Front. Eng. Manag. 2021, 8(1): 88–97
https://doi.org/10.1007/s42524-020-0063-y

RESEARCH ARTICLE

Pengfei ZHANG, Samuel T. ARIARATNAM

Life cycle cost savings analysis on traditional drainage systems from low impact development strategies

Abstract Areas that are covered with natural vegetation have been converted into asphalt, concrete, or roofed structures and have increased surface impermeability and decreased natural drainage capability. Conventional drainage systems were built to mimic natural drainage patterns to prevent the occurrence of waterlogging in developed sites. These drainage systems consist of two major components: 1) a stormwater conduit system, and 2) a runoff storage system. Runoff storage systems contain retention basins and drywells that are used to store and percolate runoff, whereas conduit systems are combination of catch basins and conduit pipes used to collect and transport runoff. The construction of these drainage systems is costly and may cause significant environmental disturbance. In this study, low impact development (LID) methods that consist of extensive green roofs (GRs) and permeable interlocking concrete pavements (PICPs) are applied in real-world construction projects. Construction project documents were reviewed, and related cost information was gathered through the accepted bidding proposals and interviews of specialty contractors in the metropolitan area of Phoenix, Arizona. Results indicate that the application of both LID methods to existing projects can save an average of 27.2% in life cycle costs (LCC) for a 50-year service life and 18.7% in LCC for a 25-year service life on the proposed drainage system, respectively.

Keywords low impact development, traditional drainage system, hydraulic benefits, life-cycle cost

Received April 2, 2019; accepted June 23, 2019

Pengfei ZHANG, Samuel T. ARIARATNAM (✉)
School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287–3005, USA
E-mail: ariaratnam@asu.edu

1 Introduction

Urbanization has caused enormous challenges regarding stormwater management in cities. The conversion of vegetation covers into concrete pavement ones has reshaped urban permeability capacity, thereby increasing runoff volume and peak flow rates. Storm-affected areas are more likely to experience increased precipitation due to climate change, which affects precipitation patterns. Thus, drainage systems are becoming more vulnerable to flooding. Drainage systems that are designed to follow site grading will be proposed to reduce the potential development-induced flooding risks.

The construction of traditional drainage systems is a common method used to reduce flooding risks that are associated with urbanization. The implementation of a drainage system generally involves significant land disturbance and excavations that alter the natural hydrological cycle and increase onsite environmental issues. These systems are also expensive to build, involve heavy construction machines, and require long working periods. The implementation of traditional drainage systems in dense urban environments have become increasingly difficult due to complicated underground environments, thereby creating a need for low footprint solutions. This need has resulted in emerging opportunities for low impact development (LID) methods, which are viewed as an environmentally friendly alternative for addressing stormwater runoff. LID methods aim to mimic natural drainage patterns by increasing urban permeability and keeping runoff close to its source. The hydrological benefits of the two LID methods, namely, extensive green roof (GR) and permeable interlocking concrete pavement (PICP), have been identified in previous experiments (Zhang and Ariaratnam, 2018).

Numerous prior research studies have assessed the runoff mitigation performance of GR and PICP. However, only few studies have compared the cost-effectiveness of LID methods and traditional drainage systems. This study aims to explore the cost-effectiveness of applying LID methods to real-world projects. The cost information of traditional drainage systems was obtained from a local specialty contractor who specializes in building underground drainage systems in the Phoenix metropolitan area. The results of this study aim to fill the knowledge gap in the life-cycle cost efficiency of green infrastructure in current urban developments.

As a continuation of a previous study (Zhang, 2019), this work presents a comprehensive cost savings analysis on the traditional drainage system after applying LID. To identify the traditional drainage system, project documents for three construction projects were reviewed to gather information, including the locations of the proposed catch basins and information regarding the conduit pipes between the catch basins.

The hydrological contribution area for each water collection point within the project area was delineated and segmented on the basis of the grading and drainage plan, respectively. The weighted runoff coefficient of each contribution area was recalculated in terms of the applicable area of extensive GR and PICP. The peak flow rate of each delineated drainage area was changed according to the modified runoff coefficient. Subsequently, the required conduit sizes for transporting stormwater can be altered.

The required conduit pipe sizes can be determined using the Manning equation, which incorporates factors such as runoff flow rate, roughness coefficient, and flow slope. This equation is commonly used to determine the required drainage pipe sizes (Flood Control District of Maricopa County, 2018). The peak flow reduction performance of a specific rainfall event was determined by reviewing the hydrological experiments performed by other scholars.

2 Literature review

The hydrological performance of the investigated LID methods must be identified to fully understand their cost benefits. As a continuation of the previous research that only considered volume reduction benefits when applying LID methods, this work includes the benefits of reduced runoff flow rate in the cost benefit analysis. Published studies on flow reduction performance are examined to gain an improved understanding of the hydrological advantages of extensive GR and PICP. The runoff reduction performance is correlated to the land cover types and the rainfall intensity or return period of the precipitation event. The following section describes prior research that were conducted in PICP and extensive GR to remarkably understand the flow reduction performance under the designed rainfall depth and intensity.

2.1 PICP

Collins et al. (2008) conducted a field study to monitor the peak flow rate in permeable pavement parking lots in eastern North Carolina. Throughout the 36 rainfall events, the parking lots installed with PICP observed an average reduction of 71% in peak flow, and even 100% maximum peak flow reduction during some smaller rainfall events. For example, only 1.2% of rainfall volume was converted into surface runoff during a storm event with 6–50 mm rainfall.

Drake et al. (2014) evaluated the hydrologic performance of three different permeable pavement systems over consecutive seasons and quantified the reduction in runoff volume and peak flow. The experiment site was constructed at a parking lot located in Ontario, Canada. Moreover, two different PICP manufacturers were selected to examine the hydrologic performance of the three different permeable pavement systems. The research results indicated that PICP could reduce peak flow rate by as much as 89% compared with traditional asphalt pavement during a 51.6 mm rainfall with an intensity of 21.8 mm per hour.

Suripin et al. (2018) observed a significant reduction in volume and peak discharge from a PICP retrofitted parking lot in Semarang, Indonesia. The field results showed that no surface runoff occurred under rainfall intensity of up to 90 mm per hour, and runoff only occurred two hours after a rainfall event with an intensity of 137 mm per hour.

Braswell et al. (2018) examined the hydraulic performance of PICP built over soil with low conductivity. The experiment occurred in four parking stalls retrofitted with PICP in Durham, North Carolina. The study results indicated that the PICP retrofitted parking stalls reduced peak flow by 98% during rainfall with an intensity of 23.6 mm per hour and by 63% during rainfall with an intensity of 20.3 mm per hour, respectively.

Shafique et al. (2018) investigated the runoff mitigation performance of PICP in a populated area in Seoul, South Korea and determined its runoff retaining performance and capability in different storm events. The research results claimed that 100% of runoff was retained under rainfall with an intensity of 40 mm per hour, and 30% to 50% of runoff was reduced under rainfall with intensity of up to 120 mm per hour, respectively. The research concluded that the PICP system can capture all rainfall runoff during small storms with intensity of less than 40 mm per hour.

2.2 Extensive GR

Hakimdavar et al. (2014) examined the impacts of rainfall characteristics and GR scale on the peak and cumulative volumes generated from extensive GR. The hydrological performance of three extensive GRs in New York City was analyzed. The results indicated that extensive GR can reduce peak flow by approximately 63.5% under 50 mm deep rainfall with an intensity of 24 mm per hour.

Razzaghmanesh and Beecham (2014) presented the hydrological investigation of four medium-scale GRs that were set up in Australia. Among the 226 recorded rainfall events, the average runoff retention coefficient for intensive and extensive GRs was determined to be 89% and 74%, respectively. The two-year experimental results also suggested that the average peak flow rate of extensive GR for average rainfall depths of 19.1 mm and 22.5 mm could be reduced by 78.7% and 44.3%, respectively. Moreover, the peak attenuation of extensive GR for a rainfall with depth of 30.8 mm was observed as 95.25%.

Hill et al. (2017) assessed the relative influence of four independent variables on the hydrological performance of 24 extensive GRs. The four design variables included native species versus sedum, mineral-based versus biologically derived planting mediums, 10 cm versus 15 cm depth, and irrigation provided daily versus none at all. During the study period, that is, from May 2013 to October 2014, the mean peak runoff coefficient was determined as 0.12. This coefficient remained consistent and was not sensitive to the four design factors. The research indicated that the mean peak runoff coefficient was robust and suitable for any extensive GR conditions.

Soulis et al. (2017) analyzed the relationship between the runoff reductions caused by different types of extensive GR systems, initial moisture conditions, and total rainfall depth. The experiment used 30 specialized lysimeters equipped with extensive GR laying and found that the reduction in runoff volume ranged between 2% and 100%, and that the peak flow reduction rate ranged between 17% and 100%. The discrepancy in the runoff reduction performance was attributed to the scope of the observed rainfall events, which had depths that varied from 0.6 to 45.4 mm and intensities that varied from 0.6 to 84 mm per hour. More importantly, the initial soil moisture of extensive GR plays an important role in the hydrological performance. For example, the lowest runoff reduction (2%) was observed in an experimental sample during a rainfall event of 43.4 mm because the initial soil was saturated and cannot hold considerable amount of water. Despite the lower runoff reduction in certain samples, the authors affirmed that GR can achieve a 100% reduction in both runoff depth and peak runoff rate during small rainfall events and under dry initial soil moisture conditions.

3 Research methodology

This study aimed to perform an integrated cost comparison between LID methods-based and traditional drainage systems. As a continuation of a previous research study, the current study considers the cost savings of not only the stormwater storage system, but also the stormwater conduit pipes, because LID methods lead to a reduced runoff flow rate. Three construction projects that are recently built in the metropolitan area of Phoenix, Arizona were assessed. Project information, including the applicable area for extensive GR and PICP, were previously measured. Project information, including the location of catch basins, construction information of the conduit pipes, and the grading plans for the sites, were examined in this work. The presented analysis maintained the original design on the drainage grading plan, depth, and slope of the conduit pipes to mitigate the influence of other construction variables on costs.

The first stage of this study involved the location of the existing catch basins and associated conduit pipes. Conduit pipes transported runoff from impervious surfaces, such as roofs, parking spaces, paved streets, and sidewalks to the water collection system. The sizes of the conduit pipes are correlated with the upstream flow rate, Manning's roughness coefficient, and pipe slopes (Eq. (4)). Watershed delineation and segmentations were performed to set the hydrology contribution area for each catch basin to determine the upstream flow rate. The watershed area for each catch basin was determined on the basis of the grading drainage plans, the grade break lines, and the existing flow path plan shown in the construction documents.

Experimental results (Collins et al., 2008; Drake et al., 2014; Hakimdavar et al., 2014; Hill et al., 2017; Soulis et al. 2017; Braswell et al., 2018; Shafique et al., 2018; Suripin et al., 2018) from the literature review were utilized to calculate the runoff coefficient for LID (Eq. (1)). Afterwards, the applicable area for extensive GR and PICP within each delineated watershed was outlined and the modified runoff coefficient for each watershed was recalculated using Eq. (2). The initial runoff flow rate and modified runoff flow rate within each delineated watershed were calculated using Eq. (3). The weighted runoff coefficient, as listed in the project documents, was utilized to determine the initial runoff flow rate. The runoff flow rate that enters each catch basin was altered according to the modified runoff coefficient for each affected watershed, thereby different sizes of conduit pipes is required downstream. Flow accumulations from upstream to downstream were considered to accurately determine the required pipe sizes.

$$C_{i(\mathrm{lid})} = C_{i(\mathrm{lc})} \times (1-PR), \tag{1}$$

where $C_{i(\mathrm{lid})}$ is the runoff coefficient for a specific LID method, $C_{i(\mathrm{lc})}$ is the runoff coefficient for the original land cover (pavement = 0.9, roof = 0.95), and PR is the peak flow reduction performance for the investigated LID methods.

$$C_{\mathrm{w}} = \frac{\sum C_i \times A_i}{\sum A_i}, \tag{2}$$

where C_{w} is the weighted runoff coefficient, C_i is the runoff coefficient associated with different land cover type, and A_i is the area of different land cover types within each watershed (acre).

$$Q = C_{\mathrm{w}} iA, \tag{3}$$

where Q is the runoff flow rate (cfs, cubic feet per second, 1 cfs = 0.028 m^3/s), i is the NOAA Atlas 14 precipitation intensity (inch/hour), and A is the watershed area (acre).

$$D = 1.33\left(\frac{nQ}{\sqrt{S}}\right)^{\frac{3}{8}}, \tag{4}$$

where D is the diameter of the conduit pipes (ft), n is the Manning's roughness coefficient, and S is the slope of the storm drain.

A life cycle costs (LCC) analysis for constructing the modified pipes was carried out by following the alternative design of the conduit pipes. To conduct a cost analysis for the alternative design, numerous accepted bidding proposals for building local drainage systems were reviewed to determine the average construction costs for various conduit pipe sizes. The net present value (NPV) was selected for the cost benefit analysis (Eq. (5)). The LCC analysis approach selected in this study adopted the whole life cost models developed by the Water Environment Research Foundation (2009). The methodology of whole life cost models combines capital costs and ongoing maintenance expenditures and estimates the life cycle costs for given LID strategies. Similar models were adopted by various researchers and organizations to analyze the LCC of different green infrastructure strategies (Uda et al., 2013; Joksimovic and Alam, 2014; City of Phoenix, 2018).

$$NPV = C_{\text{capital}} + \left|\sum_{t=0}^{n} \frac{M}{(1+i)^t} + \frac{R}{(1+i)^t}\right|, \tag{5}$$

where C_{capital} is the capital construction cost initially spent, M is the periodic maintenance cost, R is the replacement cost after the life expectancy, i is the discount rate, and n is the number of service years.

4 Case studies

4.1 Project descriptions

4.1.1 Case study #1 — Multifunctional building in Scottsdale, Arizona

The first project involved 13.76 ha (34 acres) of land disturbance for constructing a multifunctional building and was built in 2017. A drainage system that included various sizes of high-density polyethylene (HDPE) pipes, Maricopa Association of Governments (MAG) 537 single/double catch basins, above-ground retention basins, and 15 drywells, was constructed to address the runoff generated onsite. The conduit pipes used to direct the runoff were 252 m (827 feet) of 30", 268 m (879 feet) of 24", 310 m (1017 feet) of 18", 218 m (715 feet) of 15", and 673 m (2208 feet) of 12" HDPE. Conventional roof coverage accounts for 9% of the total project area, whereas the coverage rate for the asphalt parking spaces is 22.4% based on the project description.

With new construction, the runoff from the once-in-a-century storm event lasting for 2 h, which has a total of 55 mm (2.17 inches) rainfall with an intensity of 24 mm (0.94 inches) per hour, will be drained to the retention basins and subsequently percolated to the subsurface to recharge the groundwater through the drywell system. A total of 39 watersheds were delineated, and 1073 m (3520 feet) of associated conduit pipes were selected to perform the alternative design based on the grading plan and location of the catch basins.

4.1.2 Case study #2 — Multifamily development in Phoenix, Arizona

The second case study was a 5.72 ha (14.13 acres) multifamily development in Phoenix, Arizona that was built in 2018. A traditional drainage system, including underground retention tanks, various sizes of conduit pipes, 20 MAG catch basins, 12" Nyloplast area drains, and storm-drain manholes, was constructed to mitigate the increase in runoff caused by the development. In this case, the conduit pipes consisted of 183 m (600 feet) of 24", 280 m (919 feet) of 18", 390 m (1280 feet) of 12", 615 m (2018 feet) of 8", and 607 m (1991 feet) of 6" HDPE. A corrugated metal pipe (CMP) with an inner diameter of 3.05 m (10 feet) was constructed to retain the post-development runoff. The designed rainfall depth for the project was 58 mm (2.28 inches) with an intensity of 28 mm (1.1 inches) per hour. The retention capability provided by the designed retention basin was 1421 m^3, and five drywells were installed to de-water the stored runoff within 36 h after a rainfall event. Meanwhile, 1.7 ha (4.2 acres) of conventional flat roof was selected as the roof portion of the project, and 50.8 mm (2 inches) thick asphalt pavement was selected to construct the traditional parking spaces that is equivalent to approximately 0.51 ha (1.26 acres).

A total of 20 watersheds were delineated (Fig. 1), and 497 m (1631 feet) of conduit pipes was selected for the alternative design based on the drainage and grading plans for the land development (Fig. 2). Areas that are filled with different colors in Fig. 1 represent different watersheds. In Fig. 2, triangle markers indicate the location of catch basins, and lines with different colors display the size differences of the conduit pipes.

4.1.3 Case study #3 — Resort-style apartment building in Chandler, Arizona

The third project was a resort-style apartment building located in downtown Chandler, Arizona. The project was located on 2.24 ha (5.54 acres) of land development and was built in 2018. An onsite drainage system, which

Fig. 1 Watershed segregation per grading and drainage plan.

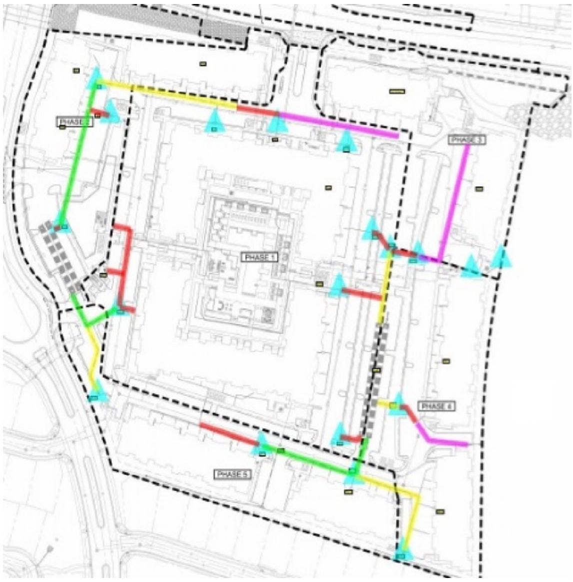

Fig. 2 Catch basins and associated conduit pipes.

included various sizes of HDPE, catch basins, underground retention basins, and drywells, was built to reduce the impact of runoff. According to the job description contained in the project documents, the designated rainfall depth was 55 mm (2.17 inches), with a peak intensity of 27 mm (1.06 inches) per hour. CMPs with an inner diameter of 2.44 m (8 feet) were constructed to provide 1132 m^3 of water retention capacity, and four drywells were proposed to discharge the stored runoff in 36 h.

A conventional flat roof was selected to be the roof portion and accounted for 29% of the project area. A 101.6 mm thick asphalt pavement was selected to cover the parking spaces and accounted for 13% of the project area. To transport the runoff, 458 m (1502 feet) of 12" and 577 m (1893 feet) of 8" HDPE were installed. A total of 17 watersheds were delineated, and 302 m (991 feet) of various sizes of HDPE were depicted between watersheds based on the grading and drainage plans.

4.2 Comparison of watershed segregation and peak flow rate

Watershed segregation was performed on the basis of existing grading and drainage plans to reduce cost variations caused by construction factors, such as grading-induced cost increment. The grade break lines were used to delineate the watershed on the ground surface, whereas the runoff generated from the roof was associated with how the roof outflow pointed and the catch basin were connected. The roof drain connection varies across different projects. For example, Case studies #2 and #3 apply rooftop disconnection and drain the runoff generated from the rooftop via overland flow, whereas Case study #1 connects the roof drain directly to the catch basin through the conduit pipes. Such construction variations distinguish the watershed segmentations from each other. Following the watershed segmentation, the applicable area for LID methods in each watershed was measured, and the modified weighted runoff coefficient was calculated using Eq. (4).

The study presents a reduction in the peak flow within each watershed for the three investigated case study projects. The difference between the initial and modified flow rates are regarded as the hydraulic benefits of applying LID methods. Figure 3 illustrates the flow rate comparison within each watershed in Case study #1, in which the results indicate that the application of LID methods can reduce 36.8% of the overall flow rate for the entire project. Figure 4 presents the flow rate variations in the watersheds for Case study #2, which exhibits an average reduction of 34.6% in the overall peak flow rate. Similarly, Fig. 5 indicates reductions in the peak flow rates for Case study #3, in which the results suggest that the application of LID methods can reduce the overall runoff flow rate by 21%. The findings show that reductions in peak flow rates within each watershed are noticeable across different case studies, especially for Case study #2, where a reduction in peak flow rate was observed in every delineated watershed (Fig. 4).

4.3 Alternative design for conduit pipes

The observation of the flow rate reduction within the majority of watersheds initiated the alternative design of existing conduit pipes. The flow accumulation at each catchment point was used to determine the combined flow rate of the downstream conduit pipes. Conduit pipes that connect watersheds were identified, and the associated pipe information, such as slope and Manning's roughness

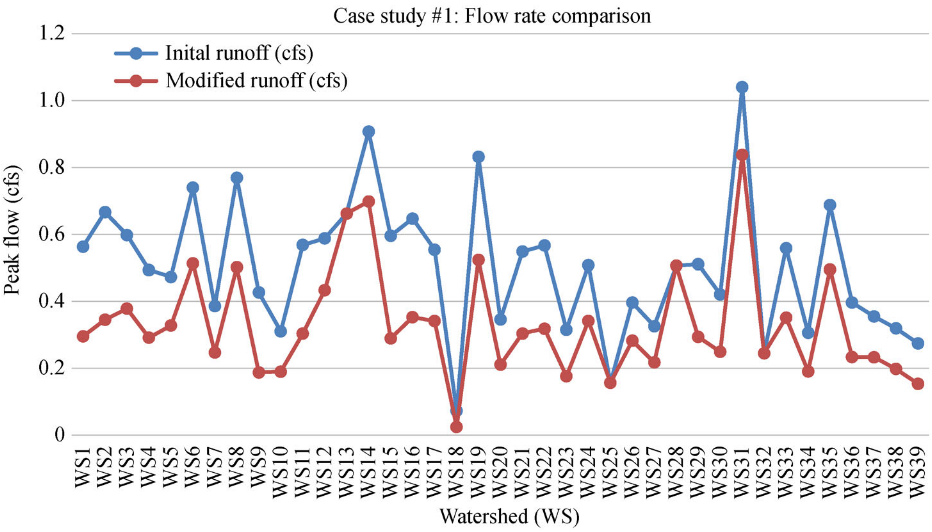

Fig. 3 Runoff flow rate comparison at each watershed (Case study #1).

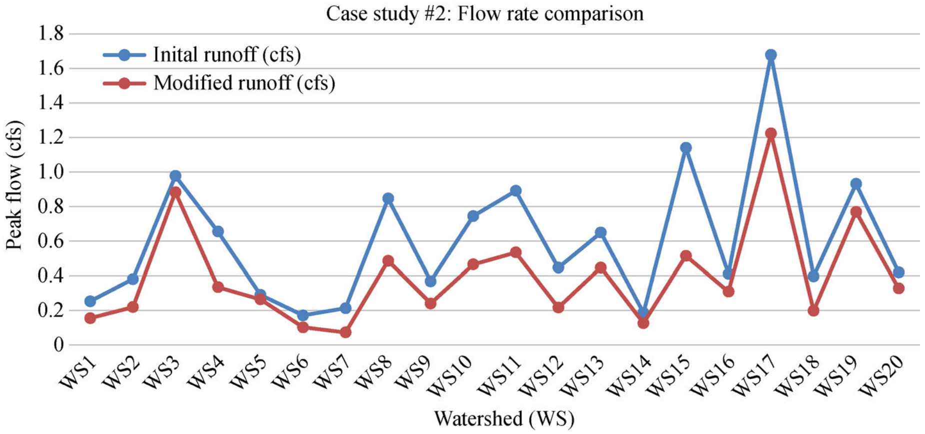

Fig. 4 Runoff flow rate comparison at each watershed (Case study #2).

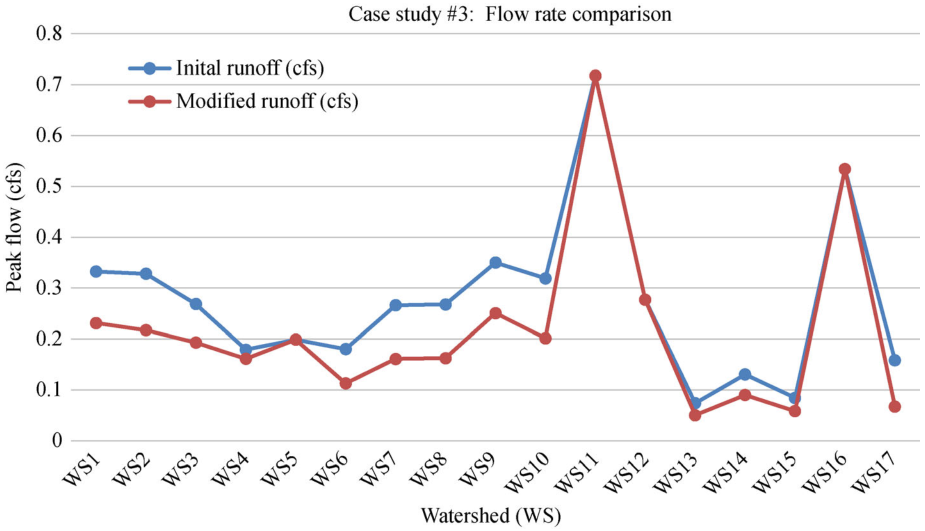

Fig. 5 Runoff flow rate comparison at each watershed (Case study #3).

coefficient, was collected. The flow directions between watersheds are presented in Table 1. The modified pipe sizes are calculated using Eq. (3). Table 1 also summarizes the results from the alternative design of conduit pipes in the three case study projects and presents the accumulated runoff flow that enters each watershed and the pipe sizes according to the changes in runoff flow.

A notable decrease in peak flow rate was found due to the application of LID methods, and the average reduction in pipe sizes in the investigated case studies was 63.5 mm (2.5 inches). The cost savings that are attributed to the reduction in the dimensions of existing pipe were analyzed. Table 2 presents the life-cycle cost savings for different service years at various discount rates. The life expectancy of HDPE can reach 50 years, and the replacement cost is 20% more than the capital cost, including that of demolition. Maintenance activities for storm drainage conduits were not commonly performed, as confirmed by a local project manager with over 30 years of experience in constructing drainage systems. This phenomenon may be attributed to the fact that storm drainage systems do not typically generate direct revenue. Thus, capital expenditures for underground pipes are spent elsewhere.

5 Results and discussion

This research mainly aims to analyze the LCC savings achieved by applying LID methods while meeting drainage requirements. This study used previous research that identified the cost savings achieved by applying stormwater storage units and supplementary drywell systems, which percolated stored runoff to the subsurface and recharged the ground water. The research objective of the previous study considers the volume reduction benefits of extensive GR and PICP, causing a certain amount of runoff to be retained onsite instead of relying on a traditional storage system. This phenomenon reduced the required volume of the stormwater storage units, thereby requiring fewer drywells. The current study considered not only the benefits of runoff volume reduction, but also the peak flow reduction, which modified the required dimensions of the conduit pipes.

Table 1 Summary for the alternative design

	From	To	Initial accumulated flow (cfs)	Modified accumulated flow (cfs)	Initial pipe size (inch)	Modified pipe size (inch)
Case Study #1	WS1	WS2	0.50	0.23	15	12
	WS2	WS3	1.05	0.46	18	15
	WS3	Outflow	1.50	0.70	18	15
	WS4	WS5	0.45	0.25	15	15
	WS5	Outflow	0.81	0.46	15	15
	WS6	WS7	0.42	0.19	15	15
	WS7	WS8	0.71	0.35	18	15
	WS8	WS9	1.18	0.55	24	22
	WS9	WS10	1.61	0.73	24	22
	WS10	WS11	1.87	0.87	24	22
	WS11	WS12	2.32	1.07	30	24
	WS12	WS13	2.81	1.40	30	26
	WS14	WS15	0.59	0.38	18	18
	WS15	WS16	1.15	0.63	18	18
	WS16	WS17	1.67	0.86	24	22
	WS17	WS18	2.10	1.08	24	22
	WS19	WS20	0.55	0.24	18	15
	WS20	WS21	0.84	0.40	24	22
	WS21	WS22	1.27	0.58	24	20
	WS22	WS23	1.72	0.78	30	24
	WS23	WS24	2.01	0.93	30	24
	WS24	WS25	2.34	1.10	30	24
	WS25	WS26	2.43	1.19	30	26
	WS26	WS27	2.72	1.37	30	26
	WS27	WS28	3.01	1.54	30	26

(*Continued*)

	From	To	Initial accumulated flow (cfs)	Modified accumulated flow (cfs)	Initial pipe size (inch)	Modified pipe size (inch)
	WS29	WS30	0.49	0.27	15	15
	WS30	WS31	0.90	0.51	15	15
	WS31	WS32	1.38	0.79	18	18
	WS33	WS34	0.49	0.28	15	15
	WS34	Outflow	0.80	0.47	15	15
	WS35	WS36	0.46	0.27	15	15
	WS36	WS37	0.84	0.48	18	18
	WS37	WS38	1.15	0.67	24	22
	WS38	WS39	1.43	0.84	24	22
	WS39	Outflow	1.71	0.99	24	22
Case Study #2	WS7	WS6	0.21	0.07	8	6
	WS6	WS5	0.38	0.17	8	6
	WS5	WS4	0.67	0.44	12	12
	WS4	WS1	1.33	0.77	18	15
	WS1	WS2	1.58	0.93	24	20
	WS2	WS3	1.96	1.15	24	20
	WS3	Outflow	2.94	2.03	24	22
	WS17	WS18	1.68	1.22	12	12
	WS16	Outflow	0.41	0.31	18	18
	WS18	Outflow	2.08	1.42	24	22
	WS8	WS9	0.85	0.49	12	10
	WS10	WS9	0.75	0.47	12	12
	WS9	Outflow	1.96	1.19	18	15
	WS19	Outflow	0.93	0.77	12	12
	WS20	Outflow	0.42	0.33	12	12
	WS11	Outflow	0.89	0.53	18	15
	WS15	WS14	1.14	0.52	24	18
	WS14	WS13	1.33	0.64	24	20
	WS12	WS13	0.45	0.22	18	15
	WS13	Outflow	2.42	1.30	24	20
Case Study #3	WS1	WS2	0.33	0.23	12	12
	WS2	WS3	0.66	0.45	12	12
	WS3	Outflow	0.93	0.64	12	12
	WS7	WS6	0.27	0.16	12	10
	WS6	WS4	0.45	0.27	12	10
	WS4	Outflow	0.63	0.44	12	12
	WS8	WS9	0.27	0.16	12	10
	WS9	WS10	0.62	0.41	12	12
	WS10	WS14	0.94	0.62	12	12
	WS13	WS14	0.07	0.05	12	12
	WS14	Outflow	1.15	0.76	12	12
	WS15	WS14	0.08	0.06	12	12
	WS17	WS16	0.16	0.07	12	10

Table 2 Life-cycle cost savings attributed to reduced pipe dimensions

Project	Service years	LCC savings at different discount rates			Average saving rate
		0%	3%	5%	
1	50	$24317.04	$16517.73	$14122.15	9%
	25	$11053.20	$11053.20	$11053.20	
2	50	$33375.01	$22670.49	$19382.58	33%
	25	$15170.46	$15170.46	$15170.46	
3	50	$3435.96	$2333.93	$1995.44	7%
	25	$1561.80	$1561.80	$1561.80	

Different design scenarios were modeled using case studies and included PICP only, extensive GR only, and a combination of the two. Aside from considering various design scenarios, this study incorporated variables, such as two different service years and various discount rates. Figure 6 illustrates the cost comparison results for Case study #1 and shows that the cost benefits of LID methods are not always recognizable. These deficits are caused by inexpensive construction costs incurred when building above-ground retention basins. The cost benefits of LID methods are observed in Case studies #2 and #3. Figure 7 illustrates the LCC analysis results from Case study #2. The results indicated that two simulation scenarios, including the application of GR only and both strategies simultaneously, reached optimum LCC savings. Cheaper construction cost for parking spaces in Case study #2 resulted in cost savings when applying PICP only. Figure 8 shows the LCC analysis results for Case study #3 and demonstrates the cost efficiency of applying LID methods in each scenario for various discount rates and service years.

The cost benefit findings are divided into two categories based on the drainage type: 1) projects installed with above-ground retention basin and 2) projects equipped with underground retention basins. The cost savings from applying LID methods are higher in the second drainage category, which can be found in Case studies #2 and #3. The alternative design in category 2) delivered an average of 27.2% and 18.7% LCC savings for 50 and 25 service years by applying PICP and GR, respectively. Meanwhile, the sole use of GR could result in an average of 34% and 22.4% LCC savings for 50 and 25 service years, respectively. The savings rate is higher when GR only is applied than both LID strategies are applied because of the different original construction costs, which are lower in GR only and higher in the combination of both LID strategies.

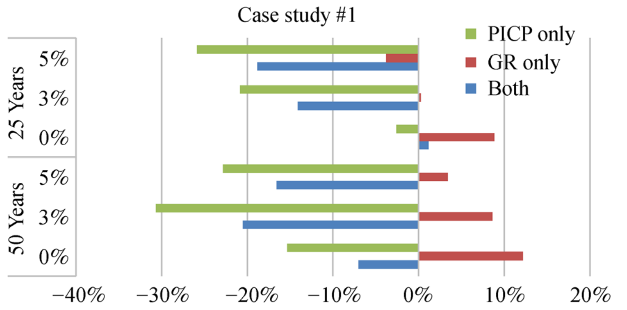

Fig. 6 LCC saving rate on the drainage system (Case study #1).

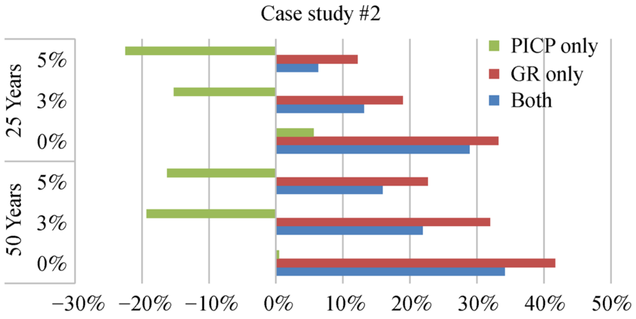

Fig. 7 LCC saving rate on the drainage system (Case study #2).

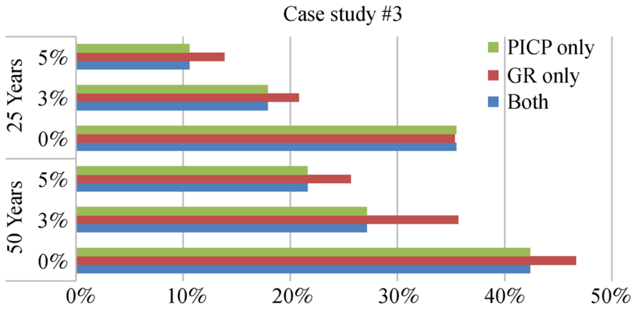

Fig. 8 LCC saving rate on the drainage system (Case study #3).

The average LCC saving rates reveal the cost benefits of using LID compared with traditional drainage systems at different project scales, whereas the specific cost saving amounts can quantify the importance of LID strategies for different projects. For detailed cost savings in designated projects, the comprehensive LCC comparison between LID and traditional drainage system demonstrated that the application of both LID strategies in Case study #2 (14.13 acres) can obtain an average saving amount of $1096555 and $485960 for 50 and 25 service years, respectively. For Case study #3 (5.54 acres), the application of both LID strategies can save an average amount of $584057 and

$269348 for 50 and 25 service years, respectively.

6 Conclusions and recommendations

This research aimed to provide stakeholders and contractors an insight into the value of LID methods. LID methods are effective at mitigating urban runoff volume and flow rate. However, knowledge gap regarding the quantification of the cost benefits of applying LID methods abounds in real-world projects. This work bridges this knowledge gap by quantifying the runoff mitigation performance of extensive GR and PICP under rainfall events and by determining the LCC savings attributed to reductions in runoff volume and peak flow rate.

As a continuation of a previous research study, the current research offers an analytical procedure to determine the cost savings regarding stormwater conduit pipes. After examining the cost savings achieved by reducing conduit pipe sizes, these cost results are shown in the LCC analysis of both LID methods-based and traditional drainage systems.

The results indicated that the application of LID methods is beneficial for designated projects installed with underground retention basins. The alternative design by applying PICP and GR in designated projects could obtain an average of 27.2% and 18.7% LCC savings for 50 and 25 service years, respectively. Meanwhile, the sole use of GR obtained an average of 34% and 22.4% LCC savings for 50 and 25 service years, respectively. For a detailed savings amount, the application of both LID strategies in Case study #2 (14.13 acres) can obtain an average saving amount of $1096555 and $485960 for 50 and 25 service years, respectively. The application of both LID strategies in Case study #3 (5.54 acres) can save an average amount of $584057 and $269348 for 50 and 25 service years, respectively.

This research contributes to a better understanding of the cost benefits of LID methods compared with traditional drainage systems based on its application in three case studies. Depending on the scope and scale of the project, these findings could assist readers in understanding the cost benefits of LID when applying it to other similar construction projects in the future. However, the cost benefit analysis presented in this work was performed on the basis of a general precipitation event. Future research should be conducted to analyze the cost benefits of LID during various rainfall events.

References

Braswell A S, Winston R J, Hunt W F (2018). Hydrologic and water quality performance of permeable pavement with internal water storage over a clay soil in Durham, North Carolina. Journal of Environmental Management, 224: 277–287

City of Phoenix (2018). Triple bottom line cost benefit analysis of green infrastructure/low impact development (GI/LID) in Phoenix, AZ. City of Phoenix Result Report. Phoenix, AZ

Collins K, Hunt W F, Hathaway J M (2008). Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina. Journal of Hydrologic Engineering, 13(12): 1146–1157

Drake J, Bradford A, Van Seters T (2014). Hydrologic performance of three partial-infiltration permeable pavements in a cold climate over low permeability soil. Journal of Hydrologic Engineering, 19(9): 04014016

Flood Control District of Maricopa County (2018). Maricopa County Drainage Policies and Standards. Maricopa, AZ

Hakimdavar R, Culligan P J, Finazzi M, Barontini S, Ranzi R (2014). Scale dynamics of extensive green roofs: Quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrologic performance. Ecological Engineering, 73: 494–508

Hill J, Drake J, Sleep B, Margolis L (2017). Influences of four extensive green roof design variables on stormwater hydrology. Journal of Hydrologic Engineering, 22(8): 04017019

Joksimovic D, Alam Z (2014). Cost efficiency of low impact development (LID) stormwater management practices. Procedia Engineering, 89: 734–741

Razzaghmanesh M, Beecham S (2014). The hydrological behaviour of extensive and intensive green roofs in a dry climate. Science of the Total Environment, 499: 284–296

Shafique M, Kim R, Kyung-Ho K (2018). Rainfall runoff mitigation by retrofitted permeable pavement in an urban area. Sustainability, 10 (4): 1231

Soulis K X, Ntoulas N, Nektarios P A, Kargas G (2017). Runoff reduction from extensive green roofs having different substrate depth and plant cover. Ecological Engineering, 102: 80–89

Suripin S, Sri Sangkawati S, Pranoto S A, Sutarto E, Hary B, Dwi K (2018). Reducing stormwater runoff from parking lot with permeable pavement. In: The 3rd International Conference on Energy, Environmental and Information System (ICENIS 2018). E3S Web of Conferences, (73): 05016

Uda M, Van Seters T, Graham C, Rocha L (2013). Evaluation of life cycle costs for low impact development stormwater management practices. Sustainable Technologies Evaluation Program, Toronto and Region Conservation Authority

Water Environment Research Foundation (2009). User's guide to the BMP and LID whole life cost models. Final Report 2009. Environmental Protection Agency

Zhang P F (2019). Life-Cycle-Cost Analysis of Using Low Impact Development Compared to Traditional Drainage Systems in Arizona: Using Value Engineering to Mitigate Urban Runoff. Dissertation for the Doctoral Degree. Tempe, AZ: Arizona State University

Zhang P F, Ariaratnam S T (2018). Meta-analysis of storm water impacts in urbanized cities including runoff control and mitigation strategies. Journal of Sustainable Development, 11(6): 27–40