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Stormwater Control Measures: Optimization Methods for Sizing and Selection

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Abstract: Stormwater management in urban areas remains a challenging water-resources and environmental problem worldwide. This work develops and tests two methods for optimizing stormwater control measures. The first method relies on a linear programming formulation to find the optimal sizes of stormwater control measures to be deployed at selected locations. The second method uses binary linear integer programming to determine the optimal type of stormwater control measures of standardized dimensions to be deployed at selected locations. Both methods minimize the total cost of deploying stormwater control measures, subject to constraints on available budget, volumetric water balance, allowable stormwater volumes, and water-quality characteristics. Two examples illustrate the step-by-step formulation of the linear programming and the binary linear integer programming methods for the optimization of stormwater control measures, and provide solutions to the problems of their optimal sizing and selection. Our results demonstrate the feasibility of meeting stormwater retention and water-quality objectives by the optimal deployment of stormwater control measures as proposed in this work. **DOI: 10.1061/(ASCE)WR.1943-5452.0000503.** © *2015 American Society of Civil Engineers.*

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Introduction

Stormwater (or storm runoff) is a major source of water-quality degradation [United States Environmental Protection Agency (USEPA) 2003; Shaver et al. 2007] and poses flood hazards in urban areas (Damodaram and Zechman 2013). Stormwater discharges into rivers, lakes, wetlands, and seas, and may recharge aquifers degrading water quality and hindering their natural and socioeconomic functions (Larsen et al. 1998; Loáiciga and Leipnik 2005; Walsh et al. 2005). Several common deleterious physical-chemical-biological characteristics of stormwater are large sediment content, nutrients, microbial pathogens, oil and grease, metals, organics, pesticides, and gross pollutants (trash, debris, floatables) (California Stormwater Quality Association 2003; USEPA 2007). Local, state, and federal agencies in the United States regulate stormwater quality through limits imposed on the total maximum daily loads (TMDLs) of pollutants reaching natural waters with urban stormwater. Because of the complexity of pollution sources, the number of pollutants, and the geographical distribution of pollutant loadings in urban areas, meeting those local, state, and federal regulations represents a permanent challenge for stormwater managers (Sample et al. 2001; Walsh et al. 2005; Shaver et al. 2007; USEPA 2010).

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Research and investment on stormwater management gained impetus in the United States after the 1972 enactment of the federal Clean Water Act (followed by several revisions thereafter, see Novotny and Olem 1994; Green 2007). This regulatory framework has given rise to an active industry of stormwater control and treatment technologies (City of Los Angeles 2011; Water Environment Research Foundation 2012). This paper refers generically to these technologies as stormwater control measures, or SCMs. SCM is herein used synonymously to the term best management practice, or BMP, which is commonly used in the technical literature. The term SCM embodies the name of its subject matter, that is, stormwater, thus its appeal and increasing acceptance (California Regional Water Quality Control Board 2014).

The effective investment in SCMs constitutes a resource allocation problem where scarce capital, land, and skilled labor are inputs to achieve costly flood control and water quality objectives (e.g., Kalman et al. 2000; Strecker et al. 2001; Sample et al. 2001; USEPA 2003; Zhen and Yu 2004; Lee et al. 2005; Liu et al. 2014). There are multiple SCMs and other management technologies (storm drains, treatment plants, reservoirs) available to control stormwater quantity and quality (City of Los Angeles 2009). Their deployment involves installation, operation, and maintenance costs (Urbonas 1995; Wong et al. 1997; Kalman et al. 2000; Sample et al. 2001; USEPA 2003; Currier et al. 2004; Lee et al. 2012). A large share of those costs stems from the number of SCMs and the geographic distribution needed to provide adequate coverage of the sources of multiple urban stormwater pollutants. The City of Los Angeles, California, for example, operates close to 50,000 SCMs over an area of $1,225\ \mathrm{km}^2$ that includes 24,000 km of streets. Behera et al. (2006) presented a probabilistic analysis of urban stormwater quality. A decision support system (DSS) for reducing pollutant loads and the cost of best management practices (BMPDSS) implementation in the Sun Valley watershed (California) was reported by Tetra Tech (2007). The BMPDSS relied on the simulation program LSPC, by Shen et al. (2004), for predicting pollutants' loads at selected locations of a watershed (see also, Ackerman et al. 2005). The USEPA's storm water management model (SWMM, USEPA 2008) is widely used for simulating stormwater quantity and quality in urban settings (Oraei Zare et al. 2012). The USEPA's SUSTAIN (System for Urban Stormwater Treatment and Analysis IntegratioN) Model has SCM siting and performance appraisal capabilities (USEPA 2009; Lee et al. 2012).

Several of the cited references dealing with SCMs applied simulation tools for predicting stormwater quantity and quality and assessing SCM performance, such as the SWMM (Oraei Zare et al. 2012), or SUSTAIN (Lee et al. 2012), or geographic information systems (GIS) coupled with decision support systems (DSS) (Sample et al. 2001). SCM performance has been commonly assessed in the pertinent literature by routing stormwater through SCM configurations and tracking its volume and quality along its downstream path. This paper links stormwater quality and quantity characteristics with SCM selection and sizing within an optimization approach that considers: (1) SCM design characteristics (geometry and structure), (2) water retention and water throughput capabilities of SCMs, (3) SCM water-purification capacity, (4) the cost of SCM implementation, operation, and maintenance, (5) the hydrologic and soil characteristics of the areas covered by a network of SCMs, and (6) principles of low-impact development (LID, Davis 2005; Beyerlein 2012; Tillinghast et al. 2012) applied to stormwater management by focusing on water-retaining SCMS. The linking of themes (1) and (6) to obtain globally optimal SCMs using linear programing represents the research novelty of this paper. The contribution of this work to the practicing urban stormwater management community rests on presenting a sizing and selection tool for SCMs that meet stormwater quantity and control requirements incorporating the physical and economic parameters relevant to SCM implementation. This paper's methodology aims at providing a practical tool for stormwater practitioners with several goals in mind. First, the methodology captures the basic stormwater management objectives, that is, the control of stormwater quantity and quality. Second, the methodology relies on fundamental principles of conservation of mass, cost considerations, and generally available or developable data with which to construct the optimization problems. Last, the methodology can be implemented in ubiquitous, widely accessible, software that does not require specialized training in optimization theory by practitioners well versed with SCMs.

The methodology for SCM sizing and selection developed in this work focuses on LID SCMs, such as vegetated swales, infiltration trenches, percolation wells, porous pavement (green streets and parking lots), detention basins (dry ponds), and other stormwater management technologies that: (1) may retain a specified fraction of stormwater near its area of origin, and (2) reduce the concentrations of pollutants in stormwater passing through SCMs. The methodology applies to single-event storms of specified durations that produce known quantities of runoff and concentrations of stormwater pollutants at specified locations within urban areas. The single-event approach is commonly used in the United States. Storm events of specified return interval and duration, say, 24-h or 48-h durations, are commonly used to calculate stormwater quantity and quality in management operations (California Regional Water Quality Control Board 2014). The following sections present the methodology for SCM optimization and clarify its application with two examples.

General Considerations

Fig. 1 shows an area where stormwater is generated with key elements that enter into the SCM sizing and selection problem. There are $i = 1,2,3, \ldots, n$ sites identified as possible locations for the deployment of SCMs, one per site. There is a volume of stormwater

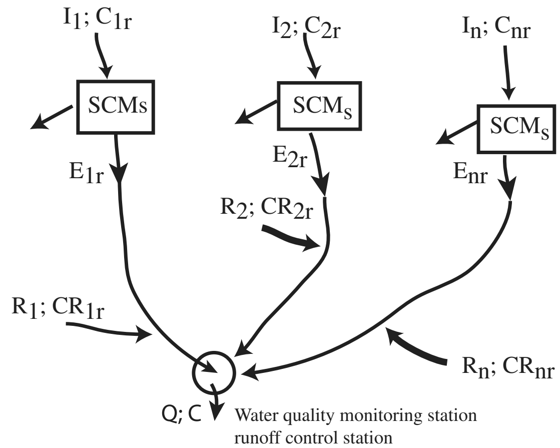

Fig. 1. Key components of the SCM optimization problem (in plan view)

I_i, $i = 1,2, \ldots, n$, arriving at each of the n SCM sites. The influent storm runoff contains R indicator pollutants with concentrations C_{ir}, $i = 1,2, \ldots, n$; $r = 1,2, \ldots, R$. At each site i there are $j = 1,2, \ldots, J$ possible SCMs to be installed, only one of which will be installed at each site. Part or all of the influent runoff goes through SCM j at site i, where some of it may be retained by the surrounding soil (V_{retained}), and the remainder may exit as flow-through volume with concentration E_{ijr}. If the influent stormwater (I_i) exceeds the capacity of a SCM to retain stormwater and pass flow through it, then a bypass volume is generated that joins the flow-through volume downstream from the SCM to form the effluent from the SCM. The volume of effluent from each SCM may be subject to regulatory maximum. It blends with unregulated storm runoff R_i, if any, originating between the SCM and the downstream location (monitoring station) where a TMDL or water-quality goal may be set by regulatory policy. There may be flood control regulations that impose maximum quantity of stormwater runoff at the monitoring station. The runoff R_i has concentration CR_{ir} of pollutant r. The concentration of the flow arriving at the monitoring station must be equal to or less than a specified TMDL or regulatory concentration goal.

Fig. 2 shows a schematic of a SCM and the various volumes of stormwater associated with it during the single-event (design) storm of specified duration. I is the volume of stormwater arriving at the SCM during the design storm with concentration C of a specific pollutant of interest. V_{through} denotes the volume of stormwater

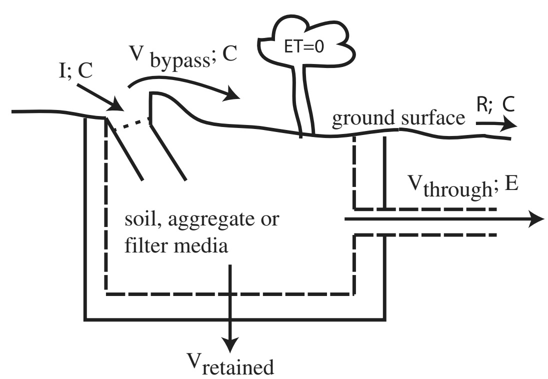

Fig. 2. Schematic of a typical SCM with stormwater volumes and concentrations

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that passes through the SCM during the design storm. This is called the flow-through volume, which exits from the SCM with a concentration E of the pollutant of interest. V_{retained} is the volume of water retained on site by the SCM during the design storm. This retained volume may be the result of percolation of captured stormwater by a SCM into the surrounding soil. At a minimum, it equals the internal water-holding capacity of a SCM, which fills up with stormwater during the design storm. V_{bypass} represents the volume of water that spills over the SCM, being neither retained nor passed through it, and has concentration C of the pollutant of interest. The evapotranspiration (ET) of any vegetation on a SCM is nil during the design storm.

In writing the water balance equation for a SCM as depicted in Fig. 2, it is assumed that its internal water-holding volume fills with water during the design storm. The equality of input volumes and output volumes dictates that

$$V_{\text{bypass}} = I - V_{\text{retained}} - V_{\text{through}} \tag{1}$$

Care must be taken to constrain the retained (V_{retained}) and flow-through (V_{through}) volumes so that their sum does not exceed the input volume of stormwater (I). The volume of water retained by SCM of type j on site i is expressed by the following formula:

$$V_{\text{retained},i,j} = a_{ij}K_{ij} + c_{ij} \tag{2}$$

$i = 1,2,3, \ldots, n$; $j = 1,2,3, \ldots, J$. The coefficients a_{ij} and c_{ij} are known characteristics of SCM j on site i; K_{ij}. denotes the unknown design dimension (or decision variable) of the SCM j on site i, which can be a length, or an area, or a volume, as elaborated upon below.

Some SCM, such as catch basins with filter media, are commonly not given credit for volume retention (Tetra Tech 2007). In this case, $a_{ij} = 0$, and $c_{ij} = 0$ in Eq. (2). SCMs that have considerable surface storage capacity and are underlain by low-permeability soils or impervious materials are covered by Eq. (2) by setting $a_{ij} = 1$ and $c_{ij} = 0$ with K_{ij} representing the unknown storage volume. Other SCMs retain stormwater on site predominantly by percolation through the surrounding, permeable, soils. In this case, the determination of the coefficients a_{ij} and c_{ij} requires the consideration of the SCM geometry, the hydraulic properties of the surrounding soil, and the duration of percolation (equal to the duration of the design storm). To illustrate, consider a SCM j on site i, as depicted in Fig. 2, and assume that the length and (unknown) width of its bottom surface are L_{ij} and W_{ij}, respectively. Stormwater percolates (vertically) during the duration of the design storm (Δt, typically 24 or 48 h) from the SCM through its bottom surface into the underlying soil, which has an infiltration capacity f. The volume of retained stormwater during the design storm equals

$$V_{\text{retained},i,j} = L_{ij} \cdot W_{ij} \cdot f \cdot \Delta t \tag{3}$$

so that $a_{ij} = L_{ij} f \Delta t$, $c_{ij} = 0$, and $K_{ij} = W_{ij}$ (the decision or design variable). Some SCMs, such as percolation wells, retain water by percolation to the soil surrounding its side and bottom surfaces. The analysis leading to their volume of retention is similar to that presented above after modification to account by the changed geometry of the percolation surface. Details of the volume-retaining equations for various SCMs can be found in Loáiciga (2014).

The flow-through volume in the j-th SCM j on site i is assumed to equal the release of a linear reservoir with effective storage V_{ij}. The linear release model is the most widely used among hydrologic/hydraulic release models for water-storage bodies (Amorocho 1973), and adopted for subsurface layers in popular hydrologic models such as the Hydrologic Modeling System (HMS, U.S. Corps of Engineers 2000). Therefore

$$V_{\text{through},i,j} = r_{ij} \cdot V_{ij} \cdot \Delta t \tag{4}$$

in which r_{ij} = release coefficient (units of 1/time), which must be determined experimentally, and Δt = duration of the design storm. The flow-through volume in Eq. (4) for SCM j on site i is rewritten as follows:

$$V_{\text{through},i,j} = b_{ij}K_{ij} + d_{ij} \tag{5}$$

The (known) coefficients b_{ij} and d_{ij} are characteristics of the SCM j on site i. To illustrate, consider a SCM j on site i, whose effective storage is V_{ij}. The linear release model states that the temporal rate of volume change ($= dV_{ij}/dt$) equals $r_{ij} \cdot V_{ij}$. Therefore, written in finite-difference form, the flow-through volume is given by Eq. (5), with $b_{ij} = r_{ij}\Delta t$, $K_{ij} = V_{ij}$, and $d_{ij} = 0$. If, for example, the depth (D_{ij}) of a SCM is the design (unknown) dimension (or decision variable), and its width (W_{ij}) and length (L_{ij}) are known, then $b_{ij} = r_{ij} \cdot W_{ij} \cdot L_{ij} \cdot \Delta t$, and $K_{ij} = D_{ij}$. In the case of percolation wells, the effective storage does not include the design variable (that is, the depth of the well), implying that $b_{ij} = 0$ and $d_{ij} = r_{ij}\Delta t V_{ij}$. Generally, the flow-through volume is minor compared with the retention and bypass volumes in SCMs that retain stormwater onsite. Further details about the calculation of the flow-through volume of SCMs are found in Loáiciga (2014).

The soil, aggregate, or filter media within a SCM reduces the concentration C_{ir} of the r-th pollutant in the input stormwater at the i-th site to a value E_{ijr} in the flow-through volume from the j-th SCM according to the following equation involving the treatment efficiency ξ_{ijr} $(0 < \xi_{ijr} < 1)$ of the SCM j on site i with respect to stormwater pollutant r:

$$\xi_{ijr} = \frac{C_{ir} - E_{ijr}}{C_{ir}} \tag{6}$$

where $i = 1,2, \ldots, n$; $j = 1,2, \ldots, J$; $r = 1,2, \ldots, R$; so that the concentration of pollutant r in the flow-through volume becomes

$$E_{ijr} = C_{ir} \cdot (1 - \xi_{ijr}) \tag{7}$$

The change in the concentration of the r-th pollutant as it moves through a SCM is quantified by mass balance of stormwater and pollutant. For example, the mass $M_{I,i,r}$ of pollutant r in the volume of stormwater I with concentration $C_{i,r}$ arriving at site i equals

$$M_{I,i,r} = I_i C_{ir} \tag{8}$$

where $i = 1, 2, \ldots, n$; $r = 1, 2, \ldots, R$. The mass of pollutant r leaving the SCM j on site i depends on the volume of stormwater retained, on the flow-through volume, and on the treatment efficiency of the SCMs, as shown in a subsequent section. Eqs. (1)–(8) are the building blocks of the SCM optimization procedures presented in the next two sections.

Linear Programming (LP) Method for Optimal SCM Sizing

Objective Function

The objective function of the LP method is to minimize the total cost of installing, operating, maintaining, and replacing SCMs at n sites. In this instance, the type (j) of SCM to be installed at each site i is predetermined. The sizes of all the SCMs at the n sites must be found optimally. The SCM to be installed at the i-th site has an unknown capacity K_i, $i = 1, 2, \ldots, n$, and a unit variable cost of SCM capacity equal to P_i. This unit cost is the sum of the unit initial installation cost and the unit operational, maintenance, and replacement (OMR) cost expressed as a present value. The various SCMs may have different unit costs and service lives. P_i is calculated by converting the streams of costs for each SCM to a present value using the same discount rate and the same period of analysis using standard engineering economic principles. The capacity of a SCM may be expressed in units of volume, or treatment area, or as a treatment length. Percolation (dry) wells, for instance, may have standardized cross-sectional areas, in which case the design variable is their depth of subsurface penetration. Other SCMs (say, infiltration trenches) may have two of their three dimensions (depth, width, length) standardized, and the third dimension unknown, in which case the unknown dimension becomes the decision variable. Some SCMs may be designed in terms of an area of treatment (such as porous pavement in parking lots). Detention ponds are commonly designed in terms of their storage capacity (say, in m^3). Consequently, the unit cost of SCM capacity (P_i), may be expressed in \$/volume, in \$/area, or as \$/length, to accommodate volumetric, areal, or longitudinal designs of SCMs, respectively, as the case might be.

The objective value of the LP method for SCM sizing is to minimize total cost of the SCMs at the n deployment sites

$$\text{Minimize } Z = \sum_{i=1}^{n} (P_i \cdot K_i + F_i) \tag{9}$$

in which the minimization is with respect to the unknown SCM capacities, or decision variables, K_i; F_i denotes a fixed, and known, cost associated with the i-th SCM that is independent of its size. The objective function in Eq. (9) may be subjected to various constraints, whose nature depends on the type of stormwater problem being addressed. The types of constraints that may arise are presented in general form next.

Capacity Constraints

The capacity of the SCM on site i may not exceed a maximum $K_{\max,i}$ and must have a minimum size $K_{\min,i}$

$$K_{\min,i} \leq K_i \leq K_{\max,i} \tag{10}$$

$i = 1,2, \ldots, n$. The maximum and minimum capacities must be specified by the analyst. Notice that there are n capacity constraints in Eq. (10), one for each SCM site.

Budgetary Constraint

The budgetary constraint, if applicable, states that the installation, operation, maintenance, and replacement cost of the n SCMs may not exceed a maximum available budget B. The budgetary constraint is as follows:

$$\sum_{i=1}^{n} (P_i \cdot K_i + F_i) \leq B \tag{11}$$

Feasibility Volumetric Constraints

It follows from mass balance that the volume of retained stormwater plus the volume of flow-through cannot exceed the volume of stormwater arriving at the SCM on site i

$$V_{\text{retained},i} + V_{\text{through},i} \leq I_i \tag{12}$$

$i = 1, 2, \ldots, n$. Dropping the sub-index j in Eq. (2), the volume of retained flow is expressed as follows:

$$V_{\text{retained},i} = a_i K_i + c_i \tag{13}$$

Likewise, the flow-through volume in Eq. (5) simplifies to the following expression once the j subindex is omitted:

$$V_{\text{through},i} = b_i K_i + d_i \tag{14}$$

Using Eqs. (13) and (14) in constraint Eq. (12) yields

$$(a_i + b_i) K_i \leq I_i - (c_i + d_i) \tag{15}$$

$i = 1, 2, \ldots, n$. The n volumetric constraints [Eq. (15)] are always required.

SCM-Specific, Performance-Volumetric Constraints

Many regulatory or permitting agencies limit the volume of stormwater (O_i) leaving site i. The SCM effluent O_i equals the sum of the bypass volume plus the flow-through volume at the SCM on site i. The bypass volume $V_{\text{bypass},i}$ at the SCM on site i equals the stormwater volume I_i minus the sum of the retained stormwater plus the flow-through volume

$$V_{\text{bypass},i} = I_i - [V_{\text{retained},i} + V_{\text{through},i}] \tag{16}$$

Using Eq. (13) for the retained volume and Eq. (14) for the flow-through volume in Eq. (16), the bypass volume is written as follows:

$$V_{\text{bypass},i} = I_i - [K_i(a_i + b_i) + c_i + d_i] \tag{17}$$

$i = 1,2, \ldots, n$. The bypass volume is, by virtue of Eq. (12), nonnegative.

To obtain the volume of stormwater O_i immediately downstream from the SCM on site i one must add the bypass volume expressed by Eq. (17) to the flow-through volume in Eq. (14). The volume O_i is then

$$O_i = V_{\text{bypass},i} + V_{\text{through},i} = I_i - (K_i a_i + c_i) \tag{18}$$

The n site-specific, performance-volumetric constraints specify that O_i may not exceed $O_{\max,i}$, where the latter is the maximum value that the SCM effluent O_i may take at site i. The constraints are expressible as follows:

$$K_i a_i \geq I_i - O_{\max,i} - c_i \tag{19}$$

$i = 1,2, \ldots, n$. Constraints [Eq. (19)] are sometimes rewritten as requirements that the volume of stormwater retained at a site i be not less than a specified percentage of the incoming stormwater I_i. Constraints [Eq. (19)] may or may not be part of an LP sizing problem, depending on local regulations of stormwater volumes.

Constraints on Maximum Runoff at Arbitrary Locations

Referring to Fig. 1, the location of the monitoring station could also be a runoff control station. The volume of stormwater Q at that location may be regulated to not exceed a maximum value $Q_{\max}$. The flow Q equals the sum of the unregulated flows R_i plus the SCM effluents, O_i

$$Q = \sum_{i=1}^{n} R_i + \sum_{i=1}^{n} [I_i - (K_i a_i + c_i)] \tag{20}$$

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The volumetric constraint is written as follows:

$$\sum_{i=1}^{n} R_i + \sum_{i=1}^{n} [I_i - (K_i a_i + c_i)] \le Q_{\max} \tag{21}$$

Eq. (21) can be generalized to a situation where a set of unregulated flows identified by the index $s = 1,2, \ldots, n_R \le n$, and a set of SCM effluents identified by the index $i = 1,2, \ldots, n_O \le n$, converge at a common runoff control location v, $v = 1,2, \ldots, n_Q \le n$, where the allowable volume of stormwater equals $Q_{\max,v}$. The corresponding constraints on maximum runoff are as follows, in standard linear programming (LP) format (with decision variables on the left-hand side of the constraint):

$$\sum_{i=1}^{n_O} K_i a_i \ge \sum_{s=1}^{n_R} R_s + \sum_{i=1}^{n_O} (I_i - c_i) - Q_{\max,v} \tag{22}$$

$v = 1,2, \ldots, n_Q$. Notice that Eq. (21) is a subcase of Eq. (22) with $n_Q = 1$, $n_O = n_R = n$. Constraints in Eq. (22) may or may not be part of the LP sizing problem depending on local regulations.

Water-Quality Constraints

The concentration C of the stormwater volume accruing at the monitoring station in Fig. 1 may not exceed a maximum value denoted by TMDL. The mass of pollutant r in the flow-through volume $K_i b_i + d_i$ on site i is

$$M_{\text{through},i,r} = (K_i b_i + d_i) \cdot E_{ir} \tag{23}$$

$i = 1,2, \ldots, n;\ \ r = 1,2, \ldots, R.$ E_{ir} is the concentration of pollutant in the flow-through volume that passes through SCM j at site i. It is given by Eq. (7) after the index j is suppressed in that equation

$$E_{ir} = C_{ir} \cdot (1 - \xi_{ir}) \tag{24}$$

In which ξ_{ir} represent the treatment efficiency of the SCM on site i with respect to pollutant r

$$\xi_{ir} = \frac{C_{ir} - E_{ir}}{C_{ir}} \tag{25}$$

The mass of pollutant r in the flow-through volume takes the following form after substituting Eq. (24) in Eq. (23):

$$M_{\text{through},i,r} = (K_i b_i + d_i) \cdot C_{ir} \cdot (1 - \xi_{ir}) \tag{26}$$

$i = 1,2, \ldots, n;\ r = 1,2, \ldots, R.$

The bypass volume $V_{\text{bypass},i}$ on site i [given by Eq. (16)] has concentration C_{ir} equal to that of the inflow volume I_i. Therefore, the mass of pollutant r in the bypass volume of the SCM on site i is

$$M_{\text{bypass},i,r} = \{I_i - [K_i \cdot (a_i + b_i) + c_i + d_i]\} \cdot C_{ir} \tag{27}$$

$i = 1,2, \ldots, n; r = 1,2, \ldots, R.$ The uncontrolled runoff R_i (if any) between site i and the TMDL control point (Fig. 1) carries a concentration of pollutant CR_{ir} in it and a mass of pollutant $M_{R,i,r}$ given by

$$M_{R,i,r} = R_i \cdot CR_{ir} \tag{28}$$

$i = 1,2, \ldots, n;\ r = 1,2, \ldots, R.$

The mass in Eq. (28) is added to those expressed in Eqs. (26) and (27) to give the mass M_{ir} of pollutant r arriving at the water-quality monitoring station from the SCM on site i and with the unregulated stormwater issuing between the same SCM and the monitoring station. The mass M_{ir} becomes, after algebraic simplifications

$$M_{ir} = R_i \cdot CR_{ir} + I_i \cdot C_{ir} - (K_i a_i + c_i) \cdot C_{ir} - (K_i b_i + d_i) \cdot C_{ir} \cdot \xi_{ir} \tag{29}$$

$i = 1,2, \ldots, n;\ r = 1,2, \ldots, R.$ It is convenient to consolidate separately in Eq. (29) the terms that involve the decision variables K_i and those that do not, as follows:

$$M_{ir} = S_{ir} - A_{ir} - K_i e_{ir} \tag{30}$$

in which:

$$S_{ir} = R_i CR_{ir} + I_i C_{ir} \tag{31}$$

$$A_{ir} = C_{ir} \cdot (c_i + d_i \xi_{ir}) \tag{32}$$

$$e_{ir} = C_{ir} \cdot (a_i + b_i \xi_{ir}) \tag{33}$$

$i = 1, 2, \ldots, n; r = 1, 2, \ldots, R.$ The total mass of pollutant r arriving at the downstream TMDL control point from all upstream sites $i = 1, 2, 3, \ldots, n$ is obtained by adding the masses M_{ir} in Eq. (29)

$$M_r = \sum_{i=1}^{n} M_{ir} = \sum_{i=1}^{n} [S_{ir} - (A_{ir} + K_i e_{ir})] \tag{34}$$

$r = 1,2, \ldots, R.$

The concentration of pollutant r in stormwater arriving at the TMDL control point equals the total mass M_r expressed by Eq. (34) divided by the total volume Q given by Eq. (20). The concentration must be equal to or less than the TMDL for pollutant r, or TMDL_r

$$\frac{M_r}{Q} \le \text{TMDL}_r \quad \text{or} \quad M_r \le Q \cdot \text{TMDL}_r \tag{35}$$

$r = 1,2,3, \ldots, R.$ Substituting Eqs. (20) and (34) into Eq. (35), and simplifying the resulting expression, produces the R water-quality constraints:

$$\sum_{i=1}^{n} K_i \cdot q_{ir} \le \sum_{i=1}^{n} (W_{ir} - v_{ir}) \tag{36}$$

$r = 1,2,3, \ldots, R$, in which:

$$q_{ir} = a_i \cdot \text{TMDL}_r - e_{ir} \tag{37}$$

$$v_{ir} = c_i \cdot \text{TMDL}_r - A_{ir} \tag{38}$$

$$W_{ir} = R_i \cdot (\text{TMDL}_r - CR_{ir}) + I_i \cdot (\text{TMDL}_r - C_{ir}) \tag{39}$$

The formulas for A_{ir} and e_{ir} are given in Eqs. (32) and (33), respectively.

The solution of the LP problem comprising Eq. (9) (the objective function), subject to capacity constraints [Eq. (10)], budgetary constraint [Eq. (11)], feasibility volumetric constraints [Eq. (15)], SCM-specific, performance volumetric constraints [Eq. (19)], constraints on maximum runoff at arbitrary locations [Eq. (22)], and water-quality constraints [Eq. (36)] would yield the optimal sizes of the SCMs that meet all the capacity, budgetary, volumetric, and water-quality constraints. The solution, if it exists, is assured to be a global optimum. Some constraints, such as the budgetary constraint, may not be necessary in some applications. Likewise, there may be cases in which water-quality constraints may not apply. In other instances, some of the volumetric constraints [such as Eq. (22)] may not be needed. Recall, however, that the feasiblity volumetric constraints [Eq. (15)] are always necessary to obtain correct results.

The next section describes an alternative optimization method that applies to situations in which the type of SCM to be deployed at site i is unknown, but the sizes of SCMs are known, say, by using standardized designs. This gives rise to a binary linear integer programming (BLIP) method for SCM selection.

Binary Linear Integer Programming (BLIP) Method for Optimal SCM Selection

The BLIP approach is pertinent when SCMs such as percolation wells, catch basins, infiltration basins, or other, are built following standardized designs at each site. In this case the SCM capacities K_{ij} are known. The unknown (decision) variables are denoted by x_{ij}, a binary integer variable that takes the value 1 when the j-th type of SCM is selected for deployment at the i-th site, and takes the value equal 0 when the j-th type of SCM is not selected for deployment at the i-th site. The problem then becomes one of choosing the best type of SCM at each site i.

Objective Function

The objective function minimizes the total cost of SCM deployment, in which F_{ij} is a fixed cost independent of the size of the SCM

$$\text{Minimize } Z = \sum_{i=1}^{n}\sum_{j=1}^{J} x_{ij} \cdot (P_{ij}^{*} + F_{ij}) \tag{40}$$

where

$$P_{ij}^{*} = P_{ij} \cdot K_{ij} \tag{41}$$

The SCM capacities K_{ij} are predetermined and conform to existing standards. The minimization in Eq. (40) is with respect to the binary, decision, variables x_{ij}.

One SCM per Site

The following constraints guarantee that only one SCM is installed per site:

$$\sum_{i=1}^{J} x_{ij} \leq 1 \tag{42}$$

$i = 1,2,3,\ldots,n$; and

$$\sum_{i=1}^{n}\sum_{j=1}^{J} x_{ij} \geq n \tag{43}$$

Capacity Constraint

Capacity constraints are satisfied by the standardized design of the SCMs.

Budgetary Constraint

The total expenditure (present value) on SCMs may not exceed the amount B

$$\sum_{i=1}^{n}\sum_{j=1}^{J} x_{ij} \cdot (P_{ij}^{*} + F_{ij}) \leq B \tag{44}$$

In some applications the budgetary constraint is not applied.

Feasibility Volumetric Constraints

These constraints require that the volume of stormwater retained plus the flow-through volume at the SCM on site i cannot exceed the available stormwater I_i [this generalizes Eq. (15)]:

$$\sum_{j=1}^{J} x_{ij} \cdot a_{ij}^{*} \leq I_i \tag{45}$$

$i = 1,2,\ldots,n$; in which:

$$a_{ij}^{*} = a_{ij}K_{ij} + c_{ij} + b_{ij}K_{ij} + d_{ij} \tag{46}$$

The feasibility volumetric constraints are always required.

SCM-Specific, Performance-Volumetric Constraints

These constraints set limits on the volume of stormwater leaving the i-th SCM site [generalizes Eq. (19)]

$$I_i - \sum_{j=1}^{J}(K_i a_i + c_i) \cdot x_{ij} \leq O_{\max,i} \tag{47}$$

$i = 1,2,\ldots,n$; Eq. (47) is rewritten in standard LP format

$$\sum_{j=1}^{J}(K_i a_i + c_i) \cdot x_{ij} \geq I_i - O_{\max,i} \tag{48}$$

$i = 1,2,\ldots,n$. Constraints [Eq. (48)] may or may not be part of the BLIP SCM selection problem, depending on local regulations on stormwater volume.

Constraints on Maximum Runoff at Specified Locations

These constraints are applicable when a set of unregulated flows R_s identified by the index $s = 1,2,\ldots,n_R \leq n$, and a set of SCM effluents O_i identified by the index $i = 1,2,\ldots,n_O \leq n$, coalesce at a common runoff control location v, $v = 1,2,\ldots,n_Q \leq n$, where the allowable volume of stormwater equals $Q_{\max,v}$. The corresponding constraints on maximum runoff are as follows [this generalizes Eq. (22)]:

$$\sum_{i=1}^{n_O}\left[\sum_{j=1}^{J}(K_{ij}a_{ij} + c_{ij}) \cdot x_{ij}\right] \geq \sum_{s=1}^{n_R} R_s + \sum_{i=1}^{n_O} I_i - Q_{\max,v} \tag{49}$$

$v = 1,2,\ldots,n_Q$. Constraints in Eq. (49) may or may not be part of the BLIP SCM selection problem, depending on local regulations on stormwater volume.

Water-Quality Constraints

These constraints do not allow the concentration of the r-pollutant to exceed the regulatory concentrations at the water-quality monitoring station. These equations are derived from the fundamental inequality that relates M_r, Q, and TMDL_r, which denote the total mass of pollutant r, the total volume of stormwater, and the regulatory concentration of pollutant r at the monitoring station, respectively [Eq. (35)]

$$M_r \leq Q \cdot \mathrm{TMDL}_r \tag{50}$$

$r = 1,2,3, \ldots, R$; in which the total volume Q of stormwater at the water-quality monitoring station is obtained by generalizing Eq. (20)

$$Q = \sum_{i=1}^{n} R_i + \sum_{i=1}^{n} \sum_{j=1}^{J} x_{ij} \cdot [I_i - (K_{ij} a_{ij} + c_{ij})] \tag{51}$$

The mass of pollutant r arriving at the water-quality monitoring station from the i-th site where the SCM j is installed and with the unregulated stormwater issuing between the same SCM site and the water-quality monitoring station equals

$$M_{ir} = M_{R,i,r} + \sum_{j=1}^{J} (M_{\mathrm{through},i,j,r} + M_{\mathrm{bypass},i,j,r}) \cdot x_{ij} \tag{52}$$

The mass of pollutant r in the flow-through volume is [this generalizes Eq. (26)]

$$M_{\mathrm{through},i,j,r} = (K_{ij} b_{ij} + d_{ij}) \cdot C_{ir} \cdot (1 - \xi_{ijr}) \tag{53}$$

The mass of pollutant r in the bypass volume equals [this is a generalization of Eq. (27)]

$$M_{\mathrm{bypass},i,j,r} = \{I_i - [K_{ij} \cdot (a_{ij} + b_{ij}) + c_{ij} + d_{ij}]\} \cdot C_{ir} \tag{54}$$

The total mass arriving at the water-quality monitoring station from all stream SCM sites and unregulated areas is obtained by summing M_{ir} in Eq. (52) over all i sites [generalizes Eq. (34)]

$$M_r = \sum_{i=1}^{n} M_{R,i,r} + \sum_{i=1}^{n} \left[\sum_{j=1}^{J} (M_{\mathrm{through},i,j,r} + M_{\mathrm{bypass},i,j,r}) \cdot x_{ij} \right] \tag{55}$$

The substitution of Eqs. (51) and (55) in Eq. (50), followed by algebraic simplification, yields the R water-quality constraints at the monitoring station

$$\sum_{i=1}^{n} \sum_{j=1}^{J} x_{ij} \cdot (K_{ij} \cdot q_{ijr} + v_{ijr}) \leq \sum_{i=1}^{n} W_{ir} \tag{56}$$

$r = 1,2,3, \ldots R$; in which

$$q_{ijr} = a_{ij} \cdot \mathrm{TMDL}_r - e_{ijr} \tag{57}$$

$$e_{ijr} = C_{ir} \cdot (a_{ij} + b_{ij} \xi_{ijr}) \tag{58}$$

$$\xi_{ijr} = \frac{C_{ir} - E_{ijr}}{C_{ir}} \tag{59}$$

$$v_{ijr} = c_{ij} \cdot \mathrm{TMDL}_r - A_{ijr} \tag{60}$$

$$A_{ijr} = C_{ir} \cdot (c_{ij} + d_{ij} \xi_{ijr}) \tag{61}$$

$$W_{ir} = R_i \cdot (\mathrm{TMDL}_r - CR_{ir}) + I_i \cdot (\mathrm{TMDL}_r - C_{ir}) \tag{62}$$

The solution of the BLIP objective function [Eq. (40)], subject to one-SCM-per-site constraints [Eqs. (42) and (43)], budgetary constraint [Eq. (44)], feasibility volumetric constraints [Eq. (45)], SCM-specific performance volumetric constraints [Eq. (48)], constraints [Eq. (49)] on maximum runoff at specified locations, and water quality constraints [Eq. (56)] would produce the optimal selection of SCMs at the n deployment sites. Some applications may not require all of the constraints. The feasibility volumetric constraints [Eq. (45)] are always necessary, however.

Example 1: LP Method for Optimal SCM Sizing

General Description

The first example illustrates the LP method for SCM sizing. Fig. 3 shows the plan view of an area 500 m long and 300 m wide where there are five sites where SCMs will be installed (thus, $i = 1, 2, 3, 4, 5$).

The SCMs in Fig. 3 are intended to capture stormwater and reduce TN (total nitrogen: ammonia, nitrate, particulate organic nitrogen, and soluble organic nitrogen) concentration in stormwater so that a TMDL of maximum 45 $\mathrm{g/m^3}$ is achieved at the control point downstream of the 500 × 300 m area. The concentration of TN in input stormwater at the SCMs and in unregulated stormwater equal $C_i = CR_i = 90\ \mathrm{g/m^3}$, $i = 1, 2, 3, 4, 5$. Site 1 is a section of a street where an infiltration trench SCM overlain by porous pavement will be placed. Sites 2 and 3, within a recreational area, will be occupied by vegetated swales with permeable granular soil. Sites 4 and 5 are dedicated to percolation wells downslope from the street transect and recreational areas. The SCMs will be designed for a rainfall event of 2.50 cm falling in $(\Delta t) = 48$ h. Approximately 60% of the area is impervious with a runoff coefficient $K = 1$, and 40% is pervious with a runoff coefficient $K = 0.5$. These conditions produce a runoff equal to 3,000 $\mathrm{m^3}$ within the area under study (calculated with a rainfall / runoff model). Table 1 shows SCM data.

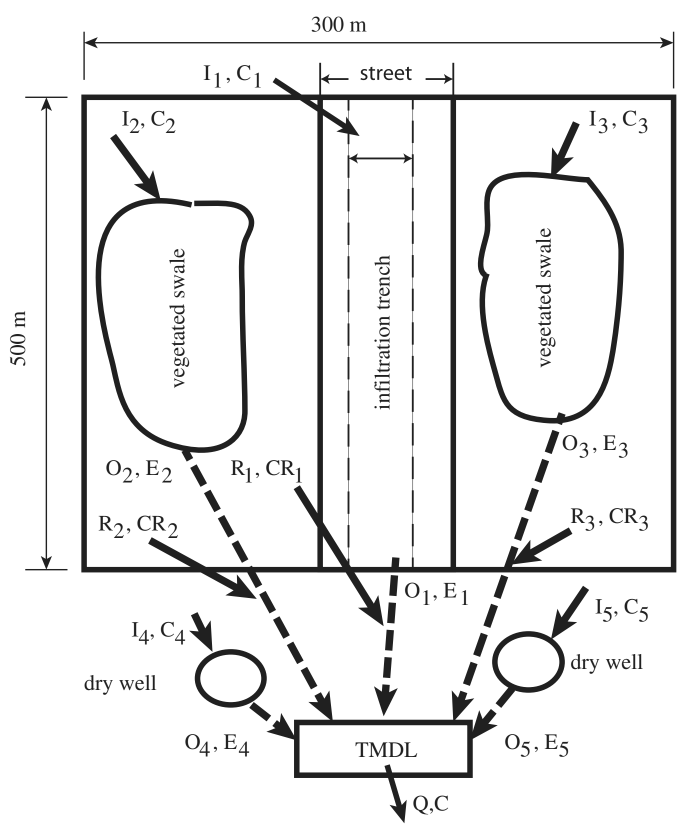

Fig. 3. Plan view of area for installation of SCMs (not drawn to scale)

Table 1. SCM Data

SCM	Variable cost (P_i) ($)	Fixed cost (F_i, $)	K_{max}	K_{min}	ξ
Infiltration trench:1 (500 long)	250,000/m	1,500	20 m (width)	3 m (width)	0.75
Vegetated swale: 2	800/m^2	1,800	10,000 m^2 (area)	1,000 m^2 (area)	0.85
Vegetated swale: 3	800/m^2	1,800	10,000 m^2 (area)	1,000 m^2 (area)	0.85
Percolation well: 4	1,570/m	4,600	20 m (depth)	10 m (depth)	0.70
Percolation well: 5	1,570/m	4,600	20 m (depth)	10 m (depth)	0.70

Note: ξ denotes the treatment efficiency of SCMs.

Runoff and concentration data are presented in Table 2. Note that volume retention is not an explicit objective in this example. Instead, the objective is to minimize the cost of SCM implementation and meeting water quality goals at the TMDL station.

Table 3 summarizes the retention (a_{ij}, c_{ij}) and flow-through coefficients (b_{ij}, d_{ij}) that enter in the volumetric balance of the SCMs considered in this example. The total budget for the SCM project is $4 million.

Results from the LP SCM Sizing Method

The data shown in Tables 1–3 were used in the LP sizing method for SCMs described by objective function Eq. (9), capacity constraints [Eq. (10)], budgetary constraint [Eq. (11)], feasibility volumetric constraints [Eq. (15)], and water-quality constraint [Eq. (36)]. The resulting LP problem was input as a spreadsheet and solved with the package Solver in Excel. Table 4 shows the optimized SCM sizes and other pertinent performance data.

Table 2. Runoff and Concentration Data for the SCM Sizing Problem

		Concentration	
Variable	Volume (m^3)	Symbol	g/m^3
I_1	381	C_1	90
I_2	1,219	C_2	90
I_3	1,219	C_3	90
I_4	50	C_4	90
I_5	50	C_5	90
R_1	31	CR_1	90
R_2	25	CR_2	90
R_3	25	CR_3	90
R_4	0	CR_4	90
R_5	0	CR_5	90
TMDL	—	C	45

Table 3. Values of the Volumetric Coefficients for the SCMs

SCM: number	a_{ij}	b_{ij}	c_{ij}	d_{ij}
Infiltration trench:1	61 m^2	50 m^2	0	0
Vegetated swale: 2	0.61 m	0.11 m	0	0
Vegetated swale: 3	0.61 m	0.11 m	0	0
Percolation well: 4	1.91 m^2	0	0.48 m^3	0.79 m^3
Percolation well: 5	1.91 m^2	0	0.48 m^3	0.79 m^3

Table 4. Optimized Results from the LP Method for Sizing SCMs

SCM	Optimal size	Cost ($)	$V_{retained}$ (m^3)
Infiltration trench:1	3 m (wide)	751,500	183
Vegetated swale: 2	1,693 m^2 (area)	1,356,244	1,033
Vegetated swale: 3	1,528 m^2 (area)	1,224,205	932
Percolation well: 4	20 m (deep)	360,000	39
Percolation well: 5	20 m (deep)	360,000	39
All SCMs	—	3,403,949	2,225

The value of the stormwater concentration at the monitoring control station equals C= 45 g/m^3, the maximum allowed. Notice that, in addition to meeting the water-quality objective, the SCMs capture 74% (or 2,225 m^3) of the total stormwater volume $I = 3{,}000$ m^3. The total of SCMs equals $3,403,949, less than the $4 million available budget.

Example 2: BLIP Method for SCM Selection

General Description

The BLIP method for SCM selection was applied to the selection of two types of SCMs: percolation wells and catch basins, to be deployed on the perimeter of a boulevard to meet stormwater-retention regulation, water-quality requirements, and a budgetary constraint. The storm-retention regulation is that the sum of the stormwater volumes retained by the SCMs must be at least 25% of the total stormwater input to the SCMs. The water-quality requirement states that the concentration C of stormwater runoff at the TMDL does not exceed 45 g/m^3 of total suspended solids (TSS). The available budget for SCM deployment equals $250,000. The design storm has depth of 5.0 cm falling in $\Delta t = 48$ h over a 100% impervious areas. The boulevard is 300 m long and 30 m wide, and the catchment area includes an additional 50×30 m upslope and downslope from the SCM-deployment area. This produces 600 m^3 of stormwater from the design storm, to which 15 m^3 of unregulated flow are added in this example. Fig. 4 shows a schematic of the geometric configuration of the study site. At each of the eight corners shown on Fig. 4 either a percolation well or a catch basin with filter media will be deployed to remove total suspended TSS from stormwater. Note that there are $i = 1, 2, 3, \ldots, n = 8$ sites in this example. In the following notation, x_{i1}, and x_{i2}, denote catch basin and percolation wells, respectively, that is, $j = 1$ for catch basins, and $j = 2$ for percolation wells. $x_{i1} = 0$ if a catch basin is not selected at the i-th site, and it equals 1 if it is selected at a site; $x_{i2} = 0$ if a percolation well is not selected at the i-th site, and it equals 1 if it is selected at a site.

The percolation wells and catch basins have standardized sizes in this instance resulting from site characteristics. The percolation wells have a diameter $\phi = 1$ m and length L = 15 m. The catch basins have width $W = 1.5$ m, effective depth $D = 2$ m, and length L = 3 m. Catch basins do not retain stormwater on site because their perimeter walls are built of impervious materials (Loáiciga 2014). Table 5 presents data on the SCMs. Table 6 contains data on stormwater volumes and concentrations.

Table 7 summarizes the volumetric data for the SCMs.

Results from the BLIP Method for SCM Selection

The BLIP problem consists in this instance on the objective function [Eq. (40)], which minimizes the cost of SCM implementation plus various constraints, subject to one-SCM-per site constraints

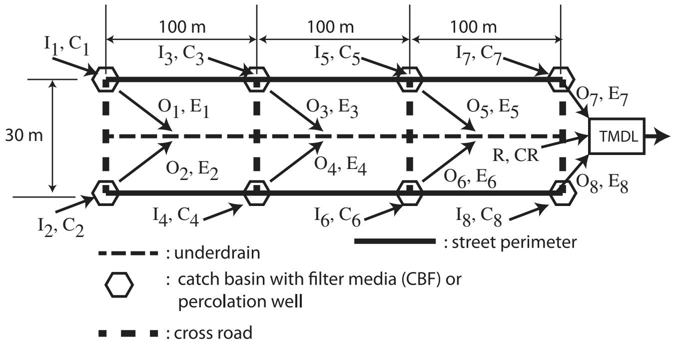

Fig. 4. Sketch of the boulevard and site locations for SCMs (plan view, not drawn to scale)

Table 5. SCM Data

SCM	Variable cost (P_i) ($)	Fixed cost (F_i, $)	Volume (K_{ij}, m^3)	v	ξ
Catch basins	1,900/m^3	900	9.0	0.50	0.95
Percolation wells	1,806/m	4,600	11.775	0.40	0.85

Note: ξ = treatment efficiency; v = porosity of fill material.

Table 6. Runoff and Concentration Data for the SCM Selection Problem

		Concentration	
Variable	Volume (m^3)	Symbol	g/m^3
$I_i, i = 1,2, \ldots, 8$	75	C_i	90
R	15	CR	90
TMDL for TSS	—	C	45

Table 7. Values of the Volumetric Coefficients for the SCMs

SCM	a_{ij}	b_{ij}	c_{ij}	d_{ij}	$V_{\text{retained},i,j}$	$V_{\text{through},i,j}$
Catch basins ($j = 1$)	0	4.8 m^2	0	0	0	43.2 m^3
Percolation wells ($j = 2$)	6.029 m^2	0	1.51 m^3	3.77 m^3	91.94 m^3	3.77 m^3

[Eqs. (42) and (43)], budgetary constraint [Eq. (44)], feasibility volumetric constraints [Eq. (45)], water-quality constraints [Eq. (56)], and the minimum stormwater-retention constraint (must retain at least 25% of the stormwater input equal to 600 m^3), which is written as follows:

$$\sum_{i=1}^{n=8}\sum_{j=1}^{J=2} x_{ij} \cdot V_{\text{retained},i,j} = \sum_{i=1}^{n=8}\sum_{j=1}^{J=2} x_{ij} \cdot (a_{ij}K_{ij} + c_{ij}) \geq 150 \text{ m}^3 \tag{63}$$

Constraint Eq. (63) is a variant of the constraint [Eq. (49)] on maximum runoff. In addition, the water-quality constraint [Eq. (56)], establishes that the TSS concentration C at the downstream TMDL site may not exceed 45 g/m^3. The solution of the BLIP problem so stated would produce the optimal selection of SCMs at the n deployment sites. The BLIP problem was coded as a spreadsheet input (with data from Tables 5–7) and solved with the package Solver in Excel.

The optimal solution is to install two percolation wells and six catch basins. Because: (1) the wells and catch basins are standardized, (2) the input of stormwater, and (3) the TSS concentrations are equal at each site and in the unregulated flow, the two percolation wells can be installed at any one of the eight possible sites, and the same holds true for the locations of the six catch basins, provided that only one SCM is installed at each site. Table 8 summarizes the performance characteristics of the optimized SCM network.

Table 8. Optimized Results from the BLIP Method for SCM Sizing

Criterion	Total cost ($)	V_{retained} (m^3)	Concentration C at TMDL point (g/m^3)
Optimized	171,388	184	37.2
Constraint	<250,000	>150	<45

The results of Table 8 indicate that the optimized selection of SCMs in this example meets the water-quality, water-retention, and budgetary constraints. Specifically, the TSS concentration at the TMDL control point equaled 37.2 g/m^3, below the maximum 45 g/m^3. The retained inflow equaled 30.7% of the total inflow, which exceeded the minimum target retention of 25%. Finally, optimized total cost of SCM implementation ($171,388) was much less than the available budget ($250,000).

Conclusion

Two optimization methods were developed and presented in this work: one for optimal sizing of SCMs, and the other for optimal selection of SCMs. The former relies on a linear programming (LP) formulation. The latter uses a binary (0,1) linear integer programming (BLIP) formulation. The two optimization methods minimize the total cost of SCM deployment while satisfying constraints on: (1) the total cost of deployment, (2) SCM capacities, (3) volumetric balance at SCM sites, (4) stormwater volumes at arbitrary sites, and (5) water quality at monitoring locations. The LP and BLIP methods are generic in their formulations and can be applied to various types of SCMs. An appealing trait of the LP and BLIP methods is that globally optimal solutions, if they exist, can be obtained with the Solver package in the ubiquitous software Excel.

This paper presented a methodology aimed at aiding stormwater practitioners with real-world problems. Our methodology is being successfully tested in the City of Los Angeles, which manages close to 50,000 SCMs for stormwater control in an urban area extending more than 1,225 km^2 with 28,000 km of streets. Two examples were presented in this paper to illustrate the application of the LP and BLIP methodologies. The two examples were successfully solved after a detailed step-by-step formulation, showing that our methodology can be implemented to size and select SCM to meet stormwater quantity and quality objectives. Further research will tackle the development of a general methodology to solve for the optimal size and type of SCMs at chosen deployment sites simultaneously, which requires the solution of a nonlinear programming problem.

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