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Physical-Economic Approach for Urban Stormwater Management: Applications in the City of Los Angeles, California

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ABSTRACT

Stormwater creates flood hazards and induces water quality deterioration in urban regions. The cumulative impacts of flood hazards posed by urban stormwater and its frequently degraded water quality are environmental concerns worldwide. This work introduces a nonlinear programming (NLP) method for the optimal selection and sizing of stormwater control measures (SCMs) in urban regions. The NLP method meets water-quantity and chemical balances, achieves cost effectiveness of stormwater control expenditures, considers the capacity of SCMs to capture and retain stormwater, and accounts for the pollutant removal efficiency of SCMs. The NLP method produces a selection of SCMs that meets stormwater management criteria effectively and compatibly with green engineering principles. Applications of this paper's methodology provides examples of SCM implementation in the City of Los Angeles, California.

INTRODUCTION

Stormwater Management and Relevant Literature

Urban stormwater is a major source of water-quality degradation in rivers, lakes, seas, wetlands, and aquifers, all of which serve natural and socioeconomic functions. The impairment of water quality in water bodies receiving urban storm runoff is chronic in metropolitan areas across the United States and elsewhere (Novotny and Olem, 1994; Wong et al., 1997; Hagekhalil et al., 2014). Urban stormwater exhibits deleterious physical-chemical-biological characteristics, large biochemical-oxygen-demand, oil and grease, water-borne pathogens, suspended and total dissolved solids, trash, heavy metals, pesticide and nutrient content that degrade the quality of receiving waters. An equally insidious threat posed by stormwater is that of urban flooding. Therefore, metropolitan flood protection planning commonly prescribes the deployment of SCMs that can capture some of the stormwater at development sites to the extent that soil permeability and other physical constraints permit it.

The flood hazard posed by stormwater and the degradation of water quality associated with urban stormwater stem from natural and anthropogenic processes.

Among the former processes are rainfall that may be affected by changing precipitation patterns amidst seasonal and inter-annual variability of storm intensity, and soils of low permeability that produce large runoff volume with or without human developments. Among the latter are expanding population and complex land use within urban areas that reduce pervious land, magnify runoff volume and its flooding threats, and increase pollutants loading into stormwater. Due to the deleterious impact that polluted stormwater has on receiving waters, State and federal regulations in the United States have been enacted to protect stormwater quality. One such tool are the allowed Total Maximum Daily Loads (TMDLs) of pollutants to natural waters from urban storm runoff. A TMDL establishes the maximum amount of a pollutant that a water body can receive and still meet water quality standards. TMDLs provide a useful framework for stormwater quality management and modelling in urban settings, as shown in this work. Regrettably, many TMDLs and other pollution discharge elimination requirements imposed on stormwater are at best infrequently met in many urban regions. The chronic non-compliance excises economic and environmental costs on regions across the United States and elsewhere. The concern about flood threats posed by urban stormwater has led to building-code regulations in municipalities nationwide and overseas that restrict the amount of stormwater generated at new or renovated development sites.

The body of technical publications in the field of stormwater quantity, stormwater quality management, impaired water quality, stormwater control measures (SCMs), TMDLs, and low impact developments (LIDs) is voluminous (Novotny and Olem, 1994; Wong et al., 1997; Grimm et al., 2008; Faustini et al., 2009; Davis 2005; Green 2007; Jefferies et al., 1999; City of Los Angeles 2009a and 2009b; Faucette 2010; USEPA 1997). The pace of activity and published knowledge rose dramatically in the United States following the enactment of the federal Clean Water Act in 1972 (followed by revisions of the Clean Water Act 1977, 1981, 1987) (Novotny and Olem, 1994; Wong et al., 1997; Beven 2004; Grimm et al., 2008; Faustini et al., 2009; Beyerlein, 2012). The Clean Water Act issued regulations to maintain the quality of the waters of the United States. One regulatory mechanism is through the setting of TMDLs, which, in turn, has given rise to a multi-billion-dollar industry of SCMs and treatment technologies nationwide and worldwide (Davis 2005; Green 2007). In this respect, the National Pollutant Discharge Elimination System (NPDES) (Clean Water Act, Section 402) has had considerable influence on the deployment of storm runoff management technologies. The NPDES requires that permits be obtained for point-source discharges to surface waters (including storm drains) under the jurisdiction of the Clean Water Act. State, county, and city regulations on stormwater volume and quality have proliferated in the United States over the last quarter century. These regulations apply to any development that affects the quantity and quality of local stormwater. They usually become part of building codes and constitute the first line of defense against stormwater quality pollution and urban flooding. 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 “stormwater” thus its appeal and increasing acceptance (California Regional Water Quality Control Board, 2014).

Capital spending in stormwater control technologies (structural or non-structural) is a classic resource allocation problem in which water-quality/quantity management targets must be met. There are multiple SCMs and other stormwater management technologies (storm drains, treatment plants, reservoirs, to cite a few) available to tackle urban stormwater quality and quantity management. At the same time, there are costs associated with implementing, maintaining, and replacing storm runoff management infrastructure. In addition, sources of pollutants are geographically distributed, and the number of deployed technologies must be such that (geographical) coverage is sufficient to capture, retain, and filter enough storm runoff and pollutants to meet TMDL targets (USEPA 2003, 2004, 2007) and to abate flood hazards. Urban areas in the United States commonly have separate stormwater and sewage collection systems. Sewage discharge is directed to treatment facilities, whereas stormwater is commonly discharged untreated into nearby water bodies. There are many stormwater pollutants that impair urban water bodies. They adversely affect aquatic life, recreational use, and water supply and food sources for humans and wildlife alike. Stormwater pollutants have been grouped into various categories that distinguish their sources and impacts (Walsh et al., 2005; Kaye et al., 2006). The City of Los Angeles' Watershed Protection Division, for example, has identified stormwater pollutants of greatest concern in its local watersheds and these have been classified into several groups as follows (City of Los Angeles 2009b and 2009c): **Trash:** trash is a stormwater pollutant consisting of improperly discarded waste materials that can find its way to water bodies such as beaches, harbors, creeks, rivers and lakes. Its accumulation rate is measured in units of volume per unit area of land per unit time (say, cubic feet per acre per day, or cubic meter per acre per day); **bacteria:** bacterial pollution in stormwater is usually measured through indicator organisms, namely total and fecal coliform and enterococcus counts (a most probable number of organisms (MPN) per unit volume of water). Despite previous research devoted to this matter, the precise identification of sources of bacterial pollution remains work in progress; **heavy Metals:** several studies have tied heavy metals in stormwater primarily to vehicular circulation; **oil and grease:** this is a pollutant discharged by automated vehicles. It is detected in stormwater predominantly as petroleum-related oil; **pesticides:** pesticides applied in residential gardens and public parks constitute a major source of stormwater pollution; **nutrients:** the primary source of nutrients into local (City of Los Angeles, for example) water bodies are point sources emanating from sewage treatment plants, although the use of fertilizers in municipalities constitutes a source of nutrients (nitrogen) in stormwater.

The classification of stormwater pollutants by the City of Los Angeles into the previous groups reflects a complex set of conditions that exist within urban watersheds. One of those is a heterogeneous land use, which comprises transportation corridors, residential districts recreational areas, and business, commercial, and industrial districts. The degree and type of stormwater pollution is related to specific urban land uses, human activities, consumer products, and the physical characteristics of urban watersheds. The microbial pollution of recreational freshwater and the pollution of recreational coastal seawater by contaminated streams (Loáiciga and Leipnik, 2005) have been studied by several authors (Loáiciga, 2001), in addition to studies relating precipitation to runoff in human-impacted watersheds (Loáiciga, 2002; Loáiciga, 2008; McMichael et al., 2005).

Methods for monitoring stormwater quality and for the statistical analysis of the stationarity and trends in stormwater water-quality time series are found, among other sources, in publications by the American Society of Civil Engineers (ASCE, 2003; Loaiciga, 2009). Other pertinent research relates to the interactions between climate, aquifer characteristics, and topography that control the recharge to aquifers in permeable terrain (Loáiciga, 2005). The latter research is relevant to SCMs that rely on the subsurface as a retention reservoir for storm runoff. Automated advances in stormwater quality have materialized as decision support systems (DSS). Tetra Tech Inc. (Tetra Tech, 2007), for example, developed a DSS for reducing pollutant loads and cost of BMPs (BMPDSS) that was implemented in the Sun Valley watershed (southern California). The BMPDSS relied on pollutant-load simulation using the C++ program LSPC by Shen et al. (2004), which simulates pollutant loads in stormwater at selected locations of a watershed (see also, Ackerman et al., 2005). Other optimization schemes for selecting stormwater control technologies have been reported by Zhen and Yu, (2004) and Lee et al. (2005), among others.

A benefit/cost analysis of stormwater improvements was reported by Kalman et al. (2000). The cost estimates for storm runoff control technologies produced by Currier et al. (2005) shows low-range and high-range benefits from investment in stormwater quality improvement in the City of Los Angeles. The analysis shows that an $8 billion dollar investment (2005 value) would produce a present value of benefits that ranges from $46 billion to $178 billion (Currier et al 2005), discounting over a 30-year period. Currie et al. (2005) stated that enhanced urban aesthetics, ecosystem improvement, increase in property values, and groundwater savings are primary contributors to benefits to be realized from investments made to improve stormwater quality in the Los Angeles region. The implication this benefit/cost estimates for investment in stormwater management is important for the objectives of this paper. It shows that stormwater quality/quantity improvements may have a very attractive benefit/cost ratio. The City of Los Angeles and the surrounding region would benefit from new investment in stormwater control with fewer beach closures, cleaner communities, healthier ecosystems, lowered health risks, improved recreational opportunities, and lower demand for potable water. In recent years, California has endured drought. Stormwater has become a source of water recharge for improved surface water/groundwater resources utilization. Other potential benefits of investments on stormwater management in the City of Los Angeles cited in the Currier et al. (2005) study are: aesthetic value of a clean ocean after removal of all ocean impairments; improved ecosystem services in near-shore marine ecological services associated with impairments that would be avoided if urban runoff quality control improvements are implemented; additional water supply (value of water) that could be infiltrated; flood control damages would be lowered, and insurance premiums would decline; property value increases from investments in stormwater management

THE STUDY AREA AND OVERVIEW OF SCMS

The study area used in this paper lies within the boundaries of the City of Los Angeles, California. Figure 1 shows a map for the City boundaries, which has an area of 473 squared miles (1,225 km^2), and 17,400 miles of streets (28,000 km), with a population of about 4 million people. Los Angeles' storm drain system consists of 1,500 miles of pipes (2,414 km), 100 miles of open channel (161 km). There are four major watersheds in the City of Los Angeles (Ballona Creek, Dominguez Channel, Los Angeles River, Santa Monica Bay) shown in Figure 1.

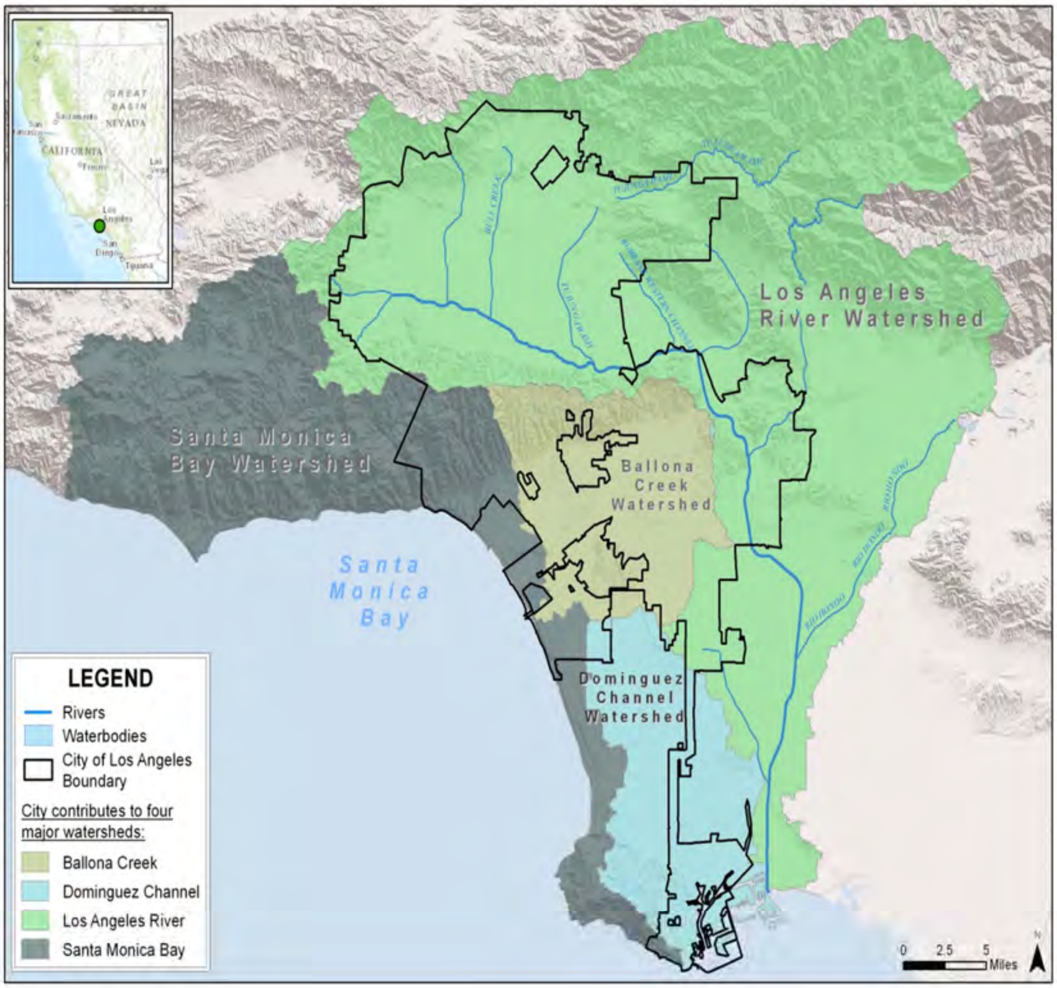


Figure 1. Boundaries of the City of Los Angeles.

The stormwater control system in Los Angeles includes about 38,000 screened catch basins and thousands of other SCMs. Its average daily dry weather and wet-weather runoffs are about 50 million gallons (189,250 m^3) and 350 billion gallons (1.325 billion m^3), respectively [LA Sanitation-City of Los Angeles data from 2013].

The City of Los Angeles has implemented many of the known types of SCMs and low-impact development (LID) stormwater control measures. It must also meet a variety of statutory TMDLs imposed on urban stormwater (Hoos, 1996). A peculiar phenomenon observed in the study area, that adversely impacts stormwater quality, is the "first flush" stormwater contamination (Larsen et al., 1998; Ma, 2002; Stenstrom and Kayhanian, 2005). This is the generation of large amounts of stormwater pollutants during the first few storms over urban areas following a dry period during the summer season. This first flush phenomenon is well established by historical stormwater-quality data from cities featuring a Mediterranean-like climate with dry summers and relatively wet winters found in the American west coast (City of Los Angeles 2009d and 2009e). Thus, an effective effort to diminish the pollution of receiving water bodies by heavily contaminated stormwater in such climatic regions must address first-flush impacts (Stenstrom and Kayhanian, 2005). One way to accomplish this is by deploying LID/SCMs that retain stormwater and its pollutants at the point of origin or through their pathways through urban areas (Davis, 2005). One effort to counter the first-flush pollutant loading was the development and implementation of the LA Recarga model by the City of Los Angeles (City of Los Angeles 2009d). The latter model simulates water and pollutant retention at SCMS by infiltration and deep percolation of stormwater at locations with suitable soil permeability and groundwater characteristics.

The principle of retaining stormwater pollutants at or near their point of origin is a theme pursued in this paper. SCMs that recharge stormwater into the subsurface have various advantages, among which are: (1) allowing stormwater infiltration and promote stormwater pollutant retention (pervious green streets, for example); and (2) increase the beneficial uses of receiving water bodies, reduce potential risks to human safety and health, preserve aquatic plant habitats, improve water quality, support water conservation, and recharge groundwater supplies. Figure 2 displays several SCMs that capture rainfall (cisterns) and retain (wholly or partly) stormwater at their points of origin. Green-street SCMs included permeable pavers, porous pavement, vegetated curb cuts, curb bump outs, and vegetated swales bordering streets. Infiltration trenches under streets, and percolation wells that capture stormwater moving through streets are part of the suite of green-street SCMs.

There are other types of SCMs that are used in conjunction with the water-retaining and filtration-type SCMs depicted in Figure 2. These include detention ponds, sedimentation basins, and screened catch basins. There are also preventive-type SCMs, such as street sweeping, that remove pollutants from streets prior to storm events. Non-structural SCMs included public education campaigns against littering, the excising of fines for dumping of polluting materials and trash, the placement of recycling bins and trash cans at locations with heavy public frequentation, and the offering of access by the public to recycling centers for disposal of toxic wastes or hazardous materials.

This paper presents a modelling approach to SCM selection and sizing, and a case study of SCM deployment within the City of Los Angeles, California. Our work relies on a dataset that includes records of rainfall, land use, soils, groundwater, streets and storm-conveyance infrastructure, non-point and point sources of pollution to stormwater, and green SCMs. The study's first objective is to provide a theoretical framework for the optimal selection and sizing of SCMs for urban stormwater quality and quantity management (or stormwater control). The second objective of this study is to provide examples of urban stormwater control in a cost-effective manner through optimal SCM deployment, extending the work of Loáiciga et al. (2014). The

SCM examples presented in this work are intended to: (1) provide a better understanding of SCM designs for green streets and alley elements; (2) promote the benefits of using green streets to manage stormwater, and improve (i) the quality of receiving water bodies, (ii) reduce potential risks for human safety and health, (iii) preserve aquatic habitats, and (iv) support water conservation and recharge groundwater.

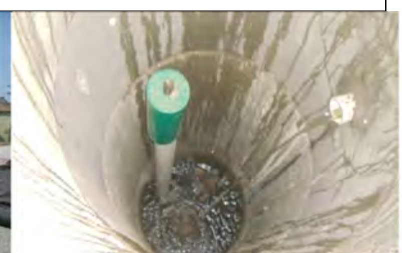
		
Grassy Swales / Vegetated Swales (Riverdale Ave Green Street, LA Sanitation Project – City of Los Angeles)	Curb Cuts (Flow-Through Planter Box on Hope St. and 11th St., Private Development Project in Downtown Los Angeles)	Porous Pavement (Los Angeles Zoo Parking Lot, LA Sanitation Project – City of Los Angeles)
		
Rain Cisterns / Rain Barrels (LA Sanitation Project – City of Los Angeles)	Infiltration Trench (Elmer Ave Green Street, LA Sanitation Project – City of Los Angeles)	Dry Wells (Glenoaks/Sunland Stormwater Infiltration, LA Sanitation Project – City of Los Angeles)

Figure 2. Several Stormwater Control Measures (SCMs) that capture rain and retain runoff) in City of Los Angeles.

Stormwater control is a perennial, resource-intensive task, involving institutional intervention and the input of capital, management, and labor to install, maintain, and replace SCMs. These authors have schematized in Figure 3 their view of the phases and institutional steps needed to achieve effective stormwater quality management using SCMs.

METHODOLOGY

Geographical/statistical vulnerability indices

The optimal allocation of SCMs in a large urban area such as the City of Los Angeles (1,225 km^2, population close to 4 million people) requires the analysis of multiple phenomena.

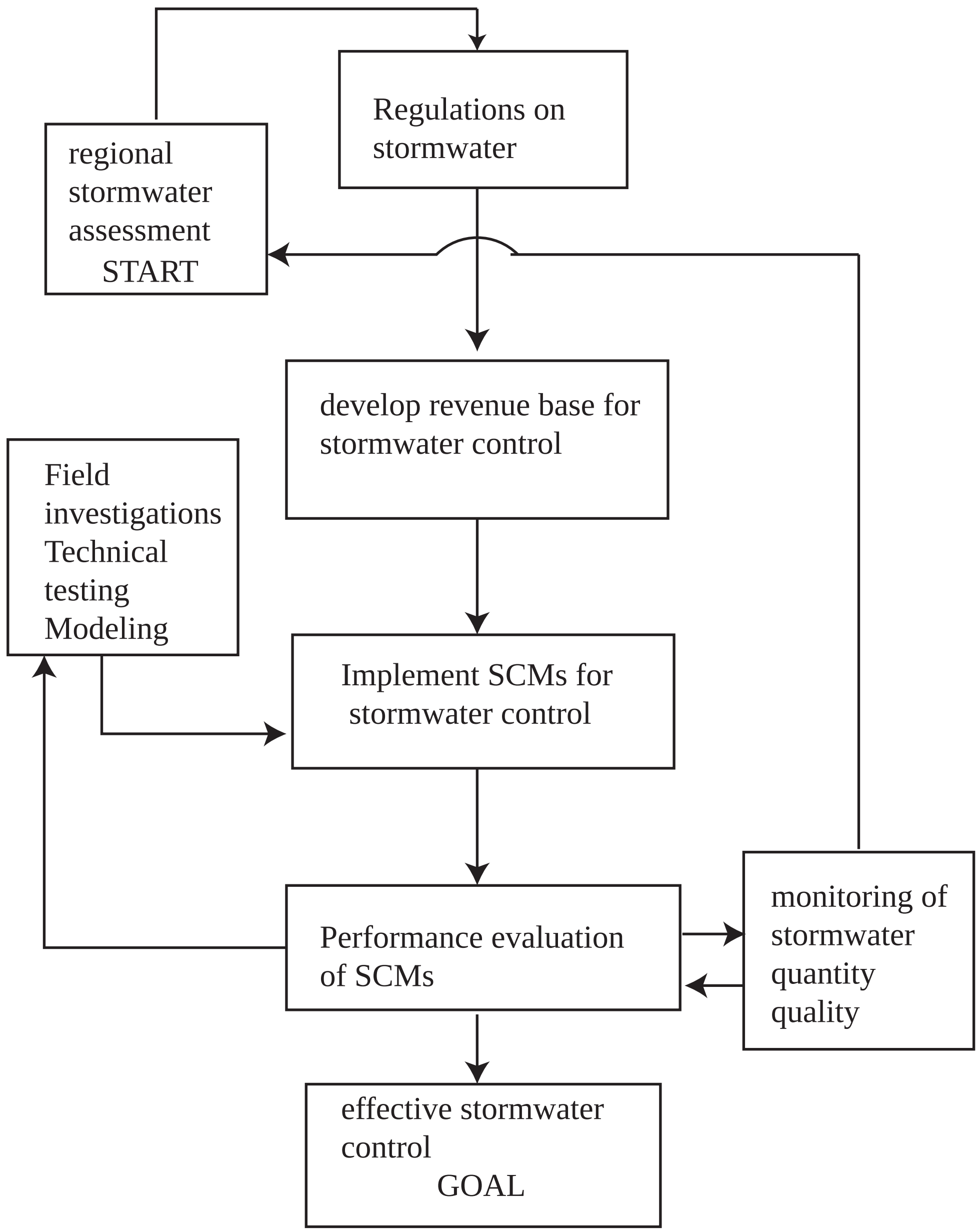


Figure 3. Key tasks necessary for successful implementation of SCMs.

Among these phenomena are watershed variables (rainfall, soils, topography, groundwater levels), land use, pollutants' sources and loading, and infrastructure (streets, storm drains) distribution. The stormwater analyst gains insightful information by determining the geographical distribution of stormwater pollutants loadings within an urban area. This produces the density of specific stormwater pollutants of interest (or indicator pollutants) expressed as a mass or volume of pollutant per unit surface area per unit time, or as a mass of pollutant per volume of runoff generated per unit time within an urban district. Trash accumulation within an urban district, for example, is expressed in cubic meters of trash per hectare per day (or in cubic yards or cubic feet of trash per acre per day). Hydrologic/environmental analysis within an urban area leads to the estimation of the runoff produced by rainfall design events or storm events and its associated concentrations of indicator pollutants in stormwater (say, dissolved total nitrogen in mg/L, or most probable number (MPN) of indicator microorganism per liter of stormwater). High demographic density and high road density per unit of land are commonly associated with high pollutant loading.

The ascertaining of pathways followed by pollutants carried in stormwater as it moves overland or through conveyance infrastructure through an urban area is essential to determining where to deploy SCMs. The size and type of SCM best suited for a specific location are determined by (i) the amount of runoff converging on the point of interest, (ii) the type of targeted pollutant and its concentration, (iii) site accessibility and physical conditions that may allow or disallow a type of SCM, (iv) cost of installation and maintenance of SCMs, and (iv) local ordinances and physical conditions that that may or may not permit certain types of SCMs to be deployed at a site. As an example, trash laden stormwater may be tackled by screened catch basins, but not by percolation wells. Or, microbially contaminated stormwater may call for the deployment of percolation wells that inject stormwater into permeable subsurface formations to be followed by biological decay underground. Critical to the selection of a percolation well or any other type of infiltrating SCM is the existence of a permeable substrate and a phreatic surface below the zone of stormwater injection.

Pollutant loading, stormwater generation by rainfall, runoff movement through an urban watershed, and land characteristics (topography, infiltration capacity of soils, groundwater depth) are all spatially distributed variables. They can be combined and displayed in map form as an index of vulnerability to stormwater quality degradation or flooding hazard. To construct such vulnerability index, this work proposes the production of digital thematic maps for a stormwater management study area of (i) soils, (ii) topography, (iii) land use (including types such as residential, commercial, industrial, parks, mixed use), (iv) rainfall depth for events of selected frequency and duration, (v) depth to groundwater, and (vi) pollution loads. The mapped thematic spatial variables are interpreted as geo-referenced random variables. Specifically, let soil infiltration capacity (= K*(x,y)), rainfall depth (P*(x,y)), land use and corresponding percentage impervious area A*(x,y), slope (S(x,y)), pollutant load L*(x,y) during an accumulation period, and depth to groundwater, D*(x,y), be random variable spatially indexed by coordinates x and y in a common geographic reference system. Each of the former random variables is normalized by a maximum value to obtain normalized (between 0 and 1) random variables, which we denote by the symbols A, D, K, L, P, and S, respectively. Probability density functions (pdfs) are then derived for Y = 1/K, A, S, L, P, and Z = 1/D using values of the chosen variables available from data sources. The stormwater quality vulnerability V(x,y) is defined as follows:

$$V(x,y) = A(x,y) \cdot L(x,y) \cdot S(x,y) \cdot P(x,y) \cdot Y(x,y) \cdot Z(x,y) \qquad (1)$$

In equation (1), the increase in any of the involved random variables on its right-hand side increases the vulnerability to stormwater quality degradation, and vice versa. The vulnerability index (1) ranges between 0 and 1. Knowing the pdfs of the variables on the right-hand side of (1) allows the derivation of the pdf of the vulnerability index V using statistical theory. Urban space is then classifiable according to the probability:

$$P[V(x,y) \leq v] = p \qquad (2)$$

Candidate non-overlapping categories for vulnerability index mapping could be $0 \leq p < 0.25$, $0.25 \leq p < 0.50$, $0.50 \leq p < 0.75$, $0.75 \leq p < 1.0$, each of these categories corresponding to a vulnerability index being low, medium, high, and very high, respectively. A color code scheme is assigned to the probability categories to prepare a color-coded vulnerability index map, as portrayed in Figure 4.

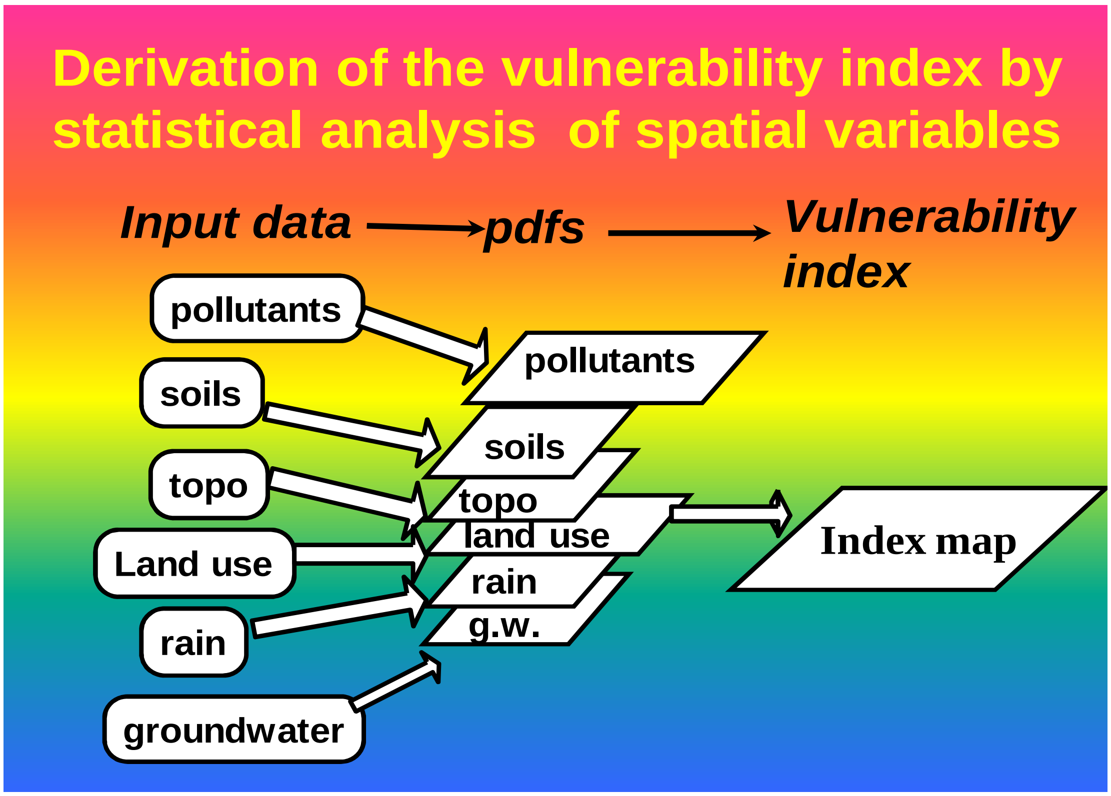


Figure 4. Processing of spatial random variables leading to a probabilistic index map of the vulnerability to stormwater quality degradation (pdfs: probability density functions; g.w.: groundwater.

A vulnerability index for flood risk associated with urban stormwater can be developed in a manner analogous to water-quality vulnerability index described by equations (1) and (2) by eliminating the variable L (pollutant loading) from the analysis.

Figure 5 shows a soils map for the Los Angeles area. The soils map also shows the saturated hydraulic conductivity in in/hr for each soil type.

Figure 6 shows a map of trash production rates within the boundaries of the City of Los Angeles.

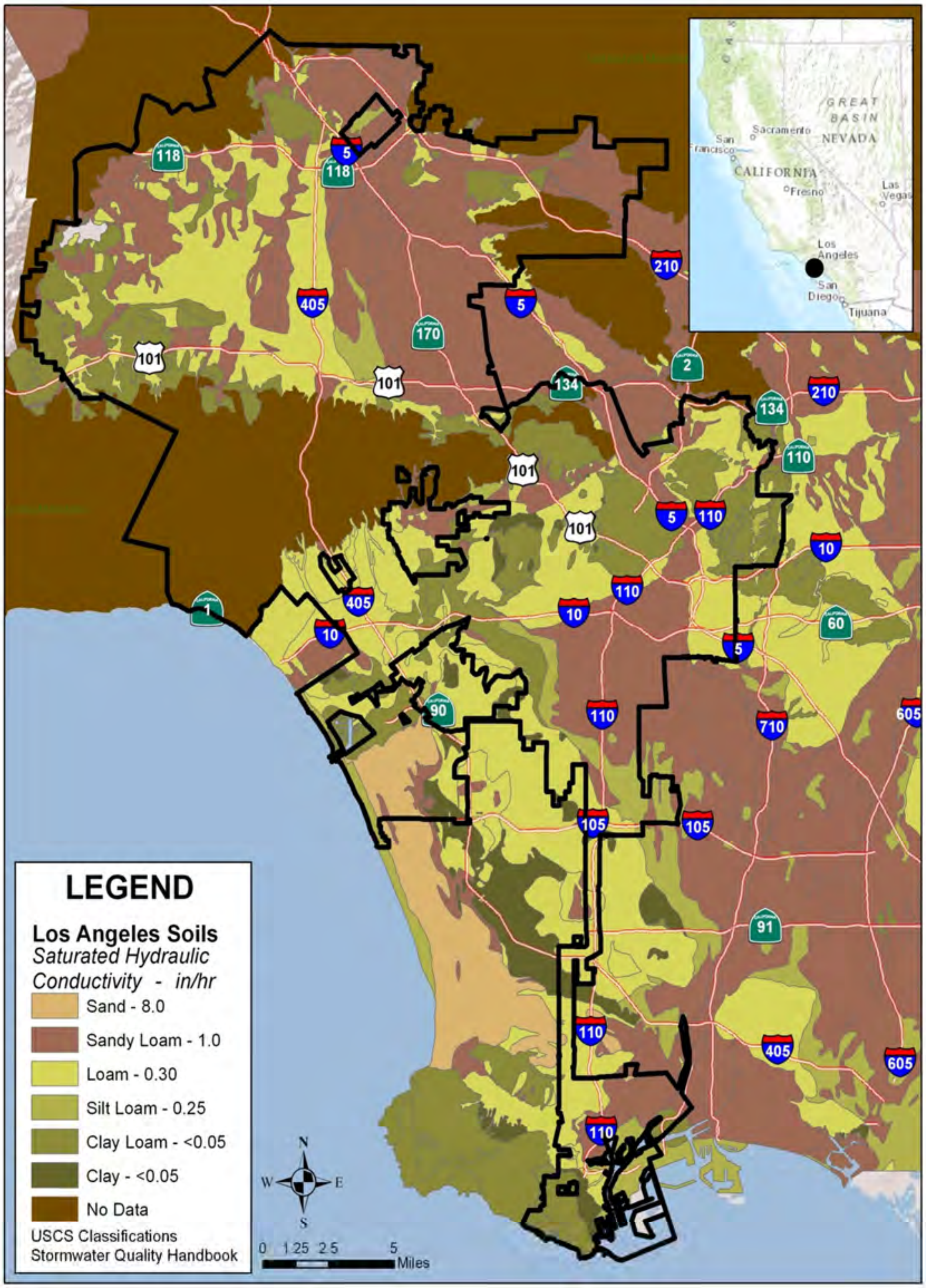


Figure 5. Soil classification map and values of saturated hydraulic conductivity for each soil type.

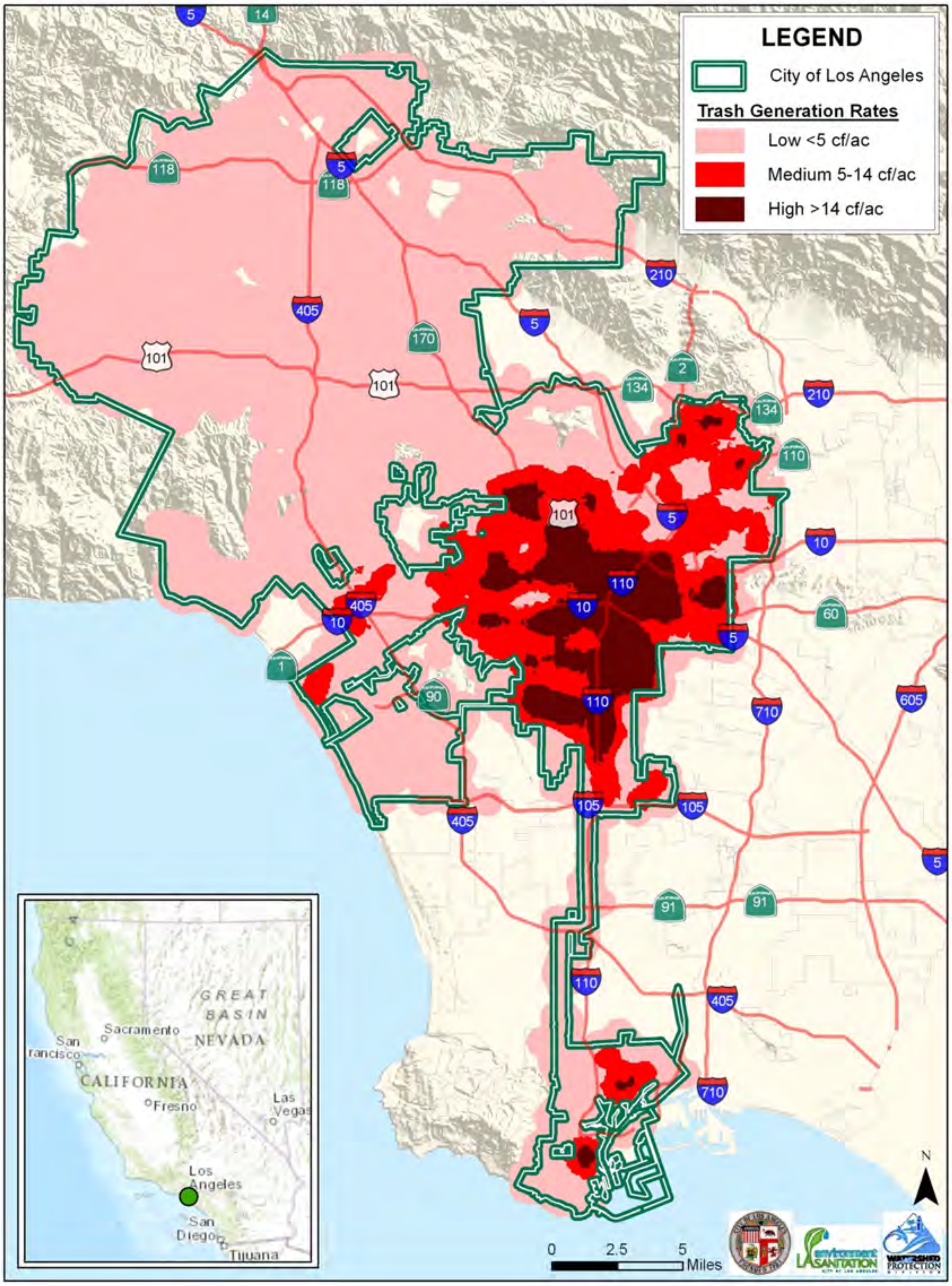


Figure 6. Trash accumulation rates in the City of Los Angeles region [Units of trash accumulation is in cubic feet per acre per day].

Notice that high trash accumulation rates occur in areas surrounding major highways and densely populated areas. Other spatially referenced data, such as rainfall distribution, topography, depth to the phreatic surface, miscellaneous pollutant loadings, streets and storm drain infrastructure are available from the Bureau of Sanitation of the City of Los Angeles. Notice in Figure 6 the high production of trash in areas surrounding major highways.

Optimal Selection and sizing of SCMs

Following the assessment of stormwater vulnerability using the geographical-statistical method of the precedent section or other suitable method, the selection and sizing of SCMs becomes a resource allocation problem. On the one hand, stormwater must meet quantity, TMDLs or other regulatory targets. On the other hand, there are finite resources to install, maintain, and replace SCMs. At the scale of stormwater control experienced in large cities, such as Los Angeles, stormwater management is a time-staged process. Areas most vulnerable to stormwater pollution are identified and prioritized. Next, the network of SCMs and other stormwater control infrastructure (detention and conveyance) is expanded over time until the entire urban area is covered. At the same time, local building codes and ordinances must prescribe onsite stormwater control and improvement guidelines for new developments, public or private, so that stormwater protection is ensured simultaneously with new growth. In addition, SCMs that retain and filter stormwater must be maintained regularly, sometimes after every major storm. One example of the former type of frequent-maintenance SCMs are screened catch basins that fill with trash. Another example is filtration media inside SCMs that become clogged with suspended solids, oil and grease, and bacterial growth.

Nonlinear programing (NLP) method for SCM Selection and Sizing

This section introduces a NLP method for SCM selection and sizing, extending the work of Loáiciga et al. (2014). The application of the NLP method presented in this section requires prior geographical, hydrologic, engineering, and environmental assessments to (i) prioritize areas where stormwater control is most pressing, (ii) identify what types of SCMs could function effectively at feasible installation locations, (iii) identify the indicator stormwater pollutants of greatest concern, (iv) establish unit costs and prototypical designs for SCMs.

A network of SCMs considered for deployment is depicted in Figure 7. There are i = 1, 2, 3, …, n sites identified as possible locations for the deployment of SCMs, one per site. There is storm runoff arriving at each of the n SCM sites with a volume I_i, i = 1, 2, …, n. The influent storm runoff contains R indicator pollutants with concentrations C_{ir}, i = 1, 2, …, n; r = 1, 2, …, R. At each site i there are j = 1, 2, …, J possible SCMs to be installed, only one of which will be installed at each site. Some of the volume of influent stormwater at SCM j on site i is retained (V_{Rij}) there, and some flows through the SCM and exits with a flow-through volume V_{Tij} and concentration E_{ijr}. Some of the influent stormwater may be bypassed (V_{Bij}) due to SCM 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, as well as on its water-quality characteristics. The sum of flow-through volume and retained volume blends with unregulated storm runoff R_i originating between the SCM at site

i and the downstream monitoring station where a water-quality or quantity requirement may be set by regulatory policy. The unregulated runoff R_i has concentration CU_{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 by be regulated there. The NLP method is developed to size SCMs for specified, single-event, design storms. These storms are usually 24 to 48 hours in duration and have associated depths of precipitation that are unique to the area where SCMs are deployed. The design-storm approach to SCM implementation is widely used in stormwater management (City of Los Angeles, 2011).

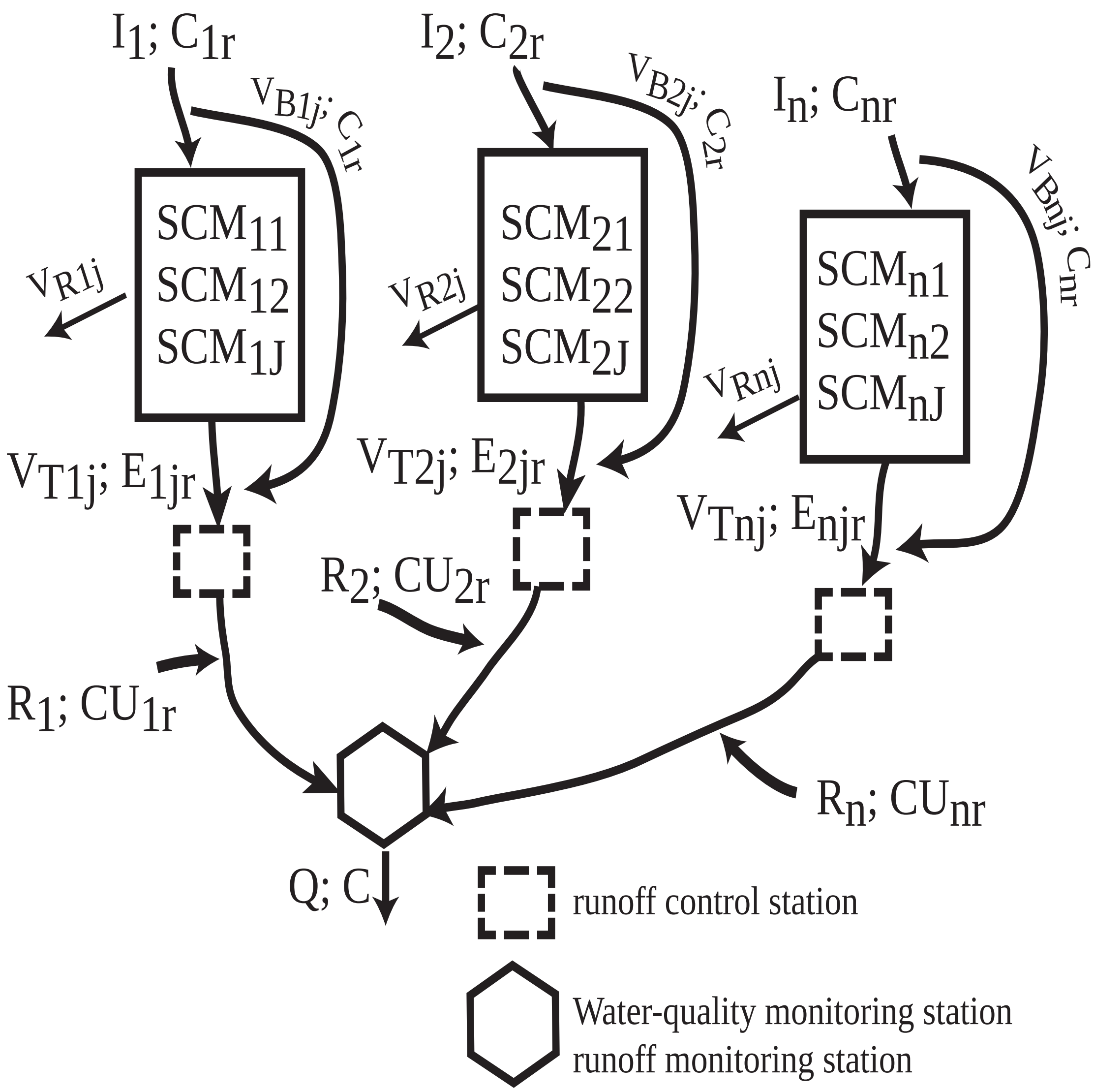


Figure 7. Schematic of SCMs configuration and other physical features. Plan view, not drawn to scale.

Figure 8 depicts a generic cross-section of a percolation well. Figure 8 shows the various volumes of stormwater that occur at SCM j on site i during the duration of a single-event storm. The diameter, column of water at full capacity, and depth of flow-through drain below the water level at full capacity are the dimensions of a percolation well, denoted by ϕ_{ij}, L_{ij}, and D_{ij}, respectively. Other SCM have various other geometric characteristics. I_i denotes the volume of stormwater arriving at the SCM with a concentration C_{ir}. V_{Tij} is the volume of stormwater that passes through the SCM, or flow-through volume, if any, with concentration E_{ijr}. V_{Rij} represents the volume of water retained on site by the SCM, if any. V_{Rij} may include percolation of captured stormwater into the surrounding soil, as shown in Figure 8. At a minimum, it equals the internal water-storing capacity of a SCM, which fills during the design storm. V_{Bij} denotes the volume of stormwater with concentration C_{ir} that bypasses the SCM, being neither passed through it nor retained on site. R_i and CU_{ir} denote the unregulated stormwater downstream of the SCM and its concentration, respectively. The fluxes shown on Figure 8 are instrumental in developing the NLP method described next.

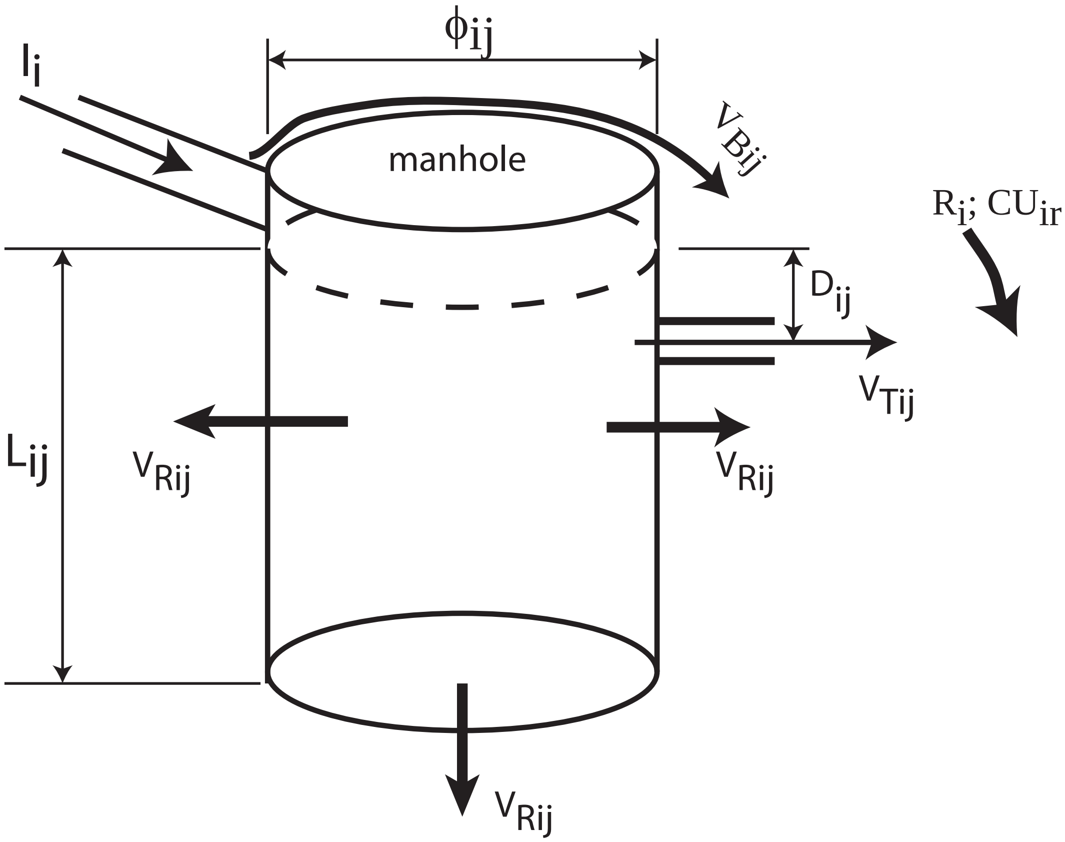


Figure 8. Percolation well and typical fluxes in SCMs. Not drawn to scale.

The objective function

The objective function of the NLP 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 j = 1, 2, …, J, at a site i = 1, 2, …, n has a to-be-determined design dimension K_{ij}, and a unit cost of SCM capacity P_{ij}. 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 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, infiltration trenches) 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 basins are a case in point, in which the unknown design variable is the volume of the SCM. Therefore, the unit cost P_{ij} 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_{ij} unrelated to the size of a SCM. The latter costs are present values in a manner analogous to the unit costs P_{ij}. A binary decision variable x_{ij}= 1 if SCM j is chosen at site i, or x_{ij}= 0 if the SCM j is not chosen at site i. There is one SCM at each possible deployment site. The possible sites i for SCM deployment are sites where storm runoff and water-quality constraints are imposed. The objective function of the NLP problem is the minimization of the total cost of SCM implementation, whose decision variables are the binary variables x_{ij} and the design (real-valued) variables K_{ij}:

$$Minimize\ Z = \sum_{i=1}^{n}\sum_{j=1}^{J}\left(P_{ij}\cdot K_{ij}\cdot x_{ij} + x_{ij}\cdot F_{ij}\right) \quad (3)$$

The objective function (3) of the NLP problem as written involves the product of the decision variables K_{ij} and x_{ij}. It is a nonlinear objective function involving binary variables.

Constraints of the NLP method

One SCM per site. Each site must have one SCM. This is accomplished by means of two constraints. The first one ensures that there is not more than one SCM per site:

$$\sum_{i=1}^{J} x_{ij} \leq 1 \qquad i = 1, 2, 3, \ldots, n \quad (4)$$

The second constraint ensures that there is at least one SCM at each site:

$$\sum_{i=1}^{n}\sum_{j=1}^{J} x_{ij} \geq n \quad (5)$$

Constraints (4) and (5) combined ensure that there will be exactly one SCM at each site.

Capacity constraints. The design variable of a SCM may not exceed a maximum K_{ijmax}, and must have a minimum size K_{ijmin}:

$$K_{ijmin} \leq K_{ij} \leq K_{ijmax} \qquad i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, J \quad (6)$$

The capacity constraints are always needed in the NLP method.

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

$$\sum_{i=1}^{n}\sum_{j=1}^{J}\left(P_{ij}\cdot K_{ij}\cdot x_{ij}+x_{ij}\cdot F_{ij}\right)\leq B \qquad (7)$$

The budgetary constraint may or may not be needed in a typical application depending on availability of funding for SCM implementation.

Volumetric constraints. The first set of volumetric constraints imposes feasibility of water balance at SCM j on site *i*. These constraints require that the volume of retained stormwater (V_{Rij}) plus the flow-through volume (V_{Tij}) must not exceed the volume of stormwater I_i arriving at site *i*. V_{Rij} equals the design variable of the SCM times a (known) retention factor a_{ij}, to which a constant c_{ij} is also added, or $V_{Rij}=a_{ij}\,K_{ij}+c_{ij}$ (see Loáiciga et al., 2004). The water-retention factor a_{ij} and constant a_{ij} are known characteristics of the SCM *j* at site *i*. The flow-through $V_{Tij}=b_{ij}\,K_{ij}\,+\,d_{ij}$. The (known) flow-through factor b_{ij} and constant d_{ij} are characteristics of the SCM *j* at site *i*. The set of volumetric feasibility constraints is written as follows:

$$\sum_{j=1}^{J}x_{ij}\cdot\left(a_{ij}K_{ij}+c_{ij}+b_{ij}K_{ij}+d_{ij}\right)\leq I_i \qquad i = 1, 2, \ldots, n \qquad (8)$$

The feasibility constraints (8) are always needed in the NLP method. The difference I_i – $[(a_{ij}+b_{ij})\,K_{ij}+c_{ij}+d_{ij}]$ equals the bypass volume V_{Bij}. 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_{ij} as follows (notice that the index *j* is summed out in the following equation):

$$V_{Bi}=\sum_{j=1}^{J}x_{ij}\cdot\left\{I_i-\left[\,K_{ij}\left(a_{ij}+b_{ij}\right)+c_{ij}+d_{ij}\right]\right\} \qquad i = 1, 2, \ldots, n \qquad (9)$$

The runoff O_{ij} immediately downstream from the SCM *j* at site *i* equals the sum of the bypass volume plus the flow-through volume. The effluent volume O_{ij} 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*, that may or may not be necessary depending on the application:

$$O_i=\sum_{j=1}^{J}x_{ij}\cdot\left[I_i-\left(K_{ij}\,a_{ij}+c_{ij}\right)\right]\leq Q_{imax} \qquad i=1,2,\ldots,n \qquad (10)$$

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:

$$Q=\sum_{i=1}^{n}R_i+\sum_{i=1}^{n}\sum_{j=1}^{J}x_{ij}\cdot\left[I_i-\left(K_{ij}\,a_{ij}+c_{ij}\right)\right] \qquad (11)$$

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):

$$Q=\sum_{i=1}^{n}R_i+\sum_{i=1}^{n}\sum_{j=1}^{J}x_{ij}\cdot\left[I_i-\left(K_{ij}\,a_{ij}+c_{ij}\right)\right]\leq Q_{max} \qquad (12)$$

Constraints (12) may or may not be required depending on the application.

Water-quality constraints. The mass of a pollutant *r* in storm runoff arriving at site i equals $M_{ir}=I_i\,C_{ir}$. The mass of pollutant r in the flow-through volume is $\left(K_{ij}b_{ij}+d_{ij}\right)\cdot E_{ijr}$. E_{ijr} is the concentration of pollutant *r* in the flow-through volume that passes through SCM *j* at site *i*. Part of the pollutant *r* is removed from flow-through by the SCM j at site *i* according to the following equation in which ξ_{ijr} is the pollutant *r* removal efficiency of SCM *j* at site *i* ($0\leq\xi_{ijr}\leq1$):

$$\xi_{ijr} = \frac{C_{ir} - E_{ijr}}{C_{ir}} \qquad i = 1, 2, \ldots, n; j = 1, 2, \ldots, J; r = 1, 2, \ldots, R \qquad (13)$$

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

$$E_{ijr} = C_{i,r} \cdot \left(1 - \xi_{ijr}\right) \qquad i = 1, 2, 3, \ldots, n; j = 1, 2, 3, \ldots, J; r = 1, 2, 3, \ldots, R \qquad (14)$$

The mass of pollutant r in the flow-through volume becomes: $Q_{ijr} = \left(K_{ij} b_{ij} + d_{ij}\right) \cdot E_{ijr} = \left(K_{ij} b_{ij} + d_{ij}\right) \cdot C_{ir} \cdot (1 - \xi_{ijr})$ (15)

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

The bypass volume V_{Bij} 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 $V_{Bij} \cdot C_{ir}$. Adding the masses of stormwater pollutant r carried by bypass, flow-through, and unregulated volumes yields the mass G_{ijr} of the pollutant arriving at the water-quality monitoring station from SCM j at site i and from the area between this SCM and the downstream water-quality monitoring station. The masses G_{ijr} are added over all SCM types j and all sites i to produce the total mass G_r of pollutant r arriving at the water-quality monitoring station from all upstream sites $i = 1, 2, 3, \ldots, n$:

$$G_r = \sum_{i=1}^{n} \left[S_{ir} - \sum_{j=1}^{J} x_{ij} \cdot \left(A_{ijr} + K_{ij}\, e_{ijr} \right) \right] \qquad (16)$$

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

in which:

$$S_{ir} = R_i\, CR_{ir} + I_i\, C_{ir} \qquad (17)$$

$$A_{ijr} = C_{ir} \cdot \left(c_{ij} + d_{ij}\, \xi_{ijr}\right) \qquad (18)$$

$$e_{ijr} = C_{ir} \cdot \left(a_{ij} + b_{ij}\, \xi_{ijr}\right) \qquad (19)$$

The concentration of pollutant r in stormwater arriving at the water-quality monitoring station equals the total mass G_r expressed by equation (16) divided by the total volume Q given by equation (11). The concentration must be equal to or less than the water-quality constraint for pollutant r:

$$G_r \leq Q \cdot TMDL_r \qquad r = 1, 2, 3, \ldots, R \qquad (20)$$

The R water-quality constraints (20) are explicitly defined after replacing Q with equation (11) and G_r with equation (16). The water quality constraints may or may not be needed depending on the particular application of SCM selection and sizing. However, if the water-quality constraints are not required in an application, then the stormwater-retention constraints (10) and/or (12) must be required to formulate a meaningful stormwater control problem. Conversely, if stormwater-retention constraints (10) and/or (12) are not required, then the water-quality constraints (20) must apply. In the most general case, the water-quality constraints and the stormwater-retention constraints are all required.

Summary of the NLP problem

The objective function is the minimization of SCM costs given by equation (3), whose decision variables are the binary variables x_{ij} and SCM design dimensions K_{ij}. The objective function is subject to one-SCM-per site constraints (equations (4) and (5), always required), SCM capacity constraints (equations (6), always required), budgetary constraint (equation (5)), may or may not be applicable), volumetric feasibility constraints (equations (6), always required), volumetric constraints immediately downstream of SCM sites (equations (10), may or not be applicable), maximum runoff constraint at the runoff monitoring station (equations (12), may or may not be applicable), and water quality constraints (equations (20), may or may not be applicable). Other constraints could be added to meet area-specific conditions.

APPLICATION OF THE NLP METHOD

Project characteristics

Figure 9 shows the general location of the Glenoaks stormwater capture project.

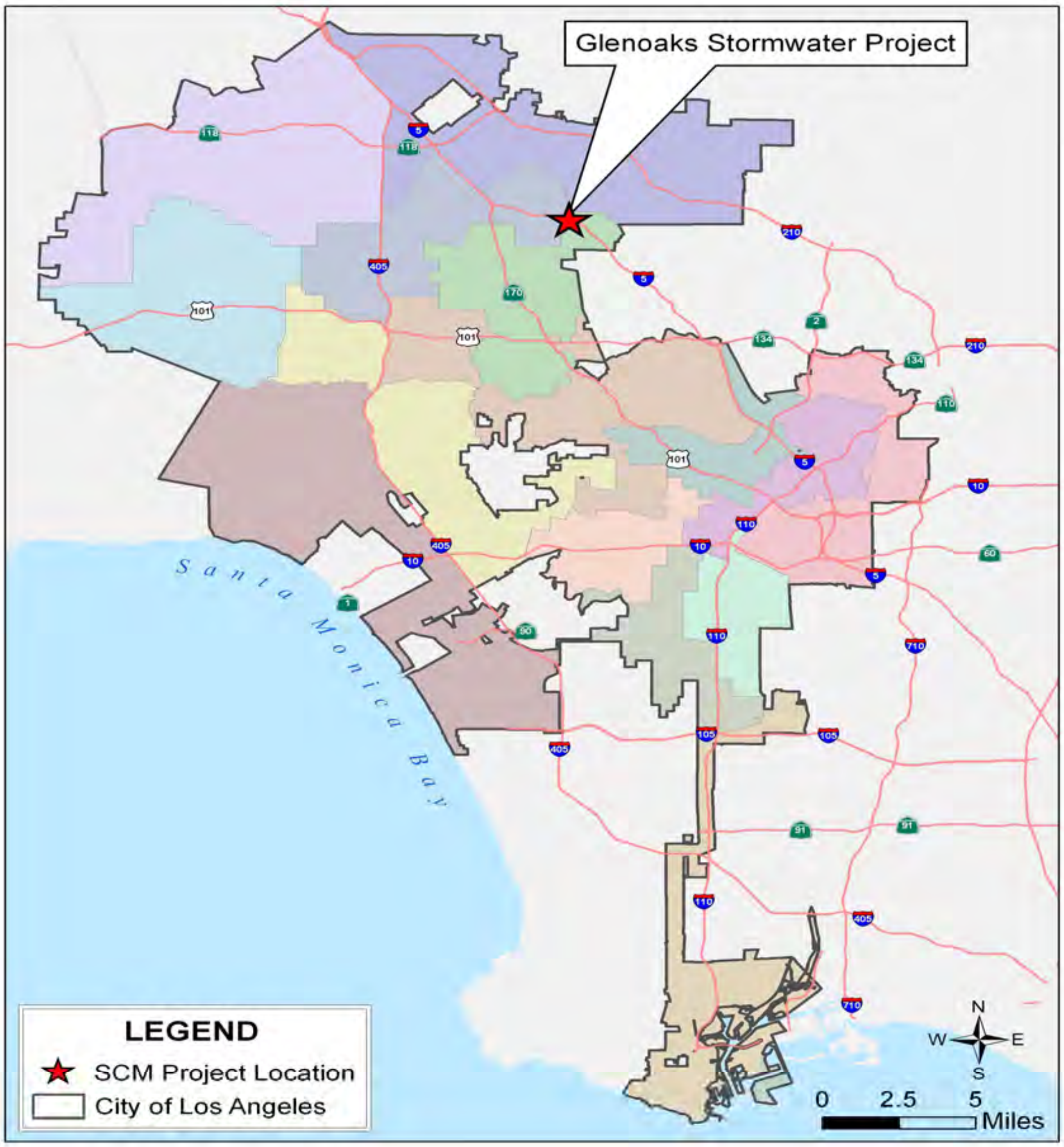


Figure 9. The LA Sanitation-City of Los Angeles Glenoaks stormwater capture project. Colored areas depict the 15 City Council districts within the City of Los Angeles.

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. Los Angeles' average daily dry weather and wet-weather runoffs are approximately 189,250 m^3 and 1.325 billion m^3, respectively(City of Los Angeles 2009C and 2011). The Glenoaks stormwater capture project covers a tributary drainage area equal to 122.21 ha (ha = hectare, 1 ha = 10,000 m^2). The 48-hour, design storm for stormwater management in the study area has a depth equal to 1.91 cm. The amount of runoff generated by the design storm in the study area equals 13,504 m^3. The soil underlying the project area is a sandy loam with infiltration rate equal to 0.0254 m/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 10 shows a map of the Glenoaks project. Most of the storm runoff generated within the project area flows southerly towards the Glenoaks and Sunland boulevards. Stormwater moves along the Glenoaks boulevard from its northwestern, upstream, end to its southeastern, downstream, end (from left to right on Figure 10).

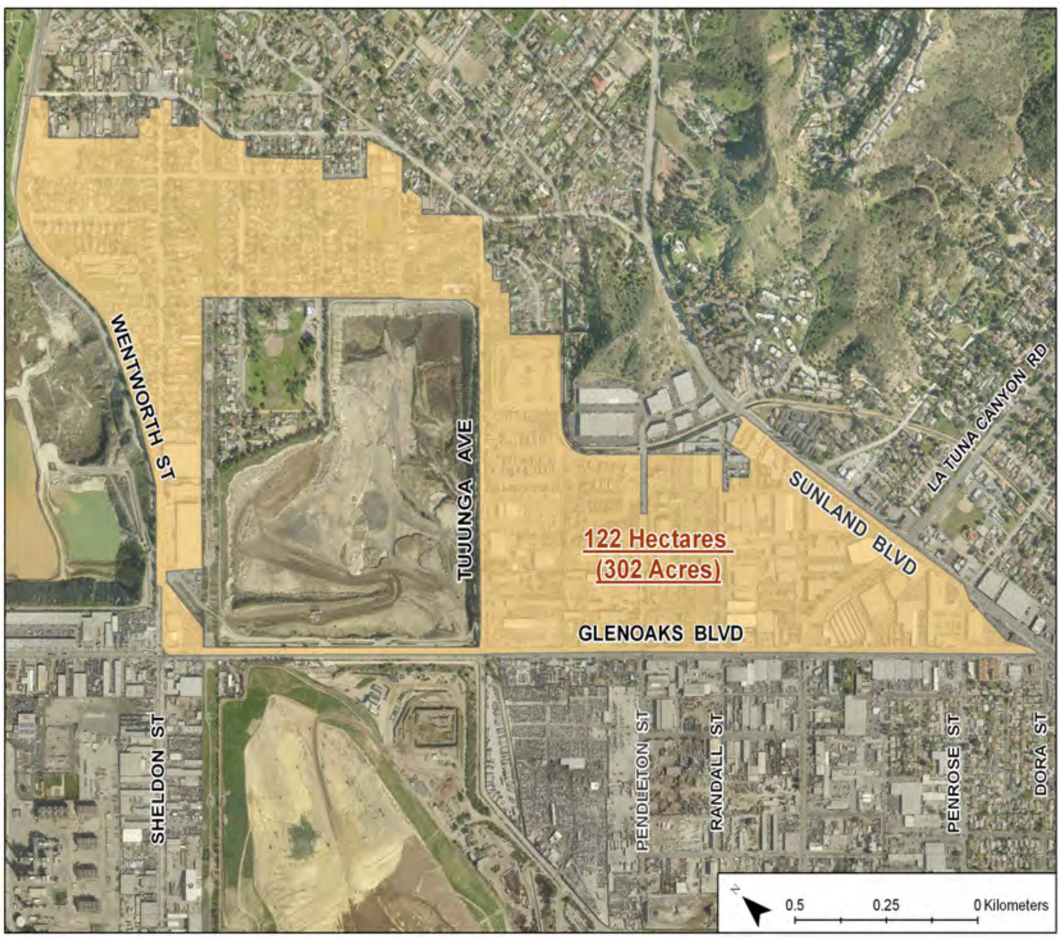


Figure 10. The Glenoaks stormwater drainage area (light-brown colored) and the Glenoaks boulevard.

The SCMs are intended for the Glenoaks boulevard. The length of the boulevard in the Glenoaks project is close to 2400 m. The potential SCMs considered for possible deployment in this example are: percolation wells (PW, on the curbs of the boulevard, one on each curb), grassy swales (GS, on the sidewalks next to the boulevard, one on each sidewalk), infiltration trenches (IT), and underground detention basins (DB). These SCMs, namely, PW, GS, IT, and DB, are assigned the index j = 1, 2, 3, and 4 respectively. For design purposes, the 2400 m Glenoaks boulevard is divided into eight 300-m long segments. Each 300-m segment is considered as a "site", therefore, i =1, 2, …, 8. Figure 11 shows schematic of typical grassy swales SCMs.

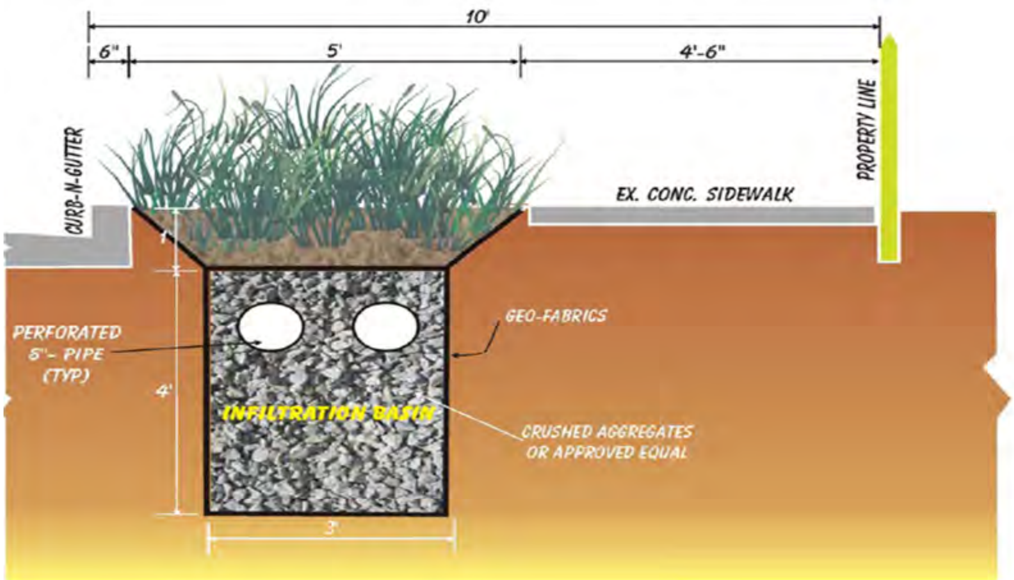


Figure 11. Vegetated infiltration swale and the vegetation grow on filter strips that retain fine particle that might clog the swale's pore space.

Figure 12 depicts the stormwater volumes (I_i = 1688 m^3) and suspended sediment concentrations (C_i = 100 g/m^3) accruing to each site on the Glenoaks boulevard, and the potential locations of the SCMs sites on or near the boulevard. Table 1 lists data on SCMs for the example. The data on Table 1 indicate that the SCM have standardized designs. Thus, the percolation wells 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 infiltration trenches are 300 m with depth of 1 m, their unknown dimension being their width. Each detention basin is 20 m long by 15 m wide, their unknown dimension being their depth.

Table 1. SCM Generic Data (ξ denotes the treatment efficiency of SCMs for suspended solids)

SCM	Total unit cost [(1)]	K_{max}	K_{min}	ξ
Percolation wells (PW, j=1)[(2)]	$ 1,610/ m	20 m (depth)	10 m (depth)	0.75
Grassy swales (GS, j=2)[(3)]	$ 231,586/m	2 m (width)	1 m (width)	0.85
Infiltration trench (IT, j=3)[(4)]	$ 139,800/m	4 m (width)	2 m (width)	0.85
Detention basin (DB, j=4)[(5)]	$ 349,500/m	8 m (depth)	4 m (depth)	0.75

[(1)]The sum of variable cost plus fixed cost equal to 10% of variable cost, per site; [(2)]well diameter = 1 m; [(3)]length = 300 m, depth = 0.46 m; [(4)]length = 300, depth = 1 m; [(5)]length = 20 m, width = 15 m. Each site may have 2 PWs or 2 GSs (reflected in their total unit cost), or either one IT or one DB.

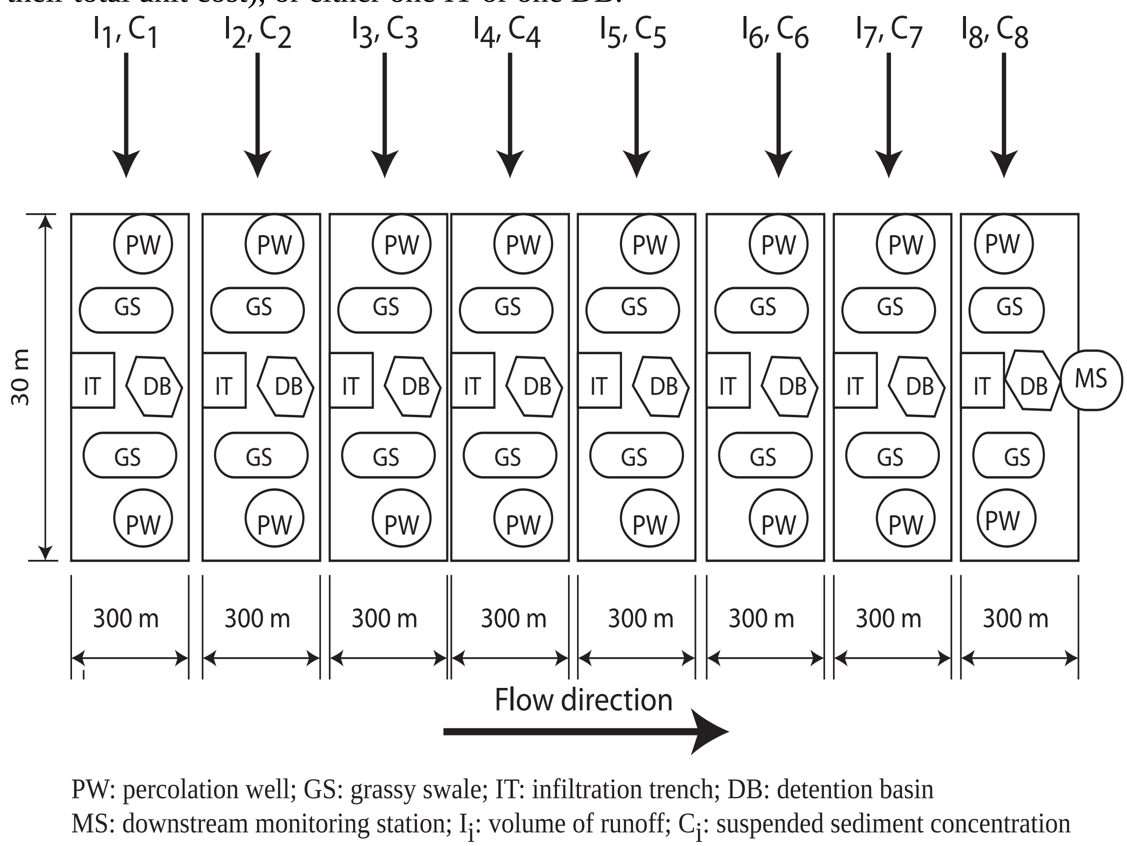


Figure 12. Schematic (not drawn to scale) of the Glenoaks boulevard with its 8 sites, each 300 m long, and possible SCMs to be deployed at each site.

Hydrologic and hydraulic properties of the SCMs

The retention coefficients of a SCM, a_{ij} and c_{ij}, and its flow-through coefficients, $b_{ij}$and d_{ij}, 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 hours in this case). The volume retention and flow-through coefficients for the SCMs considered in this work (percolation wells, grassy swales, infiltration trenches, and detention basins) are shown on Table 2.

Table 2. Hydrologic and Hydraulic Data for SCMS and Sites i = 1, 2, …, 8.

SCM	a_{ij} (m^2)	c_{ij} (m^3)	b_{ij} (m^2)	d_{ij} (m^3)	I_i (m^3)	C_i (g/m^3)
Percolation wells (PW)	7.66$^{(1)}$	1.92$^{(1)}$	0$^{(1)}$	30.2$^{(1)}$	1688	100
Grassy swales (GS)	732$^{(2)}$	0$^{(2)}$	110.4$^{(2)}$	0$^{(2)}$	1688	100
Infiltration trench (IT)	366	0	120	0	1688	100
Detention basin (DB)	300	0	0	1200	1688	100

$^{(1)}$2 PW per site; $^{(2)}$2 GS per site. R_i = 0 and $CU_i = 0$ for i = 1, 2, …, 8.

Implemented optimization model and constraints

The NLP method given by equations (3), (4), (5), (6), (7), (8), (12), and (20) was implemented with a maximum budget B = \$ 3.2 million (see budget constraint (7)). 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 x 13,504 = 10,128 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 $Q \leq 3376$ m^3 (see constraint (12)). The water quality constraint requires that the stormwater arriving at the downstream monitoring station must have a concentration of at most 50% 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.

Results and Discussion

The NLP method 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 optimal combination of SCMs is as follows: site 1: 2 percolation wells, 20 m deep each (1-m diameter by specification); sites 2 through 8: 2 grassy swales per site, each with width equal to 1.95 m (300 m long, 0.46 m deep, by specification). The optimal SCMs meet the capacity or size constraints (4), with maxima and minima given in Table 1. Recall that the depth of percolation wells may not exceed 20 m, and the width of grassy wells is limited to 2 m (see Table 1). The cost of the 2 percolation wells on site 1 amounts to \$ 32,200. These 2 wells retain 156 m^3. Each set of two grassy swales (per 300 m of boulevard) on sites 2 through 8 equaled \$ 451,593. Each set of grassy swales retained 1,428 m^3.

Overall performance variables are as follows: 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 m^3 (≅ 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/m^3, which is less than the maximum 50 g/m^3. Table 3 summarizes the results.

Table 3. Summary of SCM results.

Site number	SCM	Optimal dimension	Cost ($)	Volume retained (m^3)
i = 1	2 percolation wells	Diameter = 20 m	32,200	156
i = 2-8	2 grassy swales	Width = 1.95 m	3,161,151	9,996

The previous example has demonstrated the usefulness of the NLP in selecting and sizing SCMs. The selected and sized SCMs optimize cost and efficiency, and meet desired regulatory criteria. The NLP method selected SCMs that retain substantial amounts of stormwater by seepage into permeable soils. Equally important is the fact that the NLP method can be used to explore multiple configurations of SCMs and to conduct sensitivity analyses that explore the consequences of SCM selection and sizing such as costs, pollutant concentrations, treatment efficiencies, and other variables change.

OBSERVATIONAL STUDY

Observational data on SCM performance were gathered in the Glenoaks area described in the previous section. The observational (experimental) study involved the design, construction, and performance analysis of percolation wells and infiltration (grassy) swales. The project was finished in June 2013 with a total budget of $509,000. A total of four percolation wells and six grassy swales were installed in the Glenoaks area. These wells were shallower than those sized by the NLP method discussed above. In addition, the grassy swales were much shorter, narrower, and shallower than the ones obtained with the NLP method. The observational study represents a smaller-scale project than the one considered in the application of NLP method.

Results and Photos for Glenoaks Stormwater Capture Project North part of Los Angeles

The SCMs used for the Glenoaks project site location complied with the Standard Plans developed by City of Los Angeles LA Sanitation/Bureau of Engineering for grassy swales and percolation wells. The standard design used for grassy swales is shown in Figure 13. The standard design for percolation well is shown in Figure 14.

There were not dry-weather events during the observational period, and, therefore no samples were collected under these conditions (several site visits were made without yielding stormwater samples). Sampling of wet-weather storm events at North Los Angles locations occurred under the following criteria: (1) forecasted rainfall was equal to or greater than or 0.1 inch; and (2) the onset of rainfall was preceded by at least 72 hours of dry weather. Table 4 lists a summary of the average percent removal of pollutants.

Table 4. Summary of Average Concentrations at Inlet and Percent Removal of Pollutants for Subject area (samples taken November 2013).

Pollutant	**Unit**	Average Conc. Inlet Wet-Weather Samples	Average Removal Percentage for Wet Weather
E. Coli	MPN/100mL	15,650	100%
Enterococcus	MPN/100mL	46,150	100%
Total Coliform	MPN/100mL	230,000	100%
Cadmium (Total)	ug/L	1.4	100%
Cadmium (Dissolved)	ug/L	0.3	100%
Copper (Total)	ug/L	112	100%
Copper (Dissolved)	ug/L	39	100%
Lead (Total)	ug/L	42	100%
Lead (Dissolved)	ug/L	4	100%
Selenium (Total)	ug/L	0.5	100%
Selenium (Dissolved)	ug/L	0.3	100%
Zinc (Total)	ug/L	604	100%
Zinc (Dissolved)	ug/L	175	100%
Total Suspended Solids	ug/L	190	100%

Samples for one storm events were collected at two different locations of the installed dry wells and grassy swales on November 11, 2013. The total amount of stormwater infiltrated into the four dry wells was approximately 1 acre foot (about 1,233 m^3) during the rain event of November 11, 2013. Trash and debris were also monitored. The amount of trash and sediments in the primary chamber was about seven (7) cubic feet at a dry well and about five (5) cubic feet, respectively (1 cubic foot = 0.028317 m^3). A total of 12 cubic feet of trash and debris removed was removed. The results show the dry wells are capturing 100% of the stormwater volume through percolation in the adjacent soil. Pollutant loads are somewhat higher following long dry periods between storm events, the so-called “First Flush Phenomenon” (Stenstrom and Kayhanian, 2005).

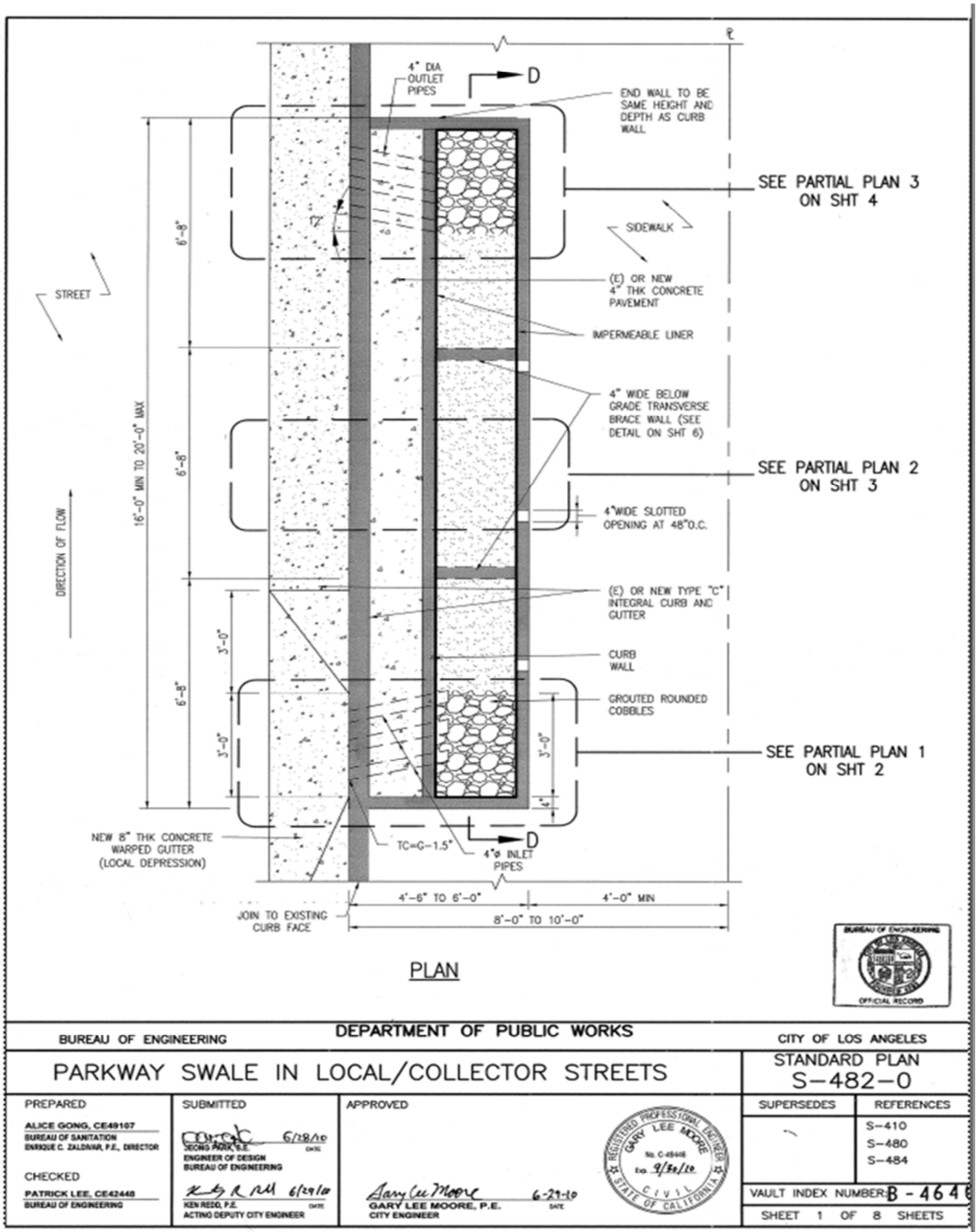


Figure 13. Profile of grassy-swale SCM for north Los Angeles.

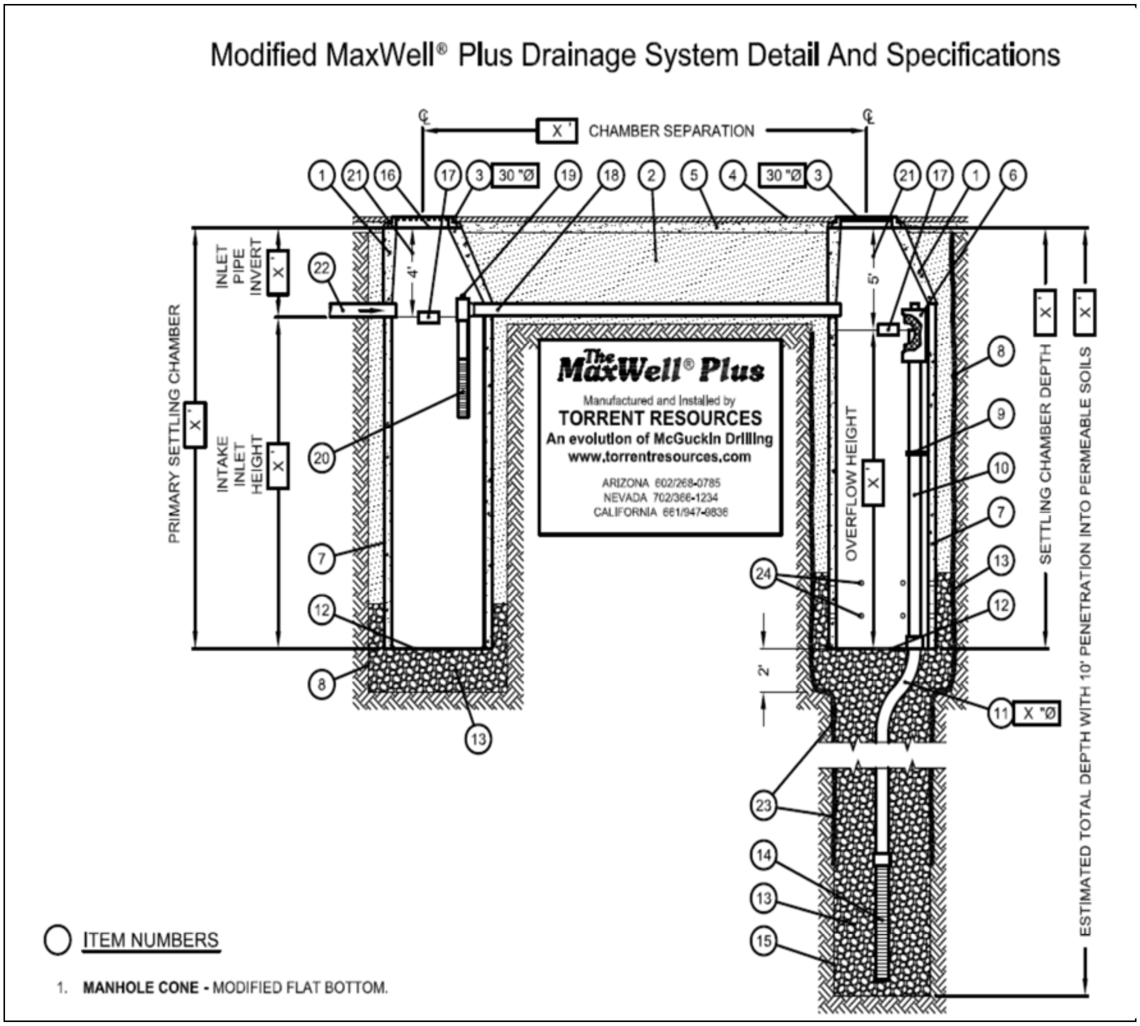


Figure 14. Profile of percolation well SCM for north Los Angeles.

Photographs from the Gleanoaks-Sunland Stormwater Project Areas are shown below: Construction photographs taken May 2013:

This photograph shows excavation in a grassy swale.

Pouring the concrete for the dry wells and catch basin site.

Post Construction photographs June 2013:

Photograph shows formed concrete for a grassy swale.

Photograph of a grassy swale under construction.

Photograph shows the secondary chamber of a finished dry well.

Photograph shows the piping for the flow meter between primary and secondary chambers to calculate the stormwater flow into the dry wells.

Photograph shows the flow meter used to calculate the stormwater flow into the dry wells.

Photographs taken in November 2013 sampling during rain event:

Photo of a grassy swale during a sampling event.

Photo of a grassy swale during a sampling event.

Photo of a catch basin during a sampling event before entering a percolation well.

Photo of the primary chamber of a percolation well after a storm event.

Photo of the secondary chamber of a percolation well after a storm event.

CONCLUSION

This paper developed and applied a nonlinear programing (NLP) method to select and size structural control measures (SCMs). The NLP method was applied to design several SCMs in the Gleonoaks area of north Los Angeles. In addition, observational data associated with a few constructed SCMs were reported in this study.

ACKNOWLEDGMENT

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