the near optimality of the NLP solution. This study's new methodology for selecting and sizing of SCMs is accurate, practical, and accessible to stormwater managers concerned with the solution of real-world problems. These traits constitute the novelty and contribution of the SCM methodology presented in this work. The NLP method herein developed and tested extends previous work by the authors on the subject matter of SCM design and selection using linear programming (LP) methodology where the selection of the best types of SCMs to be deployed was decoupled from their optimal sizing (Loáiciga *et al.*, 2015). The global optimality of the SCMs' selection and sizing solution is validated with multiple runs of an optimization EA. This work specifically focuses on SCMs capable of retaining stormwater on site by percolation in permeable soils, such as DWs, IT, vegetated swales, porous pavement with permeable subbase and subgrade, and the like. This study's methodology to SCM design is illustrated with one case study in the City of Los Angeles, California.

METHODOLOGY

Description of Stormwater Retaining SCMs

Figure 1 depicts one SCM in a network of SCMs considered for deployment to control the volume of stormwater and its water quality. There are $i = 1, 2, 3, \dots, N$ sites identified as possible locations for the deployment of SCMs, one per site. The SCM at site i of type k is denoted by SCM_{ik} and has a to-be-determined size SM_{ik} . There is a volume of stormwater I_i , $i = 1, 2, \dots, N$, arriving at each of the N SCM sites. The influent storm runoff contains R indicator pollutants with concentrations C_{ir} , $i = 1, 2, \dots, N$; $r = 1, 2, \dots, R$. Networks of SCMs are handled by taking into account the connectivity between them as shown in the example of this article.

At each site i there are $k = 1, 2, \dots, K$ possible SCMs to be installed, only one of which will be installed at each site. Some or all of the volume of influent stormwater at SCM k on site i is retained (V_{Rik}) there, and some may flow through the SCM_{ik} and exits with a flow-through volume V_{Tik} and concentration E_{ikr} . V_{Rik} includes the percolation of captured stormwater into the surrounding soil, and, at

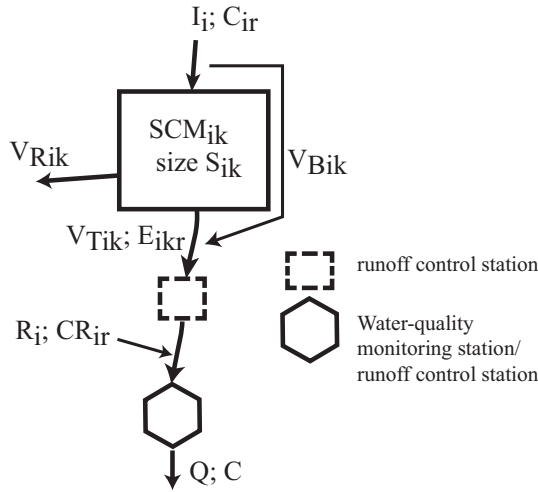


FIGURE 1. Plan View of a Schematic of SCM_{ik} , $i = 1, 2, \dots, N$; $k = 1, 2, \dots, K$, and Related Stormwater Variables.

a minimum, it equals the internal water-storing capacity of SCM_{ik} , which is assumed to fill during the design storm. Some of the influent stormwater may be bypassed (V_{Bik}) due to SCM_{ik} capacity limitations. The flow-through volume blends with the bypassed volume immediately downstream of the SCM. There may be regulations on the allowed amount of flow-through volume plus bypass volume at any SCM, and on its water quality characteristics.

The sum of flow-through and bypassed volumes blends with unregulated storm runoff R_i originating between the SCM at site i and the downstream monitoring station where a water quality and quantity requirement may be set by regulatory policy or ordinance. The unregulated runoff R_i has concentration CR_{ir} of pollutant r . The concentration C of the total flow Q at the monitoring station must be equal to or less than the regulatory requirement. Q may also be regulated there. This study's optimization method sizes and selects SCMs for specified, single-event, design storms. The design-storm approach to SCM implementation is widely used in stormwater management (City of Los Angeles, 2011). These storms are usually 24 to 48 h in duration, they have a known depth of rainfall, typically 2-10 years and have associated depths of precipitation that are unique to the area where SCMs are deployed (City of Los Angeles, 2011).

A Nonlinear Optimization Approach for Selecting and Sizing SCMs

The objective of the optimization method is to minimize the present value of the total cost of installing, operating, maintaining, and replacing SCMs at N

sites each with one SCM. A SCM_{ik} has a to-be-determined design size S_{ik} , and a unit (variable) cost of SCM capacity p_{ik} . This unit cost is the sum of the unit initial installation cost and the unit operational, maintenance, and replacement cost expressed as a present value. The design variable of a SCM is expressed in units of volume (say, m^3 , for example), or treatment area (m^2), or treatment length (units of length), depending on the type of SCM. Percolation (dry) wells typically feature standardized cross sectional areas, in which case the design variable is their depth of subsurface penetration. Other SCMs (say, IT) may have standardized depths, in which case the unknown design variable is their surface area. Some SCMs may be designed in terms of their volumetric capacity. Detention ponds are a case in point, in which the unknown design variable is the volume of the SCM. Therefore, the unit cost p_{ik} may be expressed as $\$/m^3$, or as $\$/m^2$, or as $\$/m$ to accommodate volumetric, areal, or longitudinal designs, respectively. In addition, there may be (known) fixed costs f_{ik} unrelated to the size of a SCM. The latter costs are present values in a manner analogous to the unit costs p_{ik} . A binary decision variable $x_{ik} = 1$ if SCM k is chosen at site i , or $x_{ik} = 0$ if the SCM k is not chosen at site i . There is one SCM at each possible deployment site. The optimization problem's objective function is the minimization of the total cost of SCM implementation, whose decision variables are the selection variables x_{ik} and the sizing variables S_{ik} :

$$\text{Minimize } F = \sum_{i=1}^N \sum_{k=1}^K (p_{ik} \cdot S_{ik} \cdot x_{ik} + x_{ik} \cdot f_{ik}) \quad (1)$$

The decision variables S_{ik} and x_{ik} determine the sizing and placement of the SCMs, respectively. The objective function (1) is nonlinear, it involves real-valued variables (S_{ik}) and binary integer variables (x_{ik}).

Constraints of the Nonlinear Optimization Problem

Implement One SCM Per Site. Each site must have one SCM. This is accomplished by the following constraint:

$$\sum_{k=1}^K x_{ik} = 1 \quad i = 1, 2, 3, \dots, N \quad (2)$$

SCM Capacity Constraints. The design variable of a SCM may not exceed a maximum size $S_{ik\max}$, and must have a minimum size $S_{ik\min}$:

$$S_{ik \min} \leq S_{ik} \leq S_{ik \max} \quad i = 1, 2, \dots, N; k = 1, 2, \dots, K \quad (3)$$

Budget Constraint. The budgetary constraint states that the installation, maintenance, and replacement cost of SCMs may not exceed an allocated budget B :

$$\sum_{i=1}^N \sum_{k=1}^K (p_{ik} \cdot S_{ik} \cdot x_{ik} + x_{ik} \cdot f_{ik}) \leq B \quad (4)$$

The budget constraint does not apply when there is no budgetary limitation.

Constraints on SCM Volume Fluxes. The first set of volumetric constraints imposes feasibility of water balance at SCM_{ik} . These constraints require that the volume of retained stormwater (V_{Rik}) plus the flow-through volume (V_{Tik}) must not exceed the volume of stormwater I_i arriving at site i . V_{Rik} equals the design size of the SCM times a (known) retention factor a_{ik} , to which a constant c_{ik} is also added, or $V_{Rik} = a_{ik} \cdot S_{ik} + c_{ik}$. The water retention factor a_{ik} and constant c_{ik} are estimable characteristics of the SCM k at site i . The flow-through $V_{Tik} = b_{ik} \cdot S_{ik} + d_{ik}$. The (known) flow-through factor b_{ik} and constant d_{ik} are estimable characteristics of the SCM_{ik} (see Supporting Information). The set of volumetric feasibility constraints is written as follows:

$$\sum_{k=1}^K x_{ik} \cdot (a_{ik} S_{ik} + c_{ik} + b_{ik} S_{ik} + d_{ik}) \leq I_i \quad i = 1, 2, \dots, N \quad (5)$$

The difference $I_i - [(a_{ik} + b_{ik}) S_{ik} + c_{ik} + d_{ik}]$ equals the bypass volume V_{Bik} . The type of SCM deployed at site i is unknown, therefore the bypass volume at the i -th SCM site is written as a function of the binary variables x_{ik} as follows:

$$V_{Bi} = \sum_{k=1}^K x_{ik} \cdot \{I_i - [S_{ik}(a_{ik} + b_{ik}) + c_{ik} + d_{ik}]\} \quad i = 1, 2, \dots, N \quad (6)$$

The runoff O_{ik} immediately downstream from the SCM_{ik} equals the sum of the bypass volume plus the flow-through volume. The effluent volume O_{ik} may be subjected to a constraint on maximum storm runoff (Q_{imax}) allowed immediately downstream of site i . This generates the following set of volumetric constraints immediately downstream of site i :

$$O_i = \sum_{k=1}^K x_{ik} \cdot [I_i - (S_{ik} a_{ik} + c_{ik})] \leq Q_{imax} \quad i = 1, 2, \dots, N \quad (7)$$

Adding the flows $O_i + R_i$ over all sites i yields the total flow Q accruing to the water quality and quantity monitoring station:

$$Q = \sum_{i=1}^N R_i + \sum_{i=1}^N \sum_{k=1}^K x_{ik} \cdot [I_i - (S_{ik} a_{ik} + c_{ik})] \quad (8)$$

In some instances the total flow Q may not exceed a maximum value Q_{max} at the runoff monitoring station (this is a total volumetric constraint):

$$Q = \sum_{i=1}^n R_i + \sum_{i=1}^N \sum_{k=1}^K x_{ik} \cdot [I_i - (S_{ik} a_{ik} + c_{ik})] \leq Q_{max} \quad (9)$$

Water Quality Constraints at Monitoring Stations. The mass of a pollutant r in storm runoff arriving at site i equals $M_{ir} = I_i \cdot C_{ir}$. The mass of pollutant r in the flow-through volume is $(S_{ik} b_{ik} + d_{ik}) \cdot E_{ikr}$, where E_{ikr} denotes the concentration of pollutant r in the flow-through volume that passes through SCM_{ik} . Part of the pollutant r is removed from flow through by the SCM_{ik} according to the following equation in which e_{ikr} is the pollutant r removal efficiency of SCM_{ik} ($0 \leq e_{ikr} \leq 1$):

$$e_{ikr} = \frac{C_{ir} - E_{ikr}}{C_{ir}} \quad i = 1, 2, \dots, N; k = 1, 2, \dots, K; r = 1, 2, \dots, R \quad (10)$$

Therefore, the concentration of the flow-through volume becomes:

$$E_{ikr} = C_{ir} \cdot (1 - e_{ikr}) \quad i = 1, 2, 3, \dots, N; k = 1, 2, 3, \dots, K; r = 1, 2, 3, \dots, R \quad (11)$$

The mass of pollutant r in the flow-through volume becomes:

$$Q_{ikr} = (S_{ik} b_{ik} + d_{ik}) \cdot E_{ikr} = (S_{ik} b_{ik} + d_{ik}) \cdot C_{ir} \cdot (1 - e_{ikr}) \quad (12)$$

$i = 1, 2, \dots, N; k = 1, 2, \dots, K; r = 1, 2, \dots, R$. The bypass volume V_{Bik} at site i has concentration C_{ir} equal to that of the inflow volume I_i and, thus, carries a mass of pollutant r equal to $V_{Bik} \cdot C_{ir}$. Adding the masses of stormwater pollutant r carried by

bypass, flow-through, and unregulated volumes yields the mass G_{ikr} of the pollutant arriving at the water quality monitoring station from SCM k at site i and from the area between this SCM and the downstream water quality monitoring station. The masses G_{ikr} are added over all SCM _{ik} to produce the total mass G_r of pollutant r arriving at the water quality monitoring station from all upstream sites $i = 1, 2, 3, \dots, N$:

$$G_r = \sum_{i=1}^N \left[H_{ir} - \sum_{k=1}^K x_{ik} \cdot (A_{ikr} + S_{ik} g_{ikr}) \right] \quad (13)$$

$r = 1, 2, \dots, R$ in which:

$$H_{ir} = R_i C R_{ir} + I_i C_{ir} \quad (14)$$

$$A_{ikr} = C_{ir} \cdot (c_{ik} + d_{ik} e_{ikr}) \quad (15)$$

$$g_{ikr} = C_{ir} \cdot (a_{ik} + b_{ik} e_{ikr}) \quad (16)$$

The concentration of pollutant r in stormwater arriving at the water quality monitoring station equals the total mass G_r expressed by Equation (13) divided by the total volume Q given by Equation (8). The concentration must be equal to or less than the water quality constraint for pollutant r :

$$G_r \leq Q \cdot TMDL_r \quad r = 1, 2, 3, \dots, R \quad (17)$$

The R water quality constraints (17) are explicitly defined after replacing Q with Equation (8) and G_r with Equation (13).

Summary of the SCM Nonlinear Optimization Method

The objective function is the minimization of SCM costs given by Equation (1). The objective function is subject to one-SCM-per-site constraints (Equation 2, always required), SCM capacity constraints (Equation 3, always required), budgetary constraint (Equation 4, may or may not be applicable), volumetric feasibility constraints (Equation 6, always required), volumetric constraints immediately downstream of SCM sites (Equation 8, may or may not be applicable), maximum runoff constraint at the runoff monitoring station (Equation 9, may or may not be applicable), and water quality constraints (Equation 17, may or may not be applicable). Other constraints could be added to meet relevant performance requirements.

Equations (1-17) constitute the mathematical statement of the SCM selection and design method. The selection and design method is scalable, that is,

applicable to various SCM network sizes, by resorting to the connectivity of the network of SCMs given that Equations (1-17) are applicable to any number of sites ($i = 1, 2, 3, \dots, N$), any number of SCM types ($k = 1, 2, \dots, K$), and any number of water quality characteristics ($r = 1, 2, 3, \dots, R$). In actuality, the SCM selection and sizing method herein developed was inspired by site-specific needs to control urban runoff with a limited number of water pollutants in small catchments or urban blocks as exemplified in this study's application. Regional-scale problems concerning urban flooding and water quality protection require the interfacing of continuous-simulation rainfall-runoff models with SCM design algorithms that in most cases involve large conveyance and storage infrastructure not covered by the percolation-based SCMs considered in this study's method.

The nonlinear optimization problem for SCM selection and sizing presented above is scalable to various spatial sizes of the study area where SCMs are deployed. This is accomplished by providing the correct connectivity between the deployment sites ($i = 1, 2, \dots, N$) in the pertinent equations of mass- and volume-balance presented in this work. One limitation in this respect is that this study's methodology is tailored for single-storm events typically lasting 24 and 48 h, a common SCM design practice in the U.S. The concentration times of urban sub-catchments are commonly measured in minutes. The mass- and volume-balanced equations presented in this study capture the kinematics of runoff and pollutant motion associated with single-storm events. Stormwater control measure selection and sizing applications involving very large areas with long concentration times require the implementation of continuous simulation hydrologic and water quality models that may or may not be coupled with optimization models. It is common in the latter situation to propose alternative SCM designs and evaluate their performances until achieving a design that meets functionality and regulatory criteria within allowable budgets. The latter is essentially a trial-and-error approach guided by experience and professional judgment that may not be globally optimal from economic and performance criteria, but that meets cost and performance criteria.

It is noteworthy that this study's SCM selection and sizing method can be solved with classic optimization techniques such as NLP, dynamic programming, or with EAs, such as the genetic algorithm (GA) (Holland, 1975). This study solves the SCM selection and sizing method with NLP and with an EA which is a variant of the GA. Both solution techniques are available in the software EXCEL. EXCEL's optimization package (SOLVER) has minimal demands on optimization expertise for its

implementation, thus making it well suited for applications by nonexperts.

Study Site and Project Characteristics

Figure 2 shows the general location of the Glenoaks stormwater capture project. The Glenoaks project lies within the City of Los Angeles, California, whose storm drain system features 2,414 km of pipes and 161 km of open channel. The stormwater control system in Los Angeles includes about 38,000 catch basins and thousands of other SCMs. The Glenoaks stormwater capture project covers a tributary drainage area equal to 122.21 ha (ha = hectare, 1 ha = 10,000 m²). The 48-h, design storm for stormwater management in the study area has a depth equal to 1.91 cm, corresponding to a two-year event at the study site. The amount of runoff generated by the design storm in the study area equals 13,504 m³. This runoff corresponds to the design storm for the study site and was calculated with the La Recarga rainfall-infiltration-runoff model (City of Los Angeles, 2009). The soil underlying the project area is a sandy loam with infiltration rate equal to 25.4 mm/hr. This permeable soil is suitable for SCMs that retain stormwater by seepage into the soil. The focus pollutant in this example is suspended solids (SS).

Figure 3 shows a map of the Glenoaks stormwater capture project. Most of the storm runoff generated within the project area flows southerly toward the Glenoaks and Sunland Boulevards, shown in Figure 3.

Stormwater moves along the Glenoaks Boulevard from its northwestern, upstream end to its southeastern, downstream end (from left to right on Figure 3). The SCMs will be deployed on the Glenoaks Boulevard. The length of the boulevard in the Glenoaks project equals 2,400 m. The potential SCMs considered for possible deployment in this example are as follows: dry wells (DW, on the curbs of the boulevard, one on each curb), grassy swales (GS, on the sidewalks next to the boulevard, one on each sidewalk), and infiltration trenches (IT).

The SCMs to be installed in the Glenoaks project, namely, DW, GS, and IT, are assigned the index $k = 1, 2$, and 3 , respectively. For design purposes, the 2,400 m Glenoaks Boulevard is divided into eight 300-m-long segments. Each 300 m segment is considered as a “site,” therefore, $i = 1, 2, \dots, 8$. Figure 4 depicts a schematic of the SCMs layout to be deployed at the Glenoaks site. The optimization model was written such that the selection of a DW at a site means a two-well installation, one on each side of the boulevard. Similarly, the selection of a GS at a

site involves the installation of two GSs, one on each side of the boulevard. This was done to maintain symmetry in runoff and sediment control on both sides of the boulevard.

The stormwater volume is $I_i = 1,688 \text{ m}^3$ (= total runoff 13,504 m³ divided by eight sites) and the suspended sediment concentrations equal $C_i = 100 \text{ g/m}^3$ at each of the eight sites on the Glenoaks Boulevard. Table 1 shows data on SCMs for the example. The data on Table 1 indicate that the SCMs have standardized designs. Therefore, the DWs have diameters equal to 1 m. Their unknown dimension is their length (depth). Grassy swales have a length of 300 m and a depth of 0.46 m, their unknown dimension being their width. The IT are 300 m with depth of 1 m, their unknown dimension being their width. The unit-cost data listed in Table 1 issue from the City of Los Angeles’ ample experience gained from the installation of tens of thousands of SCMs.

SCM Characteristics

The retention coefficients of a SCM, a_{ik} and c_{ik} , and its flow-through coefficients, b_{ik} and d_{ik} , determine the stormwater retention and flow-through volumes that can be achieved at each SCM and deployment site. Those coefficients depend on the geometry of the SCM, on its outflow design characteristics, on the infiltration capacity of the surrounding soils, and on the duration of the design storm (48 h in this case). The volume retention and flow-through coefficients for the SCMs considered in this work (DWs, GSs, and IT) are shown in Table 2.

RESULTS AND DISCUSSION

The SCM optimization model given by Equations (1-4, 7, 9, and 17) was implemented with a maximum budget $B = \$3.2$ million (see budget constraint Equation 4). Of the optional volumetric constraints, only a constraint on total inflow arriving at the downstream monitoring station (MS) was required, stating that at least 75% of the total storm runoff generated by the design storm in the study area (or $0.75 \times 13,504 = 10,128 \text{ m}^3$) must be retained by the SCMs. This is equivalent to requiring that the total volume of stormwater arriving at the downstream monitoring station (Q) must not exceed 25% of the total storm runoff, or $Q \leq 3,376 \text{ m}^3$ (see constraint Equation 9). The water quality constraint was that the stormwater arriving at the downstream monitoring station must have a concentration of at most 50%

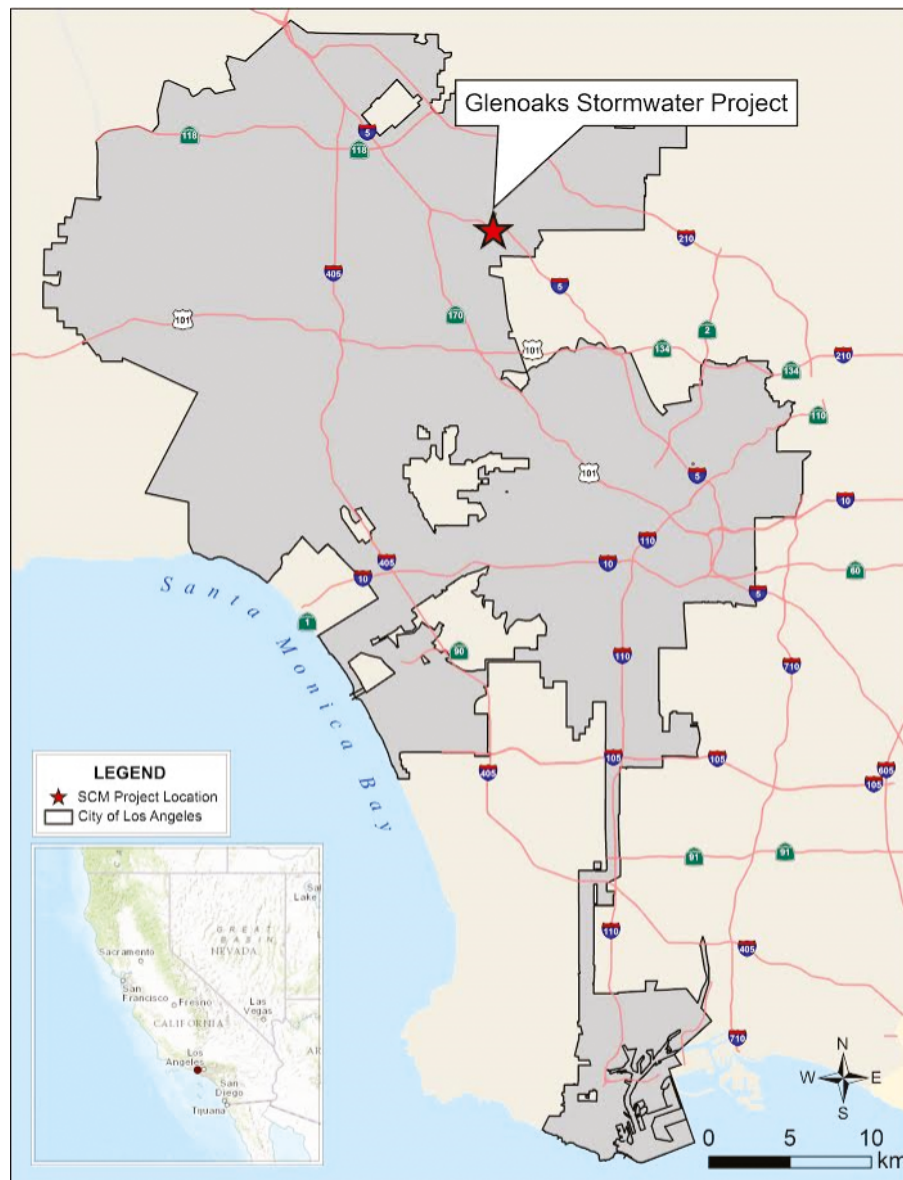


FIGURE 2. Location of the LA Sanitation-City of Los Angeles' Glenoaks Stormwater Project Site.

of that present in the stormwater arriving to the Glenoaks Boulevard, that is, the concentration of suspended solids at the downstream monitoring station may not exceed 50 g/m^3 .

The SCM optimization model was implemented with the data and constraints specified above. The model was coded in an EXCEL spreadsheet and solved with the software SOLVER available in EXCEL. The near-optimal solution of the SCM selection and sizing problem (Equations 1-17) was achieved with the GRG (generalized reduced gradient) NLP algorithm available in SOLVER. The binary nature of the x_{ik} selection variables is specified as a set of constraints in the input interface for constraints available in SOLVER. Several combinations

of feasible initial guesses of the SCMs' unknown dimensions were selected and input to the solution algorithm to verify that the calculated solution was near optimal. All the initial guesses were chosen to meet the dimensional constraints (*i.e.*, minimal and maximal sizes) and they all lead to the same optimal solution herein reported. In addition, the SCM selection and sizing problem was solved with 10 runs of the optimization evolutionary algorithm (OEA) imbedded in SOLVER for further validation of the global optimality of the solution found with NLP. Each run of an OEA employs a random seed to generate a specified number of randomly generated populations (100 populations in this study) of possible solutions with which to start the iterations in search

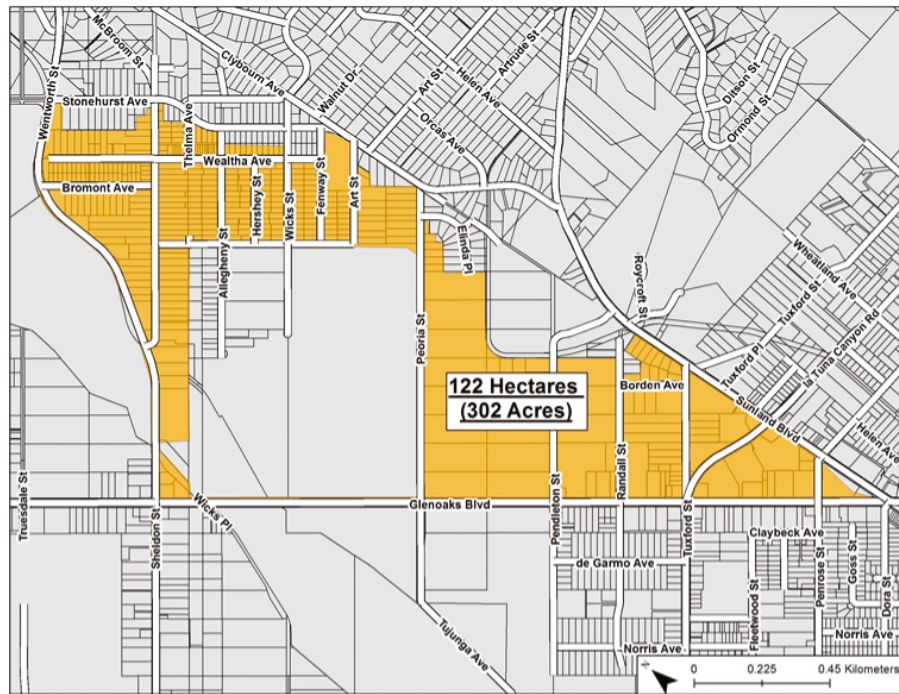


FIGURE 3. The Glenoaks Stormwater Project Drainage Area (colored light-brown) and the Glenoaks/Sunland Boulevard.

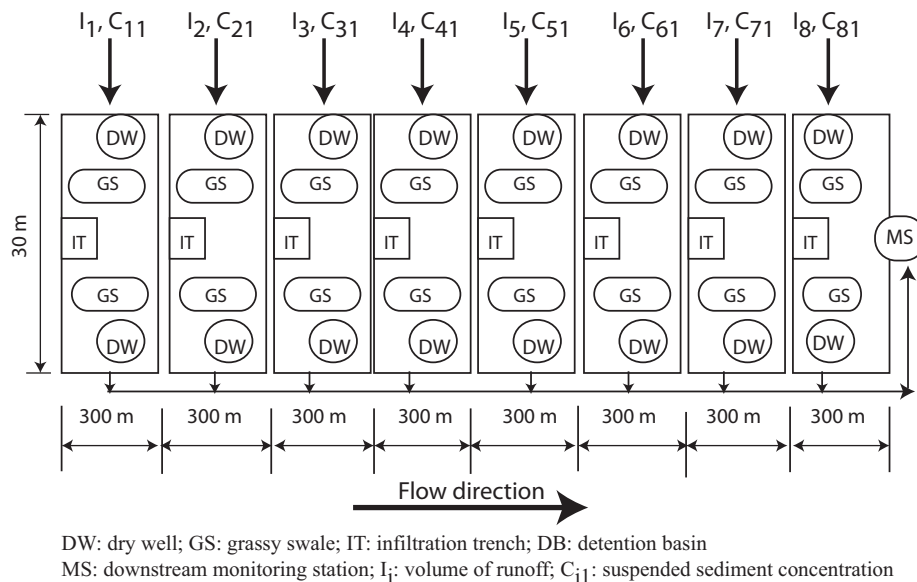


FIGURE 4. Layout of Potential Stormwater Control Measures to Be Deployed at the Study Site (plan view).

for a near-global optimal solution. Each OEA run produces a different solution that is near the global optimum (these are called near-optimal solutions). Therefore, it is customary to present results in terms of the average of the solutions calculated from the multiple runs of the OEA (10 runs are typical, see Garousi-Nejad *et al.*, 2016). The OEA in SOLVER is a modified version of the classic GA (Holland, 1975). Optimization evolutionary algorithms are becoming

widely used in optimization applications because of the fact that they are applicable to objective functions and constraints of arbitrary complexity. The main drawbacks with OEAs is that they are computationally burdensome in problems of large dimensionality and complexity, and the user must specify convergence parameters, mutation, and crossover parameters, the number of randomly generated populations of possible solutions that are employed in each run of

TABLE 1. Stormwater Control Measure (SCM) Data (e denotes the treatment efficiency of SCMs for suspended solids).

SCM	Total Unit Cost ¹	$S_{\max}$	$S_{\min}$	e^2
Dry wells (DW, $k = 1$) ³	\$1,610/m	20 m (depth)	10 m (depth)	0.75
Grassy swales (GS, $k = 2$) ⁴	\$231,586/m	2 m (width)	1 m (width)	0.85
Infiltration trench (IT, $k = 3$) ⁵	\$139,800/m	4 m (width)	2 m (width)	0.85

¹The sum of variable cost plus fixed cost equal to 10% of variable cost, per site.

²Removal efficiency.

³Well diameter = 1 m.

⁴Length = 300 m, depth = 0.46 m.

⁵Length = 300, depth = 1 m. Each site may have two DWs or two GSs (reflected in their total unit cost), or one IT.

an OEA, the random seed, and possibly other algorithmic parameters depending on the OEA, of which there are hundreds of known varieties currently (Chen, 2003). The implementation of 10 runs of an OEA is common in solving a particular problem to carry out a comparison of solutions and to calculate an average value of the objective function and the decision variables that are near the global optimum.

The near-optimal global combination of SCMs determined from the NLP model execution was as follows: site 1: two DWs, 20 m deep each (1 m diameter by specification); sites 2 through 8: two GSs per site, each with width equal to 1.95 m (300 m long, 0.46 m deep, by specification). Infiltration trenches were not chosen by the nonlinear optimization model for deployment at the study site. The optimal SCMs meet the capacity or size constraint Equation (3), with maxima and minima given in Table 1. Recall that the depth of the DWs may not exceed 20 m, and the width of grassy wells is limited to 2 m (see Table 1). The cost of the two percolation (dry) wells on site 1 amounts to \$32,200. These two percolation (dry) wells retain 156 m³. Each set of two GSs (per 300 m of boulevard) on sites 2 through 8 equaled \$451,593. Each set of GSs retained 1,428 m³.

Overall performance variables are as follows for the NLP near-optimal global solution: total cost of SCMs: \$3.19 million dollars, which complies with the

maximum budget equal to \$3.2 million; volume of stormwater at the downstream monitoring station: 3,352 m³ ($\cong 25\%$ of the total storm runoff generated by the design storm in the study area, the maximum permissible); suspended solids concentration at the downstream monitoring station: 49 g/m³, which is less than the maximum 50 g/m³.

The SOLVER OEA was run 10 times and produced an average near-optimal value of the objective function equal to \$3.195, nearly identical but slightly larger to the optimal objective function calculated with NLP. The selection of the SCMs was identical to those of the NLP solution in the 10 runs. The average dimensions of the SCMs obtained with the OEA were for all practical purposes concerning construction details identical to those of the NLP optimal solution.

A pilot SCM performance testing project was implemented in the Glenoaks Boulevard shown in Figure 3 with SCMs layout depicted in Figure 4. The pilot involved the design, construction, and performance analysis of percolation wells and infiltration (grassy) swales. The project was finished in June 2013. A total of four DWs and six GSs were installed in the Glenoaks Boulevard based on results from the optimization method. Measurement of suspended solids demonstrated that the actual removal efficiency in the SCMs was nearly 100%, and that the SCMs retained about 17% of the stormwater runoff from a 0.019 m (0.75 inch) storm. This level of performance achieved for the relative low budget is considered excellent and demonstrates the capacity of the proposed SCM optimization method to be used as a guideline for their design and selection. The SCM system in the study area is being expanded to capture more runoff.

The methodology for SCM selection and sizing proved successful in the Glenoaks project. This study's methodology may serve as a guideline for optimizing SCM deployment at other sites in the City of Los Angeles and elsewhere. Stormwater management is commonly one of several elements considered in the investment on projects that improve neighborhoods' infrastructure and quality of life. Esthetics, personal safety, and social harmony are goals that

TABLE 2. Stormwater Control Measure (SCM) Hydraulic Coefficient and Environmental Data.

SCM	a_{ik} (m ²)	c_{ik} (m ³)	b_{ik} (m ²)	d_{ik} (m ³)	I_i (m ³)	C_i (g/m ³)	R_i (m ³)	CR_i (g/m ³)
Dry wells (DW)	7.66 ¹	1.92 ¹	0 ¹	30.2 ¹	1,688	100	0	0
Grassy swales (GS)	732 ²	0 ²	110.4 ²	0 ²	1,688	100	0	0
Infiltration trench	366	0	120	0	1,688	100	0	0

¹Two DW per site.

²Two GS per site.

Sites $i = 1, 2, \dots, 8$.

are also taken into account when investing in stormwater management and urban infrastructure. This study's methodology is flexible in that one can add physical elements and constraints to it with simplicity, which makes it a scalable methodology from a spatial viewpoint. It is noteworthy, however, that this study's SCM methodology was conceived to improve local-scale stormwater management as exemplified by the Glenoaks project.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Hydrologic and hydraulic characteristics of selected SCMs used in the manuscript.

ACKNOWLEDGMENTS

This study was made possible by the assistance of many employees of the City of Los Angeles who contributed in various ways to the completion of this work.

LITERATURE CITED

- Beyerlein, D., 2012. Regional Difference in the Effectiveness of Low-Impact-Development Facilities. *Stormwater Journal* 10(1): 32-36.
- Chen, L., 2003. Real Coded Genetic Algorithm Optimization of Long Term Reservoir Operation. *Journal of the American Water Resources Association* 39(5):1157-1165.
- City of Los Angeles, 2009. La Recarga User's Manual. LA Sanitation, Los Angeles, California.
- City of Los Angeles, 2011. Development of Best Management Practices Handbook and Low Impact Development Manual. LA Sanitation, City of Los Angeles, California. http://www.lastormwater.org/wp-content/files_mf/lidhandbookfinal62212.pdf, accessed September 2013.
- Currier, B.K., J.M. Jones, and G.L. Moeller, 2004. NPDES Stormwater Cost Survey. California Water Resources Control Board, Office of Water Programs, Sacramento, California.
- Davis, A.P., 2005. Green Engineering Principles Promote Low-Impact Development. *Environmental Science & Technology* 39(16):338-344.
- Garousi-Nejad, I., O. Bozord Haddad, H.A. Loáiciga, and M.A. Mariño, 2016. Application of the Firefly Algorithm to the Optimal Operation of Reservoirs with the Purposes of Irrigation Supply and Hydropower Production. *Journal of Irrigation and Drainage Engineering* 142(10), [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0001064](https://doi.org/10.1061/(ASCE)IR.1943-4774.0001064).
- Holland, J.H., 1975. *Adaptation in Natural and Artificial Systems*. University of Michigan Press, Michigan.
- Houle, J.J., R.M. Roseen, T.P. Ballester, T.A. Puls, and J. Sherrard, 2013. Comparison of Maintenance Cost, Labor Demands, and System Performance for LID and Conventional Stormwater Management. *Journal of Environmental Engineering* 139(7):932-938.
- Kurkalova, L.A., 2015. Cost-Effective Placement of Best Management Practices in a Watershed: Lessons Learned from a Conservation Effects Assessment Project. *Journal of the American Water Works Association* 51(2):359-372.
- Lee, J.G., A. Selvakumar, K. Alvi, J. Riverson, J.X. Zhen, L. Shoemaker, and F. Lai, 2012. A Watershed-Scale Design and Optimization Model for Stormwater Best Management Practices. *Environmental Modelling & Software* 37(11):6-18.
- Limbrunner, J., R. Vogel, S. Chapra, and P. Kirshen, 2013. Classic Optimization Techniques Applied to Stormwater and Nonpoint Source Pollution Management at the Watershed Scale. *Journal of Water Resources Planning and Management* 139(5):486-491, [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000361](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000361).
- Liu, Y., R. Cibina, V.F. Braltsa, I. Chaubey, L.C. Bowling, and B.A. Engela, 2016. Optimal Selection and Placement of BMPs and LID Practices with a Rainfall-Runoff Model. *Environmental Modelling & Software* 80(6):281-296.
- Loáiciga, H.A., K.M. Sadeghi, S. Shivers, and S. Kharaghani, 2015. Stormwater Control Measures: Optimization Methods for Sizing and Selection. *Journal of Water Resources Planning and Management* 141(9), [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000503](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000503).
- Maringanti, C., I. Chaubey, and J. Popp, 2009. Development of Multiobjective Optimization Tool for the Selection and Placement of Best Management Practices for Nonpoint Sources Pollution Control. *Water Resources Research* 45(6), <https://doi.org/10.1029/2008WR007094>.
- McGarity, A., 2012. Storm-Water Investment Strategy Evaluation Model for Impaired Urban Watersheds. *Journal of Water Resources Planning and Management* 138(2), [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000157](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000157), 111-124.
- McGarity, A., 2013. Watershed Systems Analysis for Urban Storm-Water Management to Achieve Water Quality Goals. *Journal of Water Resources Planning and Management* 139(5), [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000280](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000280), 464-477.
- Sebt, A., M. Fuamba, and S. Bennis, 2016. Optimization Model for BMP Selection and Placement in a Combined Sewer. *Journal of Water Resources Planning and Management* 142(3), [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000620](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000620).
- Strecker, E.W., M.M. Quigley, B.R. Urbonas, J.E. Jones, and J.K. Clary, 2001. Determining Urban Storm Water BMP Effectiveness. *Journal of Water Resources Planning and Management* 127(3):144-149.
- USEPA (U.S. Environmental Protection Agency), 1993. EPA Guidance Manual for Developing Best Management Practices. Report EPA 833-B-93-004, Washington, D.C.
- USEPA (U.S. Environmental Protection Agency), 2008. Stormwater Management Model. User's Manual v. 5.0. Report EPA/600/R-05/040, National Risk Management Research Laboratory, Cincinnati, Ohio.
- USEPA (U.S. Environmental Protection Agency), 2009. SUSTAIN: A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality. Report EPA/600/R-09/09, Washington, D.C.
- Water Environment Research Federation, 2009. User's Guide to the BMP and LID Whole Life Cost Models Version 2.0. Alexandria, Virginia.
- Zhen, J.X. and S.L. Yu, 2004. Optimal Location and Sizing of Stormwater Basins at the Watershed Scale. *Journal of Water Resources Planning and Management* 130(4):339-347.