Original Research

Measuring performance of low impact development practices for the surface runoff management

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ABSTRACT

Continuous urbanization over the last few years has led to the increase in impervious surfaces and stormwater runoff. Low Impact Development (LID) is currently receiving increased attention as a promising strategy for surface runoff management. To analyze the performance of LID practices for surface runoff management, a long-term hydrological modeling from 2001 to 2015 along with a cost-effectiveness analysis were carried out on a campus in Dresden, Germany. Seven LID practices and six precipitation scenarios were designed and simulated in a Storm Water Management Model (SWMM). A cost-effectiveness analysis was conducted by calculating the life-cycle costs and runoff removal rate of LID practices. Results demonstrated that the LID practices significantly contributed to surface runoff mitigation in the study area. The LID performance was primarily affected by the length of the precipitation scenarios and LID implementing schemes. The runoff removal rate of the LID practices fluctuated significantly when the rainfall scenario was shorter than 12 months. When the rainfall scenario exceeded 1 year the effects on the runoff removal rate was constant. The combination of an infiltration trench, permeable pavement, and rain barrel (IT+PP+RB), was the best runoff control capacity with a removal rate ranging from 23.2% to 27.4%. Whereas, the rain barrel was the most cost-effective LID option with a cost-effectiveness (C/E) ratio ranged from 0.34 to 0.41. The modeling method was improved in this study by conducting long-term hydrological simulations with different durations rather than short-term simulations with single storms. In general, the methods and results of this study provided additional improvements and guidance for decision-making process regarding the implementation of appropriate LID practices.

1. Introduction

The increase in proportions of impermeable surfaces due to the excessive urbanization in recent years has altered the catchment hydrological characteristics [1,2]. These changes have resulted in the increase in runoff generation [3–5]. The increased runoff contributes to multiple negative impacts, such as increased burden on the drainage system and urban flooding risks, reduced ground and river base flows, and degraded water quality [6–10]. Under these circumstances, an effective storm runoff management method is essential for managing the challenges of an urbanized world [11].

Traditional grey infrastructures include gutters, stormwater sewers, tunnels, culverts, detention basins, pipes, and mechanical devices, which are used collectively in a system to capture and convey surface runoff. These systems focus on the quick and effective removal of runoff through the direct collection, conveyance, detention, and discharge into natural water bodies [4]. The increase in the drainage capacity of grey infrastructures relies on expanding and upgrading the existing systems. However, due to the increased pressures of climate change and urbanization, reinforcing the capacity of grey infrastructures has been
increasingly proven to be costly, especially for highly urbanized areas [12–14]. The rapid rise of surface imperviousness and climate change-induced extreme rainfall events make expanding and upgrading the existing drainage system challenging since these methods do not comply with the aspirations of sustainable urban development [15,16].

More recently, low impact development (LID), which is also termed as water-sensitive urban design (WSUD), is regarded as a promising strategy for sustainable urban stormwater management [6,17,18]. Contrasting conventional centralized techniques, LID technology refers to the decentralized design, which reduces stormwater by mimicking pre-development hydrology and promoting processes of infiltration and evapotranspiration in the urban watersheds [7,17]. As a result, LID technology has attracted immense research interest in the past ten years, and meaningful efforts have been made by scholars to explore LID performance for surface runoff management.

The evaluation of LID performance includes multi-scale experiments and modeling [14,15]. Most of these studies emphasized the runoff control capacity of LID for short-term precipitation scenarios which represents a single heavy storm event with different intensities and durations. However, some scholars pointed out that LID practices are normally implemented as a long term functioning engineering measure, and the technical performance in short-term scenarios do not adequately represent the average performance during the long-term implementation. For example [4], found that LID practices during a three-month precipitation scenario performed generally better than in single hourly events [19]. Also noticed that the LID practices had an annual average runoff removal rate of 51.9%, whereas the values for single rainfall events ranged from 6.4% to 100%. Furthermore, since the engineering expense related to LID practices vary with time due to differences in the initial costs as well as maintenance and operating costs, it is not accurate to evaluate the cost-effectiveness of LID practices in a short period of time.

Accordingly, in order to improve the knowledge gaps of previous studies, this study proposed two main objectives: (i) evaluate the technical performance of LID practices for surface runoff management through long-term hydrological simulations and (ii) identify the optimal LID options through long-term cost-effectiveness analyses. The methods and results of this study will provide additional guidance for the decision-making processes related to LID practice implementation.

The remainder of this study is illustrated as follows: METHODS, which explained the methods and tools, as well as source data used in this study; the RESULTS AND DISCUSSIONS, which presented the results and corresponding discussions; the CONCLUSIONS, which summarized the results and implications of this study.

2. Methods

2.1. Study area

The study area was selected in the city of Dresden in Germany and was chosen based on the available data and funding constants. As presented in Fig. 1 and Table 1, the study area is a 0.85 km² campus area with multiple land cover types, including road, building, parking lot, squares, and green land. As showed in Fig. 2, the drainage network is distributed along the roads to collect and convey the stormwater runoff to three outlets on the north edge of the study area. This area has a typical

![Fig. 1. Scope and location of the study area in Germany and Dresden region.](image)
urbanized catchment and a complete drainage system and represents a suitable site to study the runoff management performance of different LID practices.

2.2. Model theory

The U.S. Environmental Protection Agency Storm Water Management Model (SWMM) was adopted as the modeling approach in this study. As a dynamic rainfall-runoff model, the SWMM has been continuously developed for the adoption in planning, analysis, and design of urban drainage systems since 1971 [9,20–22]. During the past few years, the SWMM was widely used for short term and long term hydrological simulations by scholars. The results generated from the SWMM is a suitable model to systematically and mathematically analyze runoff quantity and quality from catchments [8,9,14,19,22–24]. The SWMM calculates the generation and transportation of stormwater runoff based on two theoretical modules, which are the hydrological and hydraulic modules, respectively [13].

The hydrological module is used to simulate hydrological events such as time-varying precipitation and rainfall interception from depression storage. This module contains various hydrological objects, including rain gauges, sub-catchments, and LID controls [9].

The hydraulic module is used to simulate some hydro-mechanic processes such as external inflow of surface runoff, flow routing through pipelines, and possible flow regimes. This module also includes involves junctions, conduits, outfalls, and other hydraulic objects. The water flow in the drainage pipe network is simulated as a one-dimensional unsteady flow (Saint-Venant equations), which consist of conservation equations of mass and momentum [25].

2.3. Model construction

Four types of data were supplied by the local authorities to develop the model for the study area: piping network, terrain condition, satellite images, and hydrological records. Specifically, the piping network including locations and dimensions of manholes and pipes were stored as a DWG file in AutoCAD, the terrain condition was stored as a DEM model in ArcGIS, the satellite images of study area were stored as a TIF file, and hydrological records (i.e., historical rainfall events and corresponding flow rate of outlets from 1995 to 2015) were stored as a TXT file.

According to previous studies [26–29], the drainage system model was ideally constructed based on the following assumptions and simplifications:

1) Rainfall intensity is the same across the whole study area;
2) Only manholes at the starting point, endpoint, and intersection of pipelines are included in the model;
3) Catchment is subdivided according to the road distribution;
4) Runoff flows into the nearest manhole.

More specifically, 30 sub-catchments were added in accordance with location and shape of 30 blocks in the study area, and each sub-

Table 1

| Land cover     | Area (m²) | Imperviousness (%) |
|---------------|-----------|--------------------|
| Road          | 298,000   | 95                 |
| Building      | 109,640   | 90                 |
| Parking lot & square | 38,200 | 85                 |
| Greenland     | 404,160   | 25                 |
| Total         | 850,000   | 61                 |

Fig. 2. Model integrating based on: (a) Catchment imperviousness, (b) Catchment topography, (c) Drainage network distribution, and (d) Drainage model in SWMM.
catchment was assigned with specific impervious rates and surface slopes on the basis of catchment imperviousness and topography as shown in Fig. 2(a) and (b). In addition to the 36 junction nodes, 41 pipe links and 3 outfalls were deployed in the model based on the current pipe network distribution shown in Fig. 2(c). The constructed drainage model in the SWMM was presented in Fig. 2(d).

2.4. Calibration and validation

Some sensitive parameters related to depression storage capacity and surface roughness can affect the accuracy of hydrological and hydraulic simulations [30–32]. Based on previous studies in Dresden [33,34], four parameters were selected as sensitive parameters in this study. These parameters include N-Impervious, N-Pervious, Dstore-Impervious, and Dstore-Pervious. These parameters represent roughness coefficient and depression storage depth of impervious and pervious areas [22].

In order to improve the model accuracy, the key parameters were firstly assigned with empirical value ranges based on existing literature and the SWMM model technical manual [9,20,32,35,36]. These parameters were then further calibrated and validated against the observed and simulated flow rates of outfalls derived from hydrological records and simulations. Considering the potential change of catchment characteristics due to urban development over the past few years, the record of the latest four years from 2012 to 2015 was selected. More specifically, four rainfall events in the period from 2012 to 2013 were used for calibration, and four rainfall events from 2014 to 2015 were used for validation.

Several indexes were developed and commonly used by previous studies, such as coefficient of determination ($R^2$) [37,38], root mean squared error (RMSE) [15,39], and Nash-Sutcliffe efficiency coefficient (NSE) [6,12,26,27,29,40,41] to determine the goodness of fit of the results. The coefficient of determination ($R^2$) is commonly used to describe the consistency of simulated and observed data in hydrological modeling because of its high sensitivity to hydrological flow changes [30,31]. $R^2$ is expressed as the squared value of Pearson’s product-moment correlation coefficient, the value ranges from 0.0 to 1.0, indicating the goodness of fit from low to high [28,42]. $R^2$ was calculated in this study using Equation (1).

$$R^2 = \left( \frac{\sum_{i=1}^{n} (O_i - \bar{O})^2 \cdot (S_i - \bar{S})}{\left( \sum_{i=1}^{n} (O_i - \bar{O})^2 \right)^{1/2} \cdot \left( \sum_{i=1}^{n} (S_i - \bar{S})^2 \right)^{1/2}} \right)$$

where, $O_i$ is the $i$th observed value, $\bar{O}$ is the average value of all observed values; $S_i$ is the $i$th simulated value, $\bar{S}$ is the average value of all simulated values.

As presented in Table 2, the $R^2$ varied between 0.905 and 0.962, indicated that the validated model was acceptable [43,44]. Fig. 3 summarizes two of the calibration and validation results. The key parameters with the empirical value range and calibrated values were listed in Table 2.

2.5. Precipitation scenario

In order to evaluate the technical performance of the LID practices for surface runoff management through long-term hydrological simulations, six long-term precipitation scenarios with different durations were designed based on observed rainfall events from 2001 to 2015. Six scenarios with a rainfall intensity unit of millimeter/day (mm/day) and durations of 3 months, 6 months, 12 months, 60 months, 120 months, and 180 months were studied. Fig. 4 displayed the hyetographs of the six precipitation scenarios.

Table 2: Results of calibration and validation for key parameters.

| Key parameter     | Empirical value range | Selected rainfall event | Usage     | Correlation coefficient ($R^2$) | Calibrated value | Reference                  |
|-------------------|-----------------------|-------------------------|-----------|---------------------------------|------------------|----------------------------|
| N-Impervious$^a$  | 0.010–0.025           | 16.05.2012              | Calibration | 0.962                           | 0.012            | [32,36]                    |
|                   |                       | 15.05.2014              | Validation | 0.955                           |                  |                            |
| N-Pervious        | 0.04–0.80             | 14.08.2012              | Calibration | 0.918                           | 0.2              | [32,35,36]                 |
|                   |                       | 19.08.2014              | Validation | 0.905                           |                  |                            |
| Dstore-Impervious (mm)$^b$ | 1.27–3.81          | 30.05.2013              | Calibration | 0.926                           | 1.27             | [9,20,32]                  |
| Dstore-Pervious (mm) | 2.54–7.62          | 06.07.2013              | Validation | 0.909                           | 2.54             | [9,20,32]                  |
|                   |                       | 22.07.2015              | Validation | 0.940                           |                  |                            |

$^a$ N-Impervious/Pervious: Manning’s roughness coefficient of the impervious/pervious area.

$^b$ Dstore-Impervious/Pervious: Depth of depression storage of the impervious/pervious area.

Fig. 3. Partial results of model calibration & validation: (a) Calibration with rainfall on 16/05/2012, and (b) Validation with rainfall on 15/05/2014.
2.6 LID implementing scenario

Over the past decade, various LID practices have been developed, including Green Roof (GR), Rain Barrel (RB), Bio-Retention (BR), Vegetative Swale (VS), Infiltration Trench (IT), and Permeable Pavement (PP). Some LID practices have been successfully implemented in many parts of the world such as Maryland (USA), Berlin (Germany), Manchester (United Kingdom), and Chongqing (China) \[33,45,46\]. The benefits of the implementation of LID have been demonstrated by previous studies. For instance Ref. \[1\], documented that PP removed 34.8% of the runoff volume \[47\], concluded that the GR decreased runoff induced flooding damage by over 35% \[48\], reported that VS reduced 44.3% of the peak flow on average, and a combination of BR and IT was able to delay when the time point of peak flow occurred by over 30% according to Ref. \[12\].

According to policies and technical manuals developed by regional and national institutes \[46,49,50\], suitable implementing scenarios of LID practices can vary based on land-use types. Therefore, a systematic analysis on the catchment characteristics of the study area is the key to the implementation of LID. As shown in Table 1, the study area mainly consists of four land-use types: buildings, roads, parking lots, squares, and green space. The first three land-use types with sealed catchments are suitable for LID implementation. After reviewing the Dresden local and German national technical manuals \[51,52\], three LID practices were selected to implement in this study area. The characteristics of selected LID practices were listed in Table 3.

Considering the possibility of both single- and combined-applications of LID practices, seven implementing scenarios of selected LID practices were designed. Three scenarios implemented three single LID practices (IT, PP, and RB), and the remaining four scenarios implemented four LID combinations (IT + RB, IT + PP, PP + RB, and IT + PP + RB). Furthermore, previous studies reported that some technical parameters related to the infiltration and storage process should also be considered during the design of implementing LID scenarios \[22,24,59,60\]. Therefore, seven implementation scenarios with different installation sites and dimensions, and technical parameters were determined based on academic papers and design manuals, listed in Table 4. Installing locations for LID practices were determined according to land-use distribution and actual conditions of the study area. The approximate locations of implemented LID practices were presented in Fig. 5.

2.7 Cost-effectiveness analysis

Cost-effectiveness is an economic indicator generally used to compare expenditures and benefits achieved based on stormwater management measures \[62,63\]. In this case, the costs were expressed as a life-cycle cost (LCC) and the effectiveness was expressed as a runoff removal rate of LID practices.

The LCC is an economic index that involves all the associated expenses throughout the lifetime \[63\]. Since the LCC

### Table 3

| LID practice | Suitable installing site | Empirical installing ratio (%) | Unit | Empirical capital cost per unit ($) | Empirical annual cost per unit ($) | Empirical lifespan (year) | Reference |
|--------------|--------------------------|--------------------------------|------|----------------------------------|-----------------------------------|--------------------------|-----------|
| IT           | Roadside                 | 9–15                           | m²   | 72.57–117.36                    | 1.86–2.86                         | 15–50                    | \[4,53,54\] |
| RB           | Private building         | 10–50                          | L    | 17.36–48.02                     | 0.25–0.63                         | 10–40                    | \[54–56\]  |
| PP           | Parking lot              | 8–40                           | m²   | 50.71–77.29                     | 1.01–1.57                         | 8–30                     | \[14,54,\] 56–58 |

* IT: Infiltration Trench, RB: Rain Barrel, PP: Permeable Pavement.
involves all of the inputs and incurred costs during the whole lifespan, the present value of cost (PVC) for approach has been used for the simplified calculation of the LCC [53]. The present value of LCC was calculated by Equation (2).

\[ PVC = C_0 + \sum_{t=0}^{T} \left( C_a \cdot \frac{1}{(1+r)^t} \right) \]  

where, \( PVC \) is the present value of life-cycle cost, $; \( C_0 \) is capital cost, $; \( C_a \) is annual operation and maintenance cost, $; \( T \) is lifespan, years; \( t \) is time variation, year; \( r \) is the discount rate, which was set as 5% according to benchmark yield of infrastructures [53].

The runoff removal rate was determined through hydrological modeling and mathematical calculations. The drainage model in the SWMM was firstly simulated in the original scenario without LID implementation to determine the original runoff volume (\( V_o \)). Subsequently, the drainage model was simulated in scenarios with LID implementation to get the modified runoff volume (\( V_m \)). Runoff removal rate \( R \) was calculated by Equation (3).

\[ R = \frac{V_o - V_m}{V_o} \times 100\% \]  

The cost-effectiveness was expressed as the \( C/E \) ratio of LCC and the runoff removal rate of the LID practices. The \( C/E \) ratio indicated the economic-technical performance of the LID practice. Therefore, the lower the ratio signifies a more effective LID practice. The \( C/E \) ratio was calculated by Equation (4).

\[ \frac{C}{E} = \frac{LCC}{R} \]  

3. Results and discussion

3.1. Technical performance of LID practices

Combining six precipitation scenarios and seven LID implementing scenarios, a total of 42 simulations were conducted in this study to analyze the technical performance of the various LID practices for runoff removal in different rainfall patterns and LID implementing schemes. The simulation results were presented in Table 5 and the detail calculations for runoff removal rates of the LID implementing scenarios were illustrated in Table S1 in the Supplementary material.

As showed in Table 5, 12.9%–27.4% of the runoff volume was reduced in six precipitation scenarios by seven of the implemented LID options. These results suggest that the LID practices achieved effective mitigation of surface runoff. In addition, it can be seen from the results that the runoff control capacity could vary among different LID options.

![Installing locations for seven LID implementing scenarios of (a) IT, (b) PP, (c) RB, (d) IT + PP, (e) IT + RB, (f) PP + RB, and (g) IT + PP + RB.](image)

Table 4

| LID practice | Installing site | Installing ratio (%) | Installing dimensions (m²) | Soil layer porosity (%) | Soil layer hydraulic conductivity (m/d) | Storage layer thickness/barrel height (mm) | Storage layer clogging factor (%) | Drain delay (hr) | Reference |
|--------------|-----------------|----------------------|-----------------------------|-------------------------|---------------------------------------|---------------------------------------|-------------------------------|-----------------|-----------|
| IT           | Roadside        | 15                   | 11,224                      | 50                      | 0.3                                   | 450                                   | 0                             | n.a.            | [22,59]  |
| RB²          | Building        | 15                   | 13,469                      | n.a.                    | n.a.                                  | 680                                   | n.a.             | 6               | [22,61]  |
| PP           | Parking lot and square | 15 | 6734                     | 50                      | 0.3                                   | 300                                   | 0                             | n.a.            | [22,60]  |
| IT + RB      | Roadside and Building | 15 + 15 | 11,224 + 13,469 | 15 + 15 | 11,224 + 6734 |
| IT + PP      | Roadside and Parking lot and Square | 15 + 15 | 11,224 + 6734 |
| PP + RB      | Building and Parking lot and Square | 15 + 15 | 13,469 + 6734 |
| IT + PP + RB | Building and Parking lot and Square | 15 + 15 | 13,469 + 6734 |

² One rain barrel with a volume of 208 L (height: 680 mm, diameter: 625 mm) is designed to collect runoff from 100 m² of private building roof, and the drain delay time was set as 6 h according to technical manual [22].

b n.a.: not applicable.
12.9%–16.2%. As for the combine-applied LID options, the combination of IT + PP + RB showed the best performance in regards to the runoff removal rate range from 23.2% to 27.4%, while the combination of PP + RB only reduced about 20% of the surface runoff. This result indicated that the runoff control capacity can vary among different LID practices, and properly combined application of the LID practices is an effective way to improve the runoff reduction rate.

In addition, the variation of rainfall patterns was proven to be an impact factor for runoff mitigation effectiveness of the LID practice. As demonstrated in Table 5, the runoff volume removal rate showed a fluctuation in six precipitation scenarios. More specifically, the runoff removal rate of LID practices was at the lowest point in a 3-month rainfall scenario, and it climbed to the peak when the rainfall duration increased to 6 months. However, the runoff removal rate showed a slight drop and then remained in a stable range when the length of the rainfall scenario was longer than 12 months. Overall, the average runoff removal rate of the selected LID practices during the whole 15 years ranged from 14.2% to 25.0%. The reason for this result was that the 3-month and 6-month precipitation scenarios length was too short to comprehensively show the alteration in the rainfall patterns with seasonal changes, which leads to a larger fluctuation in the magnitude of rainfall events and the subsequent performance of the LID practices in the first two scenarios. In contrast, when the lengths of the last four precipitation scenarios were longer than 12 months and included different rainfall patterns based on four seasons, the magnitude of the rainfall events and technical performance of the LID practices only had a slight fluctuation due to the annual climate change. This result suggests that the short-term hydrological simulations could not reflect the average technical performance of LID practices during the long-term implementation, which aligns with previous studies.

### 3.2. Economic performance of LID practices

The economic performance of the LID practices was evaluated by calculating the LCC of seven LID implementation scenarios. Considering the length of the simulation period, the lifespan of all LID practices was set to 15 years in this study. The capital and annual costs of LID practices and the median values of the empirical ranges in Table 3 were assigned to calculate the LCC for single-applied LID options. As for the LID combinations, the LCC was the sum of all the values involved with the respective LID practices. The results of the economic performance were listed in Table 6 and the detail calculations for LCC of the LID implementing scenarios were illustrated in Table S2 in the Supplementary material.

As demonstrated in Table 6, RB was the cheapest LID option with the LCC of 0.774 million US dollars, whereas PP was the most expensive single-applied LID practice with the LCC of 0.774 million US dollars. This result indicated that the engineering expenses of LID practices varied widely due to the different structures involved. More specifically, RB was the cheapest LID practice because it was a simple barrel with several pipes, which was easy to install and maintain. In contrast, PP was the most expensive one among the three LID practices because of the large excavation and material requirements during the construction stage [54]. As for the combine-applied LID options, the combination of IT + PP + RB was the most expensive scenario which cost 1.065 million US dollars, followed by the combination of IT + PP cost 1.006 million US dollars during the whole lifespan. These results support that the LID implementing scenarios could cause a strong influence on economic performance of the different options and a mathematical analysis is essential to quantify this influence.

#### 3.3. Cost-effectiveness analysis

The cost-effectiveness of the LID practices was analyzed by calculating the C/E ratio of the LCC and runoff removal rates in the long-term precipitation scenarios. The results of the cost-effectiveness analysis were listed in Table 7.

As presented in Table 7, the RB showed the lowest C/E ratio range of 0.32–0.41 and PP had the highest C/E ratio ranging from 4.79 to 5.99. As for the LID combinations, the C/E ratio of the combination of IT + PP + RB ranged from 3.88 to 4.58. Although RB did not perform well for runoff reduction, it was the most cost-effective LID option due to the lowest engineering expense. In contrast, PP was the lowest cost-effective option because of the high LCC and the low runoff removal rate. Despite the best performance for runoff removal, the combination of IT + PP + RB was not the most cost-effective option due to the high engineering expense. The LID technical performance, which was unlike the engineering expense, did not proportionally increase with the combined implementation of LID practices. Thus the combined-applied LID options generally had a higher C/E ratio relative to the single-applied LID options. This result illustrated that during the determination process for LID implementation, it is not proper to solely evaluate the LID options based on the technical performance or economic performance. The integrated consideration of both factors could be a more reasonable way for proper decision-making.

![Table 5](https://example.com/table5.png)

**Table 5** Technical performance of seven LID implementing scenarios.

| LID practice | Runoff volume removal rate (m³) |
|--------------|----------------------------------|
|              | 3 Mon 6 Mon 12 Mon 60 Mon 120 Mon 180 Mon |
| IT           | 14.93% 18.60% 17.92% 16.48% 15.96% 16.36% |
| PP           | 12.93% 16.16% 15.51% 14.20% 13.75% 14.10% |
| RB           | 14.30% 17.85% 17.14% 15.74% 15.25% 15.64% |
| IT + PP      | 19.86% 23.73% 23.01% 21.51% 20.97% 21.40% |
| IT + RB      | 21.61% 25.68% 24.87% 23.30% 22.76% 23.23% |
| PP + RB      | 18.22% 21.98% 21.24% 19.77% 19.26% 19.68% |
| IT + PP + RB | 23.24% 27.42% 26.64% 25.04% 24.46% 24.94% |

* Mon: month.

#### Table 6

**Life-cycle cost of seven LID implementing scenarios.**

| LID practice | Installing dimensions (m²) | Assigned capital cost per unit ($) | Assigned annual cost per unit ($) | Assigned lifespan (year) | PVC (million $) |
|--------------|----------------------------|-----------------------------------|----------------------------------|-------------------------|-----------------|
| IT           | 11,224                     | 11.97                             | 0.80                             | 15                      | 0.232           |
| RB           | 13,469                     | 3.68                              | 0.06                             | 15                      | 0.058           |
| PP           | 6734                       | 110.15                            | 0.44                             | 15                      | 0.774           |
| IT + RB      | 11,224 + 13,469            |                                   |                                  | 15                      | 0.291           |
| IT + PP      | 11,224 + 6734              |                                   |                                  | 15                      | 1.006           |
| PP + RB      | 13,469 + 6734              |                                   |                                  | 15                      | 0.832           |
| IT + PP + RB | 11,224 + 13,469 + 6734     |                                   |                                  | 15                      | 1.065           |

* PVC for LID combination is the sum of PVC for all involved LID practices.

#### Table 7

**Result of cost-effectiveness analysis.**

| LID practice | C/E ratio (%) |
|--------------|---------------|
|              | 3 Mon 6 Mon 12 Mon 60 Mon 120 Mon 180 Mon |
| IT           | 1.55 1.25 1.29 1.41 1.45 1.42 |
| PP           | 5.99 4.79 4.99 5.45 5.63 5.49 |
| RB           | 0.41 0.32 0.34 0.37 0.38 0.37 |
| IT + PP      | 5.07 4.24 4.37 4.68 4.80 4.70 |
| IT + RB      | 1.35 1.13 1.17 1.25 1.28 1.25 |
| PP + RB      | 4.56 3.79 3.92 4.21 4.32 4.23 |
| IT + PP + RB | 4.58 3.88 4.00 4.25 4.35 4.27 |

* C/E ratio: Cost-effectiveness ratio.
3.4. Research implications

This study evaluated the performance of LID practices for stormwater runoff control using a long-term hydrological modeling and cost-effectiveness analysis. Two contributions were expected to be made. Firstly, the modeling method was improved in this study through conducting multiple long-term hydrological simulations with different durations rather than single storm events with short-term scenarios. This improved approach allows for a more comprehensive evaluation of the LID technical performance. Secondly, results suggested that the RB was the most cost-effective LID practice and IT + PP + RB performed the best based on technical performance based on LID combination on the campus area in Dresden, Germany. These two LID options were expected to be considered in environmental policies as potential solutions for storm runoff management in both this area and other campuses across Germany.

Despite the comprehensive nature of this study, the results bring to light potential limitation of this study. This study mainly focused on the impact of the long-term rainfall duration on the LID performance, while the LID performance could also be affected by several other factors (e.g., rainfall patterns, installing dimensions, and technical parameters of LID practices), which could lead to uncertainties for LID implementation. Therefore, two potential directions will be considered in future research on this topic to improve the comprehensiveness of this study. For example, the uncertainty analysis of aforementioned influential factors and the comprehensive evaluation of the LID performance through more scenarios should be evaluated.

In summary, the methods and results of this study provided additional improvements and guidance for the decision-making process related to the LID practice implementation.

4. Conclusion

In order to analyze the performance of the LID practices for surface runoff management, long-term hydrological modeling and cost-effectiveness analysis were carried out in this study. A total of 42 long-term hydrological simulations were conducted to analyze the technical performance of the LID practices for runoff removal. Results supported that the LID technical performance was affected by the length of the precipitation scenarios and LID implementing schemes. The runoff removal rate of LID practices fluctuated largely when the rainfall scenario was shorter than 12 months and remained in a tighter range when the precipitation duration exceeded 1 year. The combination of the infiltration trench and permeable pavement, as well as rain barrel (IT + PP + RB), showed the best runoff control capacity with a removal rate range of 23.2%–27.4%.

The cost-effectiveness analysis was carried out to analyze the economic-technical performance of the LID practices. Results suggested that the RB was the most cost-effective LID option with a C/E ratio range of 0.32–0.41 and PP had the highest the C/E ratio ranging from 4.79 to 5.99. As for the LID combinations, the combination of IT + PP + RB with a C/E ratio range of 3.88–4.58 was not the best technically-economic performing option despite the highest runoff removal rate.

This study improved the modeling method through conducting multiple long-term hydrological simulations with different durations rather than single storms with short-term scenarios, which allows for a more comprehensive study of LID technical performance. The evaluation method in this study could also be used to analyze the performance of storm runoff management measures and provide additional guidance in the decision-making process for similar approaches.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esse.2020.10010.

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