Design of urban runoff pollution control based on the Sponge City concept in a large-scale high-plateau mountainous watershed: a case study in Yunnan, China

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ABSTRACT

China recently commenced the Sponge City initiative for the effective management of urban stormwater runoff. Numerous studies have been carried out to evaluate the cost-effectiveness of low impact development (LID) practices in Sponge City planning and implementation. However, most of the studies were at the site- or subcatchment scale, and few were conducted at the watershed scale, given the dramatically increased routing complexity and number of decision variables. This study demonstrates the cost-effective Sponge City planning process for a 25.90 km² high-plateau watershed in southwest China. The Stormwater Management Model was coupled with the System for Urban Stormwater Treatment and Analysis Integrated (SUSTAIN) model to perform both continuous simulations and watershed-level optimization analyses, using the reduction of 85% annual runoff volume as the optimization target. Based on over 11,000 optimization runs, a near-optimal aggregated LID scenario was identified for each subcatchment. The aggregated LID size was first converted into a generic LID storage volume for individual subcatchments, and the storage volume was then disaggregated into site-level LID layouts regarding specific site conditions. The disaggregated LID layout yielded an annual average runoff volume reduction of 87.61% and close to 85% reduction for the annual average total suspended solids, total nitrogen, and total phosphorus loads. The systematic approach outlined in this study could be used for watershed-level Sponge City planning and implementation analyses in other cities.

Key words | large-scale high-plateau mountainous watershed, low impact development, optimization, Sponge City initiative, SUSTAIN, SWMM

INTRODUCTION

Urbanization converts the natural landscape into impervious surfaces and adversely alters the hydrologic cycle, resulting in increased peak flow rates, runoff volume, and pollutant load, as well as decreased groundwater infiltration (Schueler 1994; USEPA 2000; Pauleit et al. 2005; Ahiablame et al. 2012; Kourtis et al. 2018; LeBleu et al. 2019; Li et al. 2019). Traditional stormwater management relies on gray infrastructures to remove runoff from a site as quickly as possible and then stores it at downstream facilities for slow release (USEPA 2000; Cembrano et al. 2004; Li et al. 2018a, 2018b; Mei et al. 2018). Stressors of chemical contaminants, increased temperature, and prolonged flush on stream banks cause the unsustainable ‘urban stream syndrome’, which is characterized by the degradation of
urban waterway ecological processes and benefits (Hatt et al. 2004; Rosenberg et al. 2010; Han & Lund 2012; Booth et al. 2015; Du et al. 2017).

Low impact development (LID) represents a paradigm shift in stormwater control, as it seeks to preserve the pre-development hydrology using decentralized, microscale control measures (Baek et al. 2015). Commonly used LID practices include bioretention, grass swales, porous pavement, and green roofs (Roy et al. 2008; Newcomer et al. 2014; Shao et al. 2018). In the UK, a similar framework of sustainable urban drainage systems was used to address water pollution and flood hazards (Fletcher et al. 2014). Australia, in the meantime, proposed water sensitivity urban design to protect degrading urban water resources through a range of practices, including stormwater recycling and reuse, and the goal is to make cities more sustainable, livable, and resilient (Brown et al. 2009; Ashley et al. 2013).

In rapidly urbanizing China, urban flooding, the deterioration of surface water quality, urban heat island impacts, as well as climate change pose substantial challenges to stormwater management (Li et al. 2004; Wang et al. 2008; Piao et al. 2010; Randall et al. 2019). Studies of the LID framework and other stormwater management approaches lead up to the ‘Sponge City’ initiative in 2014, and the goal was to use green infrastructures (GI) to achieve sustainable stormwater management (MOHURD 2014). A total of 30 cities were chosen as pilot Sponge Cities by 2016, and the central government allocated $6.35 billion to promote the Sponge City initiative (Randall et al. 2019). The goal was to achieve at least 70% of annual runoff volume control and to implement Sponge City designs in at least 80% of the developed areas by 2030 (MOHURD 2014; Jiang et al. 2017).

The Sponge City program is still at its early stage, and studies have been carried out to evaluate the Sponge City planning and implementation processes. For example, Gao et al. (2015) conducted cost-effective analyses for LID implementation at an industrial site in Ma’an shan, northeastern China, using 1-year rainfall. Mao et al. (2017) used the aggregated LID representations to identify the cost-effective LID implementation scheme in the 22 km² Foshan New City in southern China, in which the site-level LID layouts were simplified into four generic aggregated LID representations and the decision variables were the number of aggregated LIDs. Li et al. (2018a, 2018b) conducted a cost-effective analysis for LID layout planning in a 0.03 km² technology innovation park site in Lincang, southwestern China, using 10-year continuous simulations. Mei et al. (2018) analyzed 15 synthesized GI scenarios in a 651.80 km² watershed near Beijing in northeastern China for flood mitigation, and six design rainfall events with recurrence intervals ranging from 2 to 100 years were analyzed. Li et al. (2018a, 2018b) conducted an optimization analysis of LID implementation in a 0.24 km² watershed in Shenyang, northeastern China, and three levels (maximum, economic, and Sponge City) of simplified LID implementation scenarios were evaluated for optimal annual runoff volume control. Similarly, Randall et al. (2019) evaluated three levels (low, middle, and high) of aggregated LID implementation schemes in a 133 km² watershed in Beijing.

Existing studies reveal unique challenges facing the development of a systematic strategy for Sponge City planning and implementation. At one hand, site- or subcatchment-scale analyses are needed in matching LID site requirements with unique site characteristics such as soil, land use, slope, and groundwater level (Jia et al. 2012; Cano & Barkdoll 2017; Li et al. 2018a, 2018b). On the other hand, the dramatically increased number of decision variables and the complexity of the flow routing scheme at the watershed scale render optimization analysis computationally unfeasible, even though the cost-effectiveness analysis is essential to robust decision-making (Ahiablame et al. 2013; Riverson et al. 2014; Martin-Mikle et al. 2015; Xie et al. 2017). As a result, most of the existing studies were either conducted at the site- or subcatchment scale using high-resolution models (Qin et al. 2013; Baek et al. 2015; Gao et al. 2015; Jia et al. 2015; Li et al. 2018a, 2018b) or were conducted at the watershed scale using the simplified representation of LID implementation schemes, mostly coupled with design storm analyses to further reduce the optimization run time (Palla & Gnecco 2015; Mao et al. 2017; Mei et al. 2018; Randall et al. 2019).

Modeling tools are necessary when assessing hydrologic and water quality benefits from LID implementations (Lee et al. 2012; Kong et al. 2017). Example models include the Soil Water Assessment Tool (Arnold et al. 2012), Model for Urban Sewers (MOUSE) (DHI 2002), Model for Urban Stormwater Improvement Conceptualization (MUSIC)
(Wong et al. 2002), Stormwater Management Model (SWMM) (Rossman 2005), and System for Urban Stormwater Treatment and Analysis Integrated (SUSTAIN) (USEPA 2011). Among the models, SWMM and SUSTAIN are both in the public domain and are specifically developed for urban stormwater assessments. The two models have been applied worldwide in many stormwater management decision-support studies and have been calibrated and validated in different climate and geohydrological regions (Elliott & Trowsdale 2007; Lee et al. 2012; Joksimovic & Alam 2014; Gao et al. 2015; Jia et al. 2015; Mao et al. 2017; Li et al. 2018a, 2018b; Randall et al. 2019).

This study proposes a comprehensive approach that bridges the watershed-scale optimization analysis with site-scale implementation for the Sponge City planning analysis. The objectives of this study are to: (1) evaluate pre- and post-development runoff conditions at the watershed scale using the SWMM; (2) use the SUSTAIN model to perform the watershed-scale optimization of LID implementation using aggregated LID representation and to obtain the near-optimal aggregated LID sizes for each subcatchment. The near-optimal LID storage volume is then calculated for each subcatchment using the effective depth and the total area of the aggregated LID (i.e. bioretention area); (3) disaggregate the near-optimal LID storage volume for each subcatchment into the site-specific LID layout with regard to unique site characteristics; and (4) re-evaluate the watershed-scale hydrologic and water quality benefits using site-scale representations of disaggregated LIDs and verify both the hydrologic and water quality control benefits from the Sponge City implementation.

MATERIALS AND METHODS

Study area

The case study watershed, Haidong New District (HND), is located in Dali Prefecture, Yunnan Province, southwest China (25°39′00″–25°42′15″N, 100°16′07″–100°20′36″W) (Figure 1). The watershed area is 2,590 ha, characterized with the hilly karst landscape. The elevation difference between the highest (2,164 m) and lowest points (1,965 m) in the watershed is about 200 m (Figure 2(a)), and the average slope is about 15.1% (Figure 2(b)). When stormwater runoff from the watershed directly drains to the Erhai Lake, the water quality of which remains Class II of the National Surface Water Quality Standards in recent years (Class I being the best): The HND watershed is being rapidly developed from the current natural landscape into a new urban district, with a target imperviousness of 52.87% (Figure 3). Comparisons of the existing pre-development land use and the target post-development land-use compositions are summarized in Table 1. According to the Sponge City Construction Technology Guide, Dali is located in Zone II, where the annual average runoff volume control target is specified as 80–85% (MOHURD 2014).

The HND watershed has the subtropical monsoon climate, with an annual average rainfall depth of 620 mm and an annual average temperature of 15.6 °C. Over 80% of the annual rainfall occurs between May and October. Soils on the hilltops and hillslopes (slopes greater than 25%) are mostly weathered limestones with good drainage, and soils in valley areas (slopes less than 8%) of low elevations are typically loamy soils with poor drainage and a high groundwater table. With its close vicinity to the Erhai Lake, stormwater runoff from the post-development HND watershed is of grave concern to local authorities. The implementation of the Sponge City framework in the HND watershed is not only important to the protection of the Erhai Lake but also serves as an example for other urbanizing watersheds that are close to lakes or reservoirs.

Using the digital elevation model data, natural ditches, as well as the stormwater pipe network information, the HND watershed is divided into 76 subcatchments (Figure 4(a)), with an average subcatchment area of 34.08 ha.

The USEPA SWMM

The USEPA SWMM, Version 5.1 (Rossman 2005) is used to simulate the pre- and post-development runoff conditions from the HDN watershed. The SWMM is a dynamic hydrological/hydraulic model that simulates the rainfall-runoff, infiltration, evaporation, and flow routing processes, and it is also capable of simulating the pollutant buildup and wash-off processes. The rainfall-runoff process in the SWMM is
Figure 1 | Location of the HND at Dali Prefecture, Yunnan Province, China.

Figure 2 | (a) Elevation in the HND watershed and (b) slope in the HND watershed.
based on the nonlinear reservoir representation:

\[
\frac{dd}{dt} = \frac{i_e}{An} \left( d - d_p \right)^{5/3} S^{1/2}
\]

where \( d \) is the water depth (m), \( t \) is the time (s), \( k \) is the unit constant (1 for metric, 1.49 for English units), \( W \) is the subcatchment width (m), \( A \) is the subcatchment area (m\(^2\)), \( n \) is Manning’s roughness coefficient, \( i_e \) is the rainfall excess (m/s), \( d_p \) is the depth of depression storage (m), and \( S \) is the subcatchment slope (m/m).

The HND SWMM consists of 182 conduits, 189 junctions, and 4 outlets (Figure 4(b)). For the purposes of evaluating the runoff conditions from the whole HND watershed, a virtual outlet is used to collect runoff from the four individual outlets. Default SWMM parameter values for the HND watershed are summarized in Table 2.

### Calibration of the SWMM

After the HND SWMM was established, the model was calibrated against monitored data. Currently, the HND watershed is still under rapid development, and runoff data were collected from a monitoring station in Subcatchment #7 (Figure 5(a)). Runoff and water quality (total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP)) samples from two rainfall events, 03 August 2018 (with a total rainfall depth of 19.2 mm) and 22 August 2018 (with a total rainfall depth of 27.18 mm), were collected.
Subcatchment #7 is the campus of a vocational school and has a total area of 40.71 ha (Figure 5(a)). The land-use compositions for the subcatchment are summarized in Table 3. In order to assist with the calibration process, Subcatchment #7 is further delineated with regard to individual land-use types and the flow is routed according to the elevation and stormwater pipe network (Figure 5(b)).

The calibration process follows the procedure used in other SWMM calibration studies (Barco et al. 2008; Rabori et al. 2010). For each calibration run, hydrologic calibration parameters (i.e. depression storage, Manning’s roughness coefficient, and the percentage of imperviousness with zero storage (%PerctZero)) were first adjusted to achieve a satisfactory match between the predicted and measured hydrographs. Then, the water quality parameters (i.e. maximum pollutant buildup, rate constant, washoff coefficient, and washoff exponent) were adjusted to match the predicted and measured pollutographs. Water quality calibration was carried out for TN and TP.

Model performance evaluation was assessed with the Nash–Sutcliffe coefficient ($R_{NS}$), and it provides a comparison between the efficiency of the chosen model and a description of the data as the mean of the observations. The optimal simulation value occurs when $R_{NS}$ is close to 1, and the value is usually considered as acceptable model performance when $R_{NS}$ is greater than 0.5 (Moriasi et al. 2007; Li et al. 2016). The $R_{NS}$ is formulated as follows:

$$R_{NS} = 1 - \frac{\sum_{t=1}^{n} (Q_{t}^{obs} - Q_{t}^{sim})^2}{\sum_{t=1}^{n} (Q_{t}^{obs} - Q_{t}^{av})^2}$$  \hspace{1cm} (2)$$

where $Q_{t}^{obs}$ is the observed value at time $t$, $Q_{t}^{sim}$ is the simulation value at time $t$, $Q_{t}^{av}$ is the average observed value, $t$ is the time, and $n$ is the total number of time steps.

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### Table 2 | Default SWMM parameter values for the HND watershed

| Parameter    | Units | Range          | Parameter    | Units | Range          |
|--------------|-------|----------------|--------------|-------|----------------|
| Area         | ha    | 7.46–186.5     | Ds-Imperv    | mm    | 2.54           |
| Width        | m     | 273.1–1,365.6  | Ds-Perv      | mm    | 6.51           |
| %Imperv      | %     | 5–83           | Max.Infil    | mm/h  | 337.06         |
| N-Imperv     | –     | 0.015          | Min.Infil    | mm/h  | 8.64           |
| N-Perv       | –     | 0.2            | %PerctZero   | %     | 25             |

%Imperv: percentage of imperviousness; N-Imperv: Manning’s for impervious surfaces; N-Perv: Manning’s for pervious surfaces; Ds-Imperv: depression storage for impervious surfaces; Ds-Perv: depression storage for pervious surfaces; %PerctZero: percentage of impervious surfaces with zero depression storage.
Time series generation through the SWMM

The calibrated SWMM parameters were used to generate hydrologic and water quality runoff time series from individual land-use types. An SWMM consisting of unit areas of each land-use type was created. The daily evaporation data and hourly rainfall data from the nearby rainfall station for the period of 01 January 2011 to 31 December 2017 were used for generating runoff time series. Rainfall and evaporation data for the HND watershed for the period of 01 January 2011 to 31 May 2013 are shown in Figure 6. Continuous runoff time series were generated for land-use types of natural lawn, transportation, urban pervious areas, and urban impervious areas. The runoff time series were then used as an input to the SUSTAIN model using the external simulation option.

Typical LID designs and unit costs

Typical LID design parameters and unit costs of commonly used LIDs were retrieved from the Sponge City Technical Guidance published by the MOHURD (2014). LID design parameter values and unit costs are summarized in Table 4, and the site requirements for LIDs are summarized in Table 5. The design parameters used for the LID implementation scenario setup in the HND SUSTAIN model are also shown in Table 4.

The USEPA SUSTAIN model

The USEPA SUSTAIN model (Version 1.2) is a public domain decision-support tool designed for the stormwater management study, planning, and design analysis (Lee et al. 2012). Using the non-dominated sorting genetic algorithm-II (NSGA-II) to perform the optimization analysis, the SUSTAIN model can identify cost-effective LID implementation scenarios at the site- and watershed-scale (USEPA 2011; Lee et al. 2012; Gao et al. 2015). The SUSTAIN model incorporates algorithms from the SWMM, Hydrological Simulation Program – Fortran, and Best Management Practice Decision-Support System, and the
model consists of modules, including the BMP siting tool, land simulation module, BMP simulation module, BMP optimization module, and post-processing module (Cheng et al. 2009; USEPA 2011; Lee et al. 2012). SUSTAIN has a built-in representation for commonly used LIDs, including green roof, porous pavement, infiltration trench, the bioretention area, and wet pond, and runoff time series from various land uses could either be generated internally or developed externally (USEPA 2011; Lee et al. 2012; Li et al. 2018a, 2018b). Input parameters for typical LID practices are shown in Table 6.

In SUSTAIN, pollutant removal in LIDs is simulated in each time step using the first-order decay function, along with an optional background pollutant concentration:

\[ C_{\text{out}} = C^* + (C_{\text{in}} - C^*) e^{-K/q} \]  

where \( C^* \) is the background pollutant concentration (mg/L), \( C_{\text{in}} \) is the input concentration (mg/L), \( C_{\text{out}} \) is the output concentration (mg/L), \( q \) is the hydraulic loading or overflow rate (m/yr), \( k' = kh \) and is the rate constant (m/yr), \( k \) is the first-order decay rate (1/yr), and \( h \) is the pond depth (m).

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**Table 4** | Typical design parameter values and unit costs of commonly used LIDs (MOHURD 2014)

| LIDs          | Surface storage depth (m) (value used) | Soil/gravel layer thickness (m) (value used) | Porosity (%) (value used) | Effective depth (m) | Unit cost ($/m^2$) |
|---------------|----------------------------------------|---------------------------------------------|--------------------------|---------------------|-------------------|
| Green roof    | 0.02                                   | 0.2–0.4(0.4)                                | 30–40(35)                | 0.16                | 35                |
| Porous pavement | 0.006                                | 0.3–0.9(0.8)                               | 40–60(55)                | 0.45                | 30–35             |
| Bioretention  | 0.15–0.3(0.2)                          | 0.3–1.2(1.0)                               | 30–40(35)                | 0.55                | 90–110            |
| Dry/wet pond  | 0.8–2.5(0.8)                           | –                                           | 100                      | 0.8                 | 80                |
| Grass swale   | 0.1–0.2 (0.15)                         | 0.2–0.6 (0.3)                              | 30–40(35)                | 0.26                | 15–25             |

**Table 5** | Site requirements for different LID practices (Cheng et al. 2009)

| LIDs          | Drainage slope (%) | Drainage area (ha) | Imperviousness (%) | Buffer to roads (m) |
|---------------|--------------------|--------------------|--------------------|---------------------|
| Green roof    | –                  | –                  | >0                 | –                   |
| Porous pavement | <1                 | <1.21              | >0                 | –                   |
| Bioretention  | <5                 | <0.81              | >0                 | <30.5               |
| Rain barrel/cisterns | –              | –                  | >0                 | –                   |
Cost-effective analyses are performed in the SUSTAIN model after the user specifies the assessment point, and the optimization target could be annual average runoff volume reduction, peak flow exceedance frequency, or annual average load reduction. The multi-objective problem can be expressed as follows:

\[
\text{Minimize } \sum \text{Cost}(\text{BMP}) \tag{4}
\]

s.t.

\[
Q_{\text{max}1} \leq Q_{i} \leq Q_{\text{max}2} \text{ and/or} \\
L_{\text{max}k1} \leq L_{k} \leq L_{\text{max}k2}
\]

where \(Q_{\text{max}1}\) and \(Q_{\text{max}2}\) represent the lower and upper ranges of the annual average flow volume control targets, and \(L_{\text{max}k1}\) and \(L_{\text{max}k2}\) represent the lower and upper ranges of the annual average pollutant load control targets.

**LID performance assessment and optimization through SUSTAIN**

The SUSTAIN model was established to evaluate and optimize LID implementation scenarios in the HND watershed (Figure 7). Runoff time series from the HND SWMM were used following the external simulation option. In the watershed-scale SUSTAIN optimization setup, the bioretention area was used as the aggregated LID representation for each of the 76 subcatchments, and the optimization target was set to be 80% reduction of the annual average runoff volume. Using the aggregated LID representation was mainly to reduce the number of decision variables and the search space for the optimization analysis. Previous experiments have also shown that when the subcatchment area is 50 ha or less, the hydrologic and water quality simulation results between aggregated and distributed LID representations were less than 5% (USEPA 2009).

The goal of the optimization analysis was to identify the lease-cost bioretention area sizes (in hectares) for each subcatchment while meeting the watershed-wide annual average runoff volume control target. Similar to the HND SWMM model setup, a virtual outlet was used to collect all the runoff from the post-development with the LID scenario watershed, and the virtual outlet was used as the assessment point in the SUSTAIN optimization analysis.

Decision variables for the HND LID implementation analysis are the sizes of the bioretention area (in hectares) in each subcatchment. According to previous studies, the upper bound of the bioretention area was set to be 15% of the impervious area in each subcatchment, beyond which the marginal returns of hydrologic and water quality benefits quickly decrease (Gilroy & McCuen 2009; Tetra Tech 2010; Eckart et al. 2017). For simplification purposes, the width of the bioretention area was arbitrarily set to be 3.05 m (10 ft), and the decision variable then became the length of the bioretention area in each subcatchment. A total of 100 size steps were used between the lower bound and the upper bound (Table 7) during the optimization analysis, and the search space was 100^76 or 10^{152}. The optimization process identifies the tradeoff between aggregated LID
sizes (in hectares) in each subcatchment and the annual average runoff volume from the watershed.

**Disaggregation of the near-optimal LID sizes to the site-scale layout**

The SUSTAIN optimization analysis identifies the tradeoff between LID sizes and the annual average runoff volume reduction for the HND watershed. The near-optimal solution consists of aggregated LID sizes (in hectares) in each subcatchment. The composite LID sizes need to be disaggregated into the site-scale layout to assist with LID implementation. The disaggregation process in a subcatchment takes six steps:

1. Identify the near-optimal LID size (in hectares), $A_{LID}$, for the subcatchment from SUSTAIN optimization results;
2. Calculate the effective LID volume for the subcatchment, $Q_e$, by multiplying $A_{LID}$ with the effective depth ($d_{e-bioretention}$) of the bioretention area (from Table 4);
3. Calculate the LID to the imperviousness ratio, $R$, by dividing the near-optimal LID size ($A_{LID}$) with the total impervious area, $A_{IMP\text{-}total}$, in the subcatchment;
4. For each impervious land use in the subcatchment, assign a corresponding type of LID and then calculate the relative LID to the impervious ratio, $R_r$, by dividing the effective depth of the bioretention area ($d_{e-bioretention}$) with that of the chosen LID type;
5. Calculate the LID area to the impervious area ratio for LIDs other than the bioretention area in the subcatchment as $R^*R_r$;
6. Implement site-scale LIDs following the LID area to the impervious area ratio of $R^*R_r$ for each piece of impervious land use.

The disaggregation steps can be further explained through an example. Suppose a subcatchment has 30 ha of impervious surfaces ($A_{IMP\text{-}total}$) (roof, roads, parking lots, and public squares), and the near-optimal LID size ($A_{LID}$).
| Subcatchment | Area (ha) | Imperv % | Lower bound length (m) | Upper bound length (m) | Size step |
|--------------|-----------|----------|------------------------|------------------------|-----------|
| HD_01        | 26.60     | 60.04    | 0                      | 7,854                  | 79        |
| HD_02        | 26.50     | 50.22    | 0                      | 6,545                  | 65        |
| HD_03        | 36.15     | 59.69    | 0                      | 10,612                 | 106       |
| HD_04        | 8.82      | 49.92    | 0                      | 2,165                  | 22        |
| HD_05        | 46.95     | 77.72    | 0                      | 17,946                 | 179       |
| HD_06        | 11.85     | 65.93    | 0                      | 3,842                  | 38        |
| HD_07        | 40.71     | 60.36    | 0                      | 12,085                 | 121       |
| HD_08        | 44.70     | 60.62    | 0                      | 13,326                 | 133       |
| HD_09        | 25.36     | 68.55    | 0                      | 8,091                  | 81        |
| HD_10        | 49.22     | 56.77    | 0                      | 13,742                 | 137       |
| HD_11        | 38.57     | 63.96    | 0                      | 12,132                 | 121       |
| HD_12        | 21.84     | 60.49    | 0                      | 6,497                  | 65        |
| HD_13        | 24.55     | 45.61    | 0                      | 5,507                  | 55        |
| HD_14        | 16.04     | 54.08    | 0                      | 4,266                  | 43        |
| HD_15        | 29.93     | 54.97    | 0                      | 8,091                  | 81        |
| HD_16        | 17.32     | 53.97    | 0                      | 4,597                  | 46        |
| HD_17        | 36.34     | 62.44    | 0                      | 11,159                 | 112       |
| HD_18        | 43.34     | 58.00    | 0                      | 12,363                 | 124       |
| HD_19        | 48.60     | 67.15    | 0                      | 16,050                 | 160       |
| HD_20        | 28.74     | 53.67    | 0                      | 7,586                  | 76        |
| HD_21        | 13.43     | 54.94    | 0                      | 3,629                  | 36        |
| HD_22        | 31.76     | 62.96    | 0                      | 9,834                  | 98        |
| HD_23        | 14.39     | 50.18    | 0                      | 3,551                  | 36        |
| HD_24        | 46.57     | 61.21    | 0                      | 14,019                 | 140       |
| HD_25        | 25.44     | 61.99    | 0                      | 7,756                  | 78        |
| HD_26        | 18.71     | 55.30    | 0                      | 5,089                  | 51        |
| HD_27        | 38.82     | 56.47    | 0                      | 10,781                 | 108       |
| HD_28        | 21.45     | 63.68    | 0                      | 6,718                  | 67        |
| HD_29        | 16.72     | 64.35    | 0                      | 5,291                  | 53        |
| HD_30        | 43.31     | 50.71    | 0                      | 10,801                 | 108       |
| HD_31        | 29.40     | 61.13    | 0                      | 8,839                  | 89        |
| HD_32        | 12.86     | 42.08    | 0                      | 2,661                  | 27        |
| HD_33        | 11.46     | 81.78    | 0                      | 4,609                  | 46        |
| HD_34        | 66.80     | 62.36    | 0                      | 20,487                 | 205       |
| HD_35        | 35.26     | 63.47    | 0                      | 11,006                 | 110       |
| HD_36        | 17.16     | 79.93    | 0                      | 6,746                  | 67        |
| HD_37        | 40.50     | 82.72    | 0                      | 16,476                 | 165       |
| HD_38        | 24.65     | 82.62    | 0                      | 10,016                 | 100       |

(continued)
identified through SUSTAIN is 2.1 ha, resulting in a LID to impervious ratio $R$ of 7%. Since the effective depth of the bioretention area ($d_{e,\text{bioretention}}$) is 0.55 m, that results in an effective LID value for the subcatchment ($Q_e$) of 11,550 m$^3$. Subsequent steps for site-level disaggregation are shown in Table 8.

The example in Table 8 shows that the sum of the site-scale disaggregated LID area is 29,183 m$^2$ (2.91 ha), and that is larger than the near-optimal LID size ($A_{\text{LID}}$) for the subcatchment (2.1 ha). This is because the effective depths for green roof and porous pavement are less than those of the bioretention area, and thus larger LID areas are needed for the same LID volume. The LID to the impervious area ratio in Table 8 can be used for guiding site-scale LID implementations in individual subcatchments.

The disaggregation process also accounts for unique site conditions in the HND watershed and assigns site-scale LID types accordingly, with elevation and soil infiltration capacities being the two important factors considered. Subcatchments in the HND watershed are categorized into three elevation groups: low elevation (1,965 to 2,025 m), medium elevation (2,026 to 2,062 m), and high elevation (2,063 to 2,164 m). Previous field tests of infiltration rates indicate that subcatchments in the high- and medium-elevation groups, in general, have higher infiltration rates (e.g. larger than 230 mm/h) due to the weathered carbonate soils, and subcatchments in the low-elevation group have lower infiltration rates and a high groundwater table.

A typical site-scale layout of LID implementation in a high-elevation subcatchment is shown in Figure 8. As shown, green roofs are implemented on rooftops, and porous pavements are implemented for parking lots, sidewalks, and public squares. The runoff is then routed to bioretention areas through grass swales, and the overflow

| Impervious land use | Area (ha) | Assigned LID type | Effective depth (m) | Relative depth ratio to bioretention ($R_d$) | LID to impervious area ratio ($R\cdot R_d$) | LID area (m$^2$) | LID volume (m$^3$) |
|---------------------|----------|-------------------|---------------------|--------------------------------------------|------------------------------------------|------------------|------------------|
| Roof 5              | Green roof | 0.16              | 3.44                | 24.08%                                     | 12,040                                    | 1,926.4          |
| Road 5              | Bioretention | 0.55              | 1                   | 7%                                         | 3,500                                     | 1,925            |
| Parking lot 4       | Bioretention | 0.55              | 1                   | 7%                                         | 2,800                                     | 1,540            |
| Parking lot 6       | Porous pavement | 0.45              | 1.22                | 8.54%                                      | 5,124                                     | 2,305.8          |
| Public square 7     | Bioretention | 0.55              | 1                   | 7%                                         | 4,900                                     | 2,695            |
| Public square 3     | Dry pond | 0.8               | 0.69                | 4.83%                                      | 1,449                                     | 1,159            |
| Total               | 30       | -                 | -                   | -                                          | 29,813                                    | 11,551.2         |

Figure 8 | Typical site-scale LID layout for a high-elevation subcatchment.
from bioretention areas is routed to downstream stormwater pipes and ditches. Runoff from nearby impervious surfaces, such as roads and public squares, can also be routed to grass swales and the bioretention area along the flow path. One special arrangement is that porous pavement, grass swale, and the bioretention area are all implemented with the lined bottom. This is to discourage infiltration at the high-elevation subcatchments, mainly to protect the stability of the karst topography.

The LID site-scale layout for medium-elevation subcatchments is similar to that for the high-elevation subcatchments, with the difference being that no lined bottom is used for porous pavement, grass swale, and the bioretention area.

A typical site-scale LID layout for low-elevation subcatchments is shown in Figure 9. As shown, the routing schemes are similar to those for the medium-elevation subcatchments (porous pavement, grass swale, and the bioretention area without the lined bottom), except that dry/wet ponds are used at the downstream of the bioretention area. The detention/retention facilities could help further improve stormwater quality through the settling process, and the detained stormwater can also be used for municipal purposes (e.g., irrigation and sprinkling). Excess runoff from the dry/wet ponds is routed to stormwater pipes and eventually discharged into the Erhai Lake.

**Re-evaluation of site-scale hydrologic and water quality performances**

After the watershed-scale near-optimal LID sizes were disaggregated into site-scale LID layouts for each subcatchment, continuous simulations were carried out for the time period of 01 January 2011 to 31 December 2017 in SUSTAIN to verify the LID implementation performances. The annual average runoff volume reduction and annual average pollutant load reduction percentages were evaluated against runoff conditions from the post-development HND watershed.

**RESULTS AND DISCUSSION**

**SWMM calibration**

Hydrologic and water quality calibration results of Subcatchment #7 for the two monitored events are shown in Figures 10 and 11. The observed event mean concentrations (EMCs) for TSS, TN, and TP for the 03 August 2018 event are 75, 2.71, and 0.28 mg/L, respectively. The observed EMCs for TSS, TN, and TP for the 22 August 2018 event are 106, 4.06, and 0.55 mg/L, respectively. Hydrographs and pollutant time series from the calibrated SWMM overall match those from the observed values.
water quality parameters of the calibrated SWMM are summarized in Tables 9 and 10, respectively. The average runoff volume difference from the calibration is 14.76%, and the average EMC differences between the predicted and the observed values for TSS, TN, and TP are 10.69, 4.91, and 18.32%, respectively. The $R_{NS}$ of the two events for TSS, TN, and TP are 0.81, 0.65, 0.74 and 0.72, 0.58, 0.64, respectively. The calibration results indicated that the model structure and parameters matched the runoff-producing pattern and the calibrated SWMM were suitable for simulating runoff scenarios in the study area.

**SUSTAIN optimization analysis**

The optimization process was carried out between total LID sizes and the percentages of annual runoff volume reduction as compared to that of the post-development watershed. Each dot in the figure represents an evaluated LID scenario (which consists of individual LID sizes from the 76 subcatchments) during the optimization process. A total number of 11,533 scenarios (dots) were evaluated, and the dash frontline formed by the dots in Figure 12 represents the Pareto front, which is the tradeoff relationship between total LID sizes and the percentage of runoff volume reduction for the HND watershed. According to the tradeoff curve, an annual runoff volume reduction of 80% corresponds to a total LID area of approximately 80 ha. Figure 12 also shows that for the same level of 80% runoff volume reduction, the LID area could be as much as 157 ha, almost doubling the near-optimal solution.

The optimization results demonstrate the potential for the LID practices in mitigating the post-development runoff conditions. It is shown that with appropriate LID sizing, the annual average post-development runoff volume could be reduced by as much as 90% from the HND watershed. The tradeoff curve also shows that on the tradeoff
curve, there exists a reflection point beyond which the marginal returns in runoff volume reduction starts to level off. Similar patterns are observed in many other LID implementation optimization studies as well (Baek et al. 2015; Mao et al. 2011; Li et al. 2012, 2016).

The optimization process demonstrates the high efficiency of the NSGA-II in identifying the tradeoff between the aggregated LID size and the percentage of annual average runoff volume reduction. The current search space for the HND watershed is \(10^{152}\). However, if detailed site-scale LID representations were used, the computational cost for the optimization analysis would become too expensive using the NSGA-II approach. When the number of

| Table 9 | Calibrated SWMM hydrologic parameters |
| --- | --- | --- |
| Parameter name | Unit | Calibrated values |
| N-Imperv | – | 0.013 |
| N-perv | – | 0.4 |
| Ds-Imperv | mm | 2 |
| Ds-perv | mm | 6 |
| %Perc1Zero | % | 24 |

| Table 10 | Calibrated SWMM water quality parameters |
| --- | --- | --- | --- |
| Land-use name | Water quality parameters | Pollutants |
| --- | --- | --- | --- | --- |
| | Unit | TN | TP | TSS |
| Road | Maximum buildup | kg/ha | 8 | 1.5 | 260 |
| Rate constant | d\(^{-1}\) | 0.5 | 0.5 | 0.5 |
| Coefficient | – | 0.065 | 0.075 | 0.08 |
| Exponent | – | 1.6 | 1.9 | 1.75 |
| Rooftop | Maximum buildup | kg/ha | 6 | 0.8 | 140 |
| Rate constant | d\(^{-1}\) | 0.5 | 0.5 | 0.5 |
| Coefficient | – | 0.045 | 0.05 | 0.04 |
| Exponent | – | 1.1 | 0.9 | 0.8 |
| Urban pervious land | Maximum buildup | kg/ha | 10 | 0.6 | 100 |
| Rate constant | d\(^{-1}\) | 0.5 | 0.5 | 0.5 |
| Coefficient | – | 0.006 | 0.005 | 0.009 |
| Exponent | – | 1.25 | 1.1 | 1.25 |
| Natural lawn | Maximum buildup | kg/ha | 2 | 0.1 | 200 |
| Rate constant | d\(^{-1}\) | 0.5 | 0.5 | 0.5 |
| Coefficient | – | 0.015 | 0.01 | 0.02 |
| Exponent | – | 1.3 | 1.2 | 1.4 |

Figure 11 | (a) Hydrologic calibration results of the 22 August 2018 event; (b) TSS calibration results of the 22 August 2018 event; (c) TN calibration results of the 22 August 2018 event and (d) TP calibration results of the 22 August 2018 event.
subcatchments or decision variable continues to increase, new optimization techniques combined with machine learning have to be explored (Yaseen et al. 2019).

The optimization of LID scenarios was carried out using the hourly runoff time series for the period of 01 January 2011 to 31 December 2017. In comparison to the design storm approach, the continuous simulation can represent the ponding, infiltration, and evaporation processes in LIDs, as well as the pollutant buildup, washoff, and first-order decay processes (Lee et al. 2012). Using such a detailed representation, the optimization framework is able to fully assess the cumulative hydrologic and water quality benefits from LID implementation under a wide range of weather conditions, rather than performing only flooding-related analysis (Baek et al. 2015).

**Disaggregation of the near-optimal LID solution**

The six-step methodology for disaggregating the watershed-scale near-optimal LID solution to site-scale layouts was applied to each of the 76 subcatchments. The effective LID volume, LID to imperviousness ratio, and relative LID to impervious ratio were estimated for each subcatchment and site-level impervious land use. Engineering judgments were made when necessary regarding slight adjustments of LID sizes to accommodate individual site characteristics. The disaggregated site-level LIDs in each subcatchment are summarized in Table 11.

The disaggregation of the near-optimal LID to site-scale layouts shows that the bioretention is the largest LID used in many subcatchments. This is mainly due to two reasons. First, the bioretention area has been reported to be highly efficient in controlling the stormwater quantity and quality in many previous studies (Joksimovic & Alam 2014; Mao et al. 2017; Eaton 2018) and, thus, is a preferred choice for the site-scale analysis. Second, the post-development land use in the HND watershed is mostly low-density residential, commercial, and institutional land uses, which have large pervious space and thus warrant the bioretention area implementation.

![Figure 12](image_url) | The tradeoff relationship between total LID areas and the annual runoff volume reduction percentages.
Table 11 | Disaggregated site-level LiDs in each subcatchment (LiD areas are in ha)

| Subcatchment | Area (ha) | Imperv% | Green roof | Porous pavement | Bioretention | Dry/wet pond | Grass swale |
|--------------|-----------|---------|------------|----------------|--------------|--------------|-------------|
| HD_01        | 26.60     | 60.04   | 0.34       | 0.54           | 0.88         | 0.16         | 0.05        |
| HD_02        | 26.50     | 50.22   | 0.28       | 0.45           | 0.73         | 0.13         | 0.04        |
| HD_03        | 36.15     | 59.69   | 0.46       | 0.73           | 1.19         | 0.22         | 0.07        |
| HD_04        | 8.82      | 49.92   | 0.09       | 0.15           | 0.24         | 0.04         | 0.01        |
| HD_05        | 46.95     | 77.72   | 0.78       | 1.23           | 2.01         | 0.36         | 0.12        |
| HD_06        | 11.85     | 65.93   | 0.03       | 0.26           | 0.43         | 0.08         | 0.03        |
| HD_07        | 40.71     | 60.36   | 0.52       | 0.83           | 1.35         | 0.25         | 0.08        |
| HD_08        | 44.70     | 60.62   | 0.58       | 0.91           | 1.49         | 0.27         | 0.09        |
| HD_09        | 25.36     | 68.55   | 0.37       | 0.58           | 0.96         | 0.17         | 0.06        |
| HD_10        | 49.22     | 56.77   | 0.10       | 0.94           | 1.54         | 0.28         | 0.09        |
| HD_11        | 38.57     | 63.96   | 0.53       | 0.83           | 1.36         | 0.25         | 0.08        |
| HD_12        | 21.84     | 60.49   | 0.05       | 0.44           | 0.73         | 0.13         | 0.04        |
| HD_13        | 24.55     | 45.61   | 0.04       | 0.38           | 0.62         | 0.11         | 0.04        |
| HD_14        | 16.04     | 54.08   | 0.18       | 0.29           | 0.48         | 0.09         | 0.03        |
| HD_15        | 29.93     | 54.97   | 0.35       | 0.55           | 0.90         | 0.16         | 0.05        |
| HD_16        | 17.32     | 53.97   | 0.20       | 0.31           | 0.51         | 0.09         | 0.03        |
| HD_17        | 36.34     | 62.44   | 0.48       | 0.76           | 1.25         | 0.23         | 0.08        |
| HD_18        | 43.34     | 58.00   | 0.54       | 0.85           | 1.38         | 0.25         | 0.08        |
| HD_19        | 48.60     | 67.15   | 0.70       | 1.10           | 1.79         | 0.33         | 0.11        |
| HD_20        | 28.74     | 53.67   | 0.33       | 0.52           | 0.85         | 0.15         | 0.05        |
| HD_21        | 13.43     | 54.94   | 0.16       | 0.25           | 0.41         | 0.07         | 0.02        |
| HD_22        | 31.76     | 62.96   | 0.43       | 0.67           | 1.10         | 0.20         | 0.07        |
| HD_23        | 14.39     | 50.18   | 0.15       | 0.24           | 0.40         | 0.07         | 0.02        |
| HD_24        | 46.57     | 61.21   | 0.61       | 0.96           | 1.57         | 0.29         | 0.09        |
| HD_25        | 25.44     | 61.99   | 0.34       | 0.53           | 0.87         | 0.16         | 0.05        |
| HD_26        | 18.71     | 55.30   | 0.22       | 0.35           | 0.57         | 0.10         | 0.03        |
| HD_27        | 38.82     | 56.47   | 0.47       | 0.74           | 1.21         | 0.22         | 0.07        |
| HD_28        | 21.45     | 63.68   | 0.05       | 0.46           | 0.75         | 0.14         | 0.05        |
| HD_29        | 16.72     | 64.35   | 0.23       | 0.36           | 0.59         | 0.11         | 0.04        |
| HD_30        | 43.31     | 50.71   | 0.08       | 0.74           | 1.21         | 0.22         | 0.07        |
| HD_31        | 29.40     | 61.13   | 0.38       | 0.60           | 0.99         | 0.18         | 0.06        |
| HD_32        | 12.86     | 42.08   | 0.12       | 0.18           | 0.30         | 0.05         | 0.02        |
| HD_33        | 11.46     | 81.78   | 0.20       | 0.32           | 0.52         | 0.09         | 0.03        |
| HD_34        | 66.80     | 62.36   | 0.15       | 1.40           | 2.29         | 0.42         | 0.14        |
| HD_35        | 35.26     | 63.47   | 0.48       | 0.75           | 1.23         | 0.22         | 0.07        |
| HD_36        | 17.16     | 79.93   | 0.05       | 0.46           | 0.75         | 0.14         | 0.05        |
| HD_37        | 40.50     | 82.72   | 0.12       | 1.13           | 1.84         | 0.34         | 0.11        |
| HD_38        | 24.65     | 82.62   | 0.07       | 0.68           | 1.12         | 0.20         | 0.07        |
| HD_39        | 186.49    | 74.14   | 2.95       | 4.65           | 7.60         | 1.38         | 0.46        |
| HD_40        | 8.09      | 62.41   | 0.02       | 0.17           | 0.28         | 0.05         | 0.02        |

(continued)
| Subcatchment | Area (ha) | Imperv% | Green roof | Porous pavement | Bioretention | Dry/wet pond | Grass swale |
|--------------|----------|---------|------------|----------------|--------------|--------------|-------------|
| HD_41        | 43.94    | 57.42   | 0.54       | 0.85           | 1.39         | 0.25         | 0.08        |
| HD_42        | 24.07    | 40.70   | 0.03       | 0.33           | 0.54         | 0.10         | 0.03        |
| HD_43        | 15.25    | 62.75   | 0.20       | 0.32           | 0.53         | 0.10         | 0.03        |
| HD_44        | 37.91    | 53.13   | 0.43       | 0.68           | 1.11         | 0.20         | 0.07        |
| HD_45        | 29.46    | 82.59   | 0.52       | 0.82           | 1.34         | 0.24         | 0.08        |
| HD_46        | 30.06    | 61.90   | 0.40       | 0.63           | 1.02         | 0.19         | 0.06        |
| HD_47        | 26.56    | 58.25   | 0.05       | 0.52           | 0.85         | 0.15         | 0.05        |
| HD_48        | 25.60    | 57.86   | 0.32       | 0.50           | 0.81         | 0.15         | 0.05        |
| HD_49        | 15.55    | 52.16   | 0.03       | 0.27           | 0.45         | 0.08         | 0.03        |
| HD_50        | 25.53    | 66.31   | 0.06       | 0.57           | 0.93         | 0.17         | 0.06        |
| HD_51        | 21.76    | 56.51   | 0.04       | 0.41           | 0.68         | 0.12         | 0.04        |
| HD_52        | 47.86    | 58.50   | 0.10       | 0.94           | 1.54         | 0.28         | 0.09        |
| HD_53        | 18.14    | 48.61   | 0.03       | 0.30           | 0.48         | 0.09         | 0.03        |
| HD_54        | 15.87    | 58.84   | 0.20       | 0.31           | 0.51         | 0.09         | 0.03        |
| HD_55        | 25.43    | 64.88   | 0.35       | 0.55           | 0.91         | 0.17         | 0.05        |
| HD_56        | 31.91    | 60.18   | 0.07       | 0.65           | 1.06         | 0.19         | 0.06        |
| HD_57        | 12.73    | 59.85   | 0.16       | 0.26           | 0.42         | 0.08         | 0.03        |
| HD_58        | 7.46     | 57.78   | 0.02       | 0.14           | 0.24         | 0.04         | 0.01        |
| HD_59        | 22.40    | 53.15   | 0.25       | 0.40           | 0.65         | 0.12         | 0.04        |
| HD_60        | 14.15    | 59.98   | 0.03       | 0.29           | 0.47         | 0.08         | 0.03        |
| HD_61        | 13.63    | 53.32   | 0.15       | 0.24           | 0.40         | 0.07         | 0.02        |
| HD_62        | 10.54    | 66.35   | 0.15       | 0.24           | 0.38         | 0.07         | 0.02        |
| HD_63        | 20.06    | 59.61   | 0.25       | 0.40           | 0.66         | 0.12         | 0.04        |
| HD_64        | 17.83    | 81.56   | 0.31       | 0.49           | 0.80         | 0.15         | 0.05        |
| HD_65        | 98.30    | 44.79   | 0.94       | 1.48           | 2.42         | 0.44         | 0.15        |
| HD_66        | 36.94    | 55.03   | 0.07       | 0.68           | 1.12         | 0.20         | 0.07        |
| HD_67        | 42.43    | 57.08   | 0.52       | 0.81           | 1.33         | 0.24         | 0.08        |
| HD_68        | 59.17    | 41.55   | 0.09       | 0.83           | 1.35         | 0.25         | 0.08        |
| HD_69        | 120.75   | 50.25   | 1.29       | 2.04           | 3.34         | 0.61         | 0.20        |
| HD_70        | 76.92    | 53.65   | 0.88       | 1.39           | 2.27         | 0.41         | 0.14        |
| HD_71        | 49.54    | 57.38   | 0.61       | 0.96           | 1.56         | 0.28         | 0.09        |
| HD_72        | 46.52    | 67.77   | 0.67       | 1.06           | 1.73         | 0.32         | 0.10        |
| HD_73        | 31.81    | 55.60   | 0.38       | 0.59           | 0.97         | 0.18         | 0.06        |
| HD_74        | 30.04    | 59.84   | 0.06       | 0.60           | 0.99         | 0.18         | 0.06        |
| HD_75        | 31.61    | 53.41   | 0.06       | 0.57           | 0.93         | 0.17         | 0.06        |
| HD_76        | 87.13    | 57.05   | 0.18       | 1.67           | 2.73         | 0.50         | 0.17        |
Re-evaluation of the site-scale LID layout

The disaggregated site-scale LID layouts for the HND watershed were implemented in the SUSTAIN model. Continuous simulations were carried out for the time period of 01 January 2011 to 31 December 2017. The runoff volume and pollutant load were compared against those from the post-development watershed, and the percentage reductions were calculated. As shown in Table 12, the disaggregated site-scale LID scenario achieves an annual average runoff volume reduction of 87.61%, and annual average pollutant load reductions for TSS, TN, and TP are 83.16, 84.42, and 82.53%, respectively.

The disaggregated site-level LID scenario achieved a better performance in annual runoff volume reduction (87.61%) than the composite LID volume (80%). This is because in the disaggregated site-scale LID layouts, individual LIDs were implemented in the series and thus achieved additional hydrologic and water quality benefits. Similar effects were also reported in previous studies, in which LID practices yielded higher benefits when implemented in the series than those when implemented individually (Joksimovic & Alam 2014; Eaton 2018).

Disaggregation of the near-optimal LID scenario is a manual process involving engineering judgments, and thus the hydrologic and water quality benefits could vary depending on the choice of LID types at individual sites. The careful study of site requirements of each LID type and individual site characteristics are required during this process. Whenever possible, LIDs with higher hydrologic and water quality efficiency are preferred over the ones that are less cost-effective (Gao et al. 2015; Mao et al. 2017; Zhang et al. 2018).

| Runoff conditions | Post-development | Site-scale LID scenario | Reduction (%) |
|-------------------|------------------|-------------------------|---------------|
| Annual average runoff volume (106 m³/yr) | 7.02 | 0.87 | 87.61 |
| TSS load (ton/yr) | 159.42 | 28.78 | 83.16 |
| TN load (ton/yr) | 3.98 | 0.62 | 84.42 |
| TP load (ton/yr) | 0.63 | 0.11 | 82.53 |

The LID sizing strategy presented in this study combines the watershed-scale optimization and the site-scale disaggregation for Sponge City planning. While the first step identifies the cost-effective LID sizes for each subcatchment and sets the LID volume for each subcatchment, the second step matches site-specific characteristics with LID site requirements, while ensuring the near-optimal LID volume (expressed as the aggregated LID area) stays the same for the subcatchment. Overall, this approach represents a feasible alternative to both a detailed representation of the site-scale optimization, which is computationally too expensive to execute, and an overly simplified watershed-scale analysis, which cannot guide LID implementations on the ground. The high percentage reductions in both the annual average runoff and pollutant loads prove that this approach is very promising in ensuring successful achievement of the Sponge City objectives.

Limitations

There are several limitations to this study. Firstly, the aggregated LID representation ignored land-use layouts in the individual subcatchment, and this could potentially result in mismatch during the disaggregation process. For an unlikely scenario, a subcatchment consisting of mainly buildings may find an insufficient rooftop to implement green roofs, as the required LID sizes are much larger. Engineering judgments are crucial in such circumstances to appropriate size LIDs or even balance the LID volume among neighboring subcatchments if necessary. Secondly, while the SWMM was calibrated using monitored data, the SUSTAIN model was not calibrated to local data, and thus the actual LID hydrological and water quality benefits could differ from what is reported in this study. Lastly, the long-term maintenance operation and management (O&M) costs are not included in this analysis.

Future research directions

This study shows that LID practices can effectively reduce the post-development stormwater peak flow rate and the annual total runoff volume. However, for high-plateau mountainous watersheds such as the HND watershed, heavy rainfall events during summer time could cause
severe peak flow rates and flooding, and the steep slope could only worsen the situation. Therefore, efforts are needed to investigate the potential combination of traditional stormwater control measures (e.g. regional stormwater ponds) and the LID practices in achieving flooding prevention during the extreme events. The real-time control technologies could also be used to achieve better management of stormwater. In addition, stormwater management studies need to consider climate change impacts and its influences on receiving water quantity and quality (Zhang et al. 2018).

As the HND watershed is still under development and the site conditions are constantly changing, no LID performance data are available at this time. It is recommended that monitoring stations be established in the HND watershed, and future studies need to include the calibration of LID practices using local data.

CONCLUSIONS

In this study, we developed a SUSTAIN model for a 25.90 km² watershed in the HND in southwest China. Composite LID volumes were identified for each subcatchment through the optimization analysis, and the results were then disaggregated to site-scale LIDs based on specific site conditions and engineering judgment. The resulting site-scale LID implementation reduced the annual average runoff volume by 87.61%, and the reduction of annual pollutant load reductions for TSS, TN, and TP were close to 85%, exceeding the Sponge City requirements for runoff volume control. The bioretention area was mostly used across all subcatchments due to its cost-effectiveness in treating stormwater runoff. The two-step Sponge City planning and implementation strategy is a good balance between the high-level cost-effectiveness analysis and the site-scale implementation analysis and could potentially be used for Sponge City planning in other cities.

This study demonstrates that LID practices can help achieve stormwater control targets set by the Sponge City program. For the Sponge City initiative to be successful in China, further studies are needed to evaluate LID performances at different climate regions, and possible combinations with traditional gray stormwater control measures are also needed in future studies.

ACKNOWLEDGEMENT

We thank Yumin Shang, Xiaoli Niu, and Ningbo Li of the Development and Management Commission of HND for their practical engineering advices during the LID siting process. Dr Rui Zou provided tremendous computational support for the LID optimization analysis.

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First received 21 June 2019; accepted in revised form 14 November 2019. Available online 13 December 2019.