Journal of Engineering Research and Reports

20(1): 6-19, 2021; Article no.JERR.63833
ISSN: 2582-2926

Cost Analysis of Green Infrastructure Compared to Conventional Stormwater Storage

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Authors' contributions

This work was carried out in collaboration between both authors. Author PZ designed the study, performed the analysis and wrote the first draft of the manuscript. Author STA supervised the study and analyzed the data. Both the authors managed the literature search writing of the final manuscript. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JERR/2021/v20i117243
Editor(s):
(1) Dr. Harekrushna Sutar, Indira Gandhi Institute of Technology, India.
Reviewers:
(1) Jazmin Carbajal Avila, Instituto Tecnológico de Acapulco, Mexico.
(2) Shamrita Zaman, North South University, Bangladesh.
Complete Peer review History: http://www.sdiarticle4.com/review-history/63833

Original Research Article

Received 25 October 2020
Accepted 30 December 2020
Published 11 January 2021

ABSTRACT

Low Impact Development (LID), or green infrastructure, refers to a land planning and engineering design practice to address urban storm runoff. The nature of LID is to mimic the pre-development environment to retain runoff through infiltration, retention, and evaporation. Despite the fact that numerous studies have analyzed the performance of runoff volume reduction and peak flow of various green infrastructures, little is known regarding the economic benefits of adopting LID practices. In this research, three completed construction projects in the Phoenix, Arizona metropolitan area were selected to perform an alternative LID design including extensive green roof (GR) and permeable interlocking concrete pavement (PICP), to determine the cost effectiveness of using LID to reduce the use of a conventional stormwater storage system. A life cycle cost (LCC) analysis was conducted to better understand the cost benefits of applying LID to meet current drainage design criteria as per the project requirements. The results found that applying LID resulted in an average LCC saving rate of 23% compared to a conventional stormwater storage system over a 50 year service life and 15.1% over a full LID (GR+PICP) strategy. Furthermore, it was discovered that LID has little cost savings benefits when constructing above-ground retention basins due to cheaper associated construction costs.

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Keywords: Low impact development; conventional drainage systems; life cycle cost; stormwater storage.

1. INTRODUCTION

Flooding impacts are generally a key considered in proposed new land development. As a part of the new land development, in-ground drainage systems are commonly designed and built to divert runoff water away from landscaping and properties. However, the natural water cycle system is often disrupted from urban development where impermeable materials such as concrete and pavement are often used in the built environment. Subsequently, urban infiltration capability is decreased and additionally groundwater resources are utilized for human activities. Urbanization induced stormwater impacts are not only reflected by the increased runoff volume rate, decreased infiltration capability, and reduced groundwater recharge rate, but also by the economic impact. A review of historical extreme rainfall impacts for ten typical urbanized areas revealed that stormwater impacts are destructively followed by billions of dollars of direct economic losses, fatalities, damaged properties and relocation of affected residence [1]. For example, on September 8th, 2014, the Phoenix, Arizona area was significantly impacted following a historical rain event of 139 mm (5.5 in.) over eight hours [1]. It was estimated that the incident resulted in approximately $18 million USD in direct loss and damages. To mitigate the stormwater impacts, the drainage systems have been developed to prevent flooding damage. A functional drainage system is capable of temporarily storing and draining excess runoff generated from post-development. An integrated drainage system consists of two parts including conduit systems and storage systems. Conduit systems are mainly comprised of routing pipes, catch basins, and storm manholes [2]. The stormwater storage system is comprised of water storage facilities and drywells, which is a method of discharging ponded water by subsurface injection and consequently to recharge the groundwater [3]. In this research, hydraulic benefit of runoff volume reduction from applying Low Impact Development (LID) is considered and subsequently, the proposed storage system can be decreased.

For the drainage system design, three types of design storm distributions were used for application in Maricopa County, an area of 23,890 km^2 encompassing 4.5 million residents, including the 6-hour local storm, the 24-hour general storm and the 2-hour storm. Based on the terms described in the drainage design manual, the 100-yr, 2-hour design storm distribution was used to design the stormwater storage system, the 6-hour storm distribution was used for flood studies and design of stormwater drainage facilities in Maricopa County containing drainage areas less than 51.8 km^2, and the 24-hour storm distribution was used to perform the flood studies for any area larger than 259 km^2 [3]. In this research, the projects selected were smaller scale land developments and the rainfall distribution of 100-years, 2-hrs was the defined condition for designing the stormwater storage system.

The primary objective of this research was to perform a Value Engineering (VE) study on traditional stormwater storage systems. The purpose of conducting a VE study is to substitute traditional method with an alternative design, while achieving the same performance as the initial design. Performing a VE study helps to determine cost savings from alternative designs. As an alternative and sustainable approach, LID is a proven method for reducing stormwater runoff and managing runoff quality [4]. In this paper, three land development projects were evaluated examining alternative LID's designed for each to study cost effectiveness. Two LID strategies including extensive green roof (GR) and permeable interlocking concrete pavements (PICP) were considered in the analysis [4,5,6]. Cost information on infrastructural capital investment and operation and maintenance (O&M) for a traditional drainage system were analyzed from a selection of historical projects. Similar cost information for LID strategies was gathered from local design engineers who are experienced in land development adopting green strategies. Additionally, Uda et al. [7] developed LCC analysis spreadsheets based on previous studies, which were used in this study. For each of the three reviewed projects, three life cost analysis sheets were created included: 1) applying both GR and PICP; 2) GR exclusively; and 3) PICP exclusively. Nine analysis were conducted to determine cost savings on a stormwater storage system according to runoff volume reduction applying LIDs.

1.1 Problem Statement

For urban development such as residential, commercial and industrial, an on-site drainage system is a part of the critical developments that needed to be considered since the existing land environment is disturbed during construction. The key to a well-designed drainage system is the effectiveness to receive and store excess runoff in storage facilities such as underground water tanks or detention basins. The construction of stormwater storage facilities is expensive and usually involves extensive land excavations and soil disturbance. For example, corrugated metal pipe (CMP) is the underground stormwater storage facility commonly used in the local region, especially in projects with limited space, where underground space is preferred to be primarily utilized [3]. The size of the stormwater storage facility is directly correlated with the land cover scenarios. The larger the landscape coverage onsite, which is more permeable and tends to retain the received precipitation, the smaller the size of the stormwater storage facility required. Conversely, with the majority of the site covered with an impervious material (i.e., concrete and/or asphalt), the more substantial the portion of precipitation that can be transformed as runoff resulting in a larger size of stormwater storage facility required. Aside from the stormwater storage facility, the drywell(s) as the auxiliary unit are required to drain the temporarily stored runoff. According to the drainage design manual in Maricopa Country, the designed drywell(s) is required to remove the stored runoff in 36 hours after the runoff event has ended [8]. Thus, in Arizona, an integral stormwater storage system commonly consists of stormwater storage facilities and drywells.

However, building a stormwater storage system is expensive and is becoming more difficult to implement in dense urban areas due to the inherently complicated underground environment. Li et al. [9] identified enablers and barriers to implementing such systems. They found that socio-political barriers, financial investment, and governance have the most negative effects to adopting green infrastructure compared to technical challenges. Furthermore, several researchers examined cost-benefit analysis and economics of such stormwater systems [10],[11],[12],[13]. These studies concluded that there are definite social and economic benefits of green infrastructure for sustainable urban stormwater management. This research analyzed two sustainable alternatives and quantified the cost benefits of the associated alternatives compared to the traditional stormwater storage system.

2. METHODOLOGY

The study is project orientated to apply the alternative LID designs for mitigating runoff and consequently, saving the LCC on the traditional stormwater storage facilities such as above ground retention basins, underground water tanks and drywells as the supplements to the stormwater storage units. The study area is located on Arizona and all construction costs, either the traditional drainage or LID, are Arizona based. The price for the labor, material, and equipment may vary across different States. It is aimed at to offer insights to stakeholders and contractors of the cost effectiveness of LID in comparison to building the stormwater storage system.

Two LID strategies were considered in this research included GR and PICP. The area of the traditional roof or parking space for applying the LID strategies was measured on the scaled project drawings using the quantity takeoff software called PlanSwift® [14]. Only the paved parking spaces with the individual dimension of 2.74 m wide and 6.1m long were selected to apply the PICP while the driveway paved with asphalt concrete were not since the traffic damage is much more significant on the driveways than parking space, which would increase the maintenance cost and frequency on the installed PICP.

To determine the runoff reduction performance from applying the LIDs, the calculation shown in Eq. 2 was used, which modifies the displayed Eq. 1 from the Storm Water Policies and Standards for City of Phoenix [2].

$$V = C_w\left(\frac{P}{1000}\right)A \tag{1}$$

$$V_r = \sum (C - C_r)(\frac{P}{1000})A \tag{2}$$

Where V = design runoff volume (m^3); V_r = runoff volume after applying LID (m^3); C_w = weighted runoff coefficient shown in the project document; C = runoff coefficient for different land cover type; C_r = runoff volume reduction coefficient of LIDs; P = designed rainfall depth according to the location of the project (mm); A = onsite drainage area (m^2).

The method shown in Equation 1 is for the estimation of runoff volume for the design of storm drains and retention stormwater storage facilities. The runoff coefficient (C) used in the method is a dimensionless coefficient relating to the amount of precipitation effectively transforming to runoff. The difference in land use types could lead to different runoff coefficient. For example, the runoff coefficients to streets, residential lots, and landscape area are varied and the stormwater design manual is providing the suggested value for each of them. Not only could the land cover type affect the runoff coefficient, but also the rainfall intensity or return period of the precipitation event. For example, the runoff coefficient of different rainfall return periods for the same land use scenario is different. Based on the stormwater design manual, runoff coefficient is 0.8 under the 2- to 10-year return period for the heavy industrial area while 0.95 under the 100-year return period for the same land type [2],[8].

2.1 Runoff Reduction Performance of LID Measures

Given the fact that the runoff reduction performance for the LID strategies is correlated to the specific rainfall event, the designed rainfall event in the project document was selected in determining the runoff reduction performance of GR and PICP. The 100-yr, 2-hr design rainfall for runoff is 55 mm for the case study site. Zhang and Ariaratnam [1] found that GR can achieve an average of 61% volume runoff reduction and 56% for permeable pavement across the different project sites and rainfall events. For the research presented in this paper, specific designs of the GR and PICP were pre-determined and the correlated runoff reduction performance reviewed under similar rainfall events.

An integrated GR consists of a vegetation layer, growing medium layer, and waterproof layer. GR is typically characterized as intensive (i.e., 152.4 mm to 609.6 mm of medium and large vegetation) or extensive (i.e., 76.2 mm to 152.4 mm of medium and smaller vegetation). The application of the extensive GR with 100 mm growing medium was considered in this research and is ideal for efficient stormwater management requiring low maintenance [15]. Ideally, the application of extensive GR eliminates the irrigation requirements enabling the 100 mm growing medium to absorb and retain water effectively [16].

Previous studies were reviewed to evaluate the runoff reduction performance of extensive GR under a specific rainfall events. Getter et al. [17] analyzed runoff from twelve extensive GR platforms with the research indicating that an extensive GR with 2% slope could retain 85.6% of heavy rainfall (>10.0 mm) and delay the peak flow for an extended period. Carpenter and Kaluvakolanu [18] conducted a field study to collect 6-months of runoff data for a type of roof with 4% roof slope including an asphalt roof (for control purpose), vegetated extensive GR, and a stone ballasted roof. The summarized runoff data suggests that the overall extensive GR can retain 68.25% of rainfall, 54.3% for rainfall event of total 32.26 mm of precipitation and 35.4% for rainfall event of total 74.68 mm of precipitation. Voyde et al. [19] monitored the runoff reduction performance of a 235 m^2 extensive GR for a year in Auckland, New Zealand. The field study result indicated that the extensive GR could retain an average of 82% of rainfall, 42% for the rainfall event with 55 mm of total precipitation depth and 50% for a rainfall event with 30 mm of total precipitation depth. Stovin et al. [20] measured runoff retention capability for a typical extensive GR configuration in the United Kingdom and concluded that the extensive GR could hold 59.1% of rainfall for an annual rainfall of 496 mm. Therefore, it is concluded that the typical extensive GR can retain an average of 55% rainfall for the designed precipitation event.

PICP consists of concrete pavers, permeable joint material, open-graded bedding coarse, open-graded base reservoir and open graded subbase reservoir [21]. A major benefit of PICP is that paving material forming is not time-sensitive and is ready for traffic immediately upon installation. The strategy of PICP is to infiltrate water to the underlying aggregate storage layers and dewater through an underdrain as required. For this research, the runoff reduction performance for the designated PICP under the designed rainfall intensity was analyzed. Collins et al. [22] performed a hydrological study for a permeable pavement parking lot from June 2006 to July 2007 in an attempt to measure the difference in surface runoff volumes, total outflow volumes, and time to peak. The research concluded that PICP retains an average of 98.8% of rainfall with precipitation depths ranging from 6 mm to 50 mm while an average of 80% of rainfall was converted as surface runoff from the event with a total precipitation depth of 135 mm. The Interlocking Concrete Pavement Institute (ICPI) [23] published a report claiming that the infiltration rate for PICP could be as high as

1,270 mm per hour with regular maintenance and runoff reduction can be as much as 100% from a 75 mm rain event. Winston et al. [24] studied the hydrologic performance of four permeable pavements in Northeast Ohio to determine hydrological benefits. The site studies found that permeable pavement can substantially reduce stormwater runoff volume and peak flow rate. The experiment performed on the sites installed with PICP revealed that the PICP can retain 91.6% of total 602 mm inflow and 75.8% of total 543 mm inflow. Subsequently, it was estimated that the design PICP could retain a minimum of 80% of rainfall for the designed rain event of 55 mm.

Based on the investigated runoff reduction performance of extensive GR and PICP under the designed precipitation events, reduced runoff volumes from applying both alternatives should result in cost savings in comparison to existing stormwater storage facilities and drywells.

3. CASE STUDIES

To gain a better understanding of the projects located in the Phoenix metropolitan area, three different types of projects were studied in this research: 1) commercial; 2) residential; and 3) multifunctional. Project data, including roof area and parking lot area, were retrieved from the scaled project plans. Detailed cost breakdowns from the proposed and accepted bidding proposals were used to determine the cost of construction for the drainage system. Table 1 presents supplemental background information on the design of drainage systems including: weighted runoff coefficient; designed rainfall depth; and on-site stormwater retain capability. Detailed descriptions for the three case studies are presented in the following sections.

3.1 Case Study #1: Multifunctional Building in Scottsdale, Arizona USA

The first case study project studied is a multifunctional building located in Scottsdale, Arizona and built in 2017 (Fig. 1). The site was 13.76 ha (34 acres) of land development for a hotel, conference center, restaurant and office spaces. The drainage system constructed for this project consisted of various sizes of High-Density Polyethylene (HDPE) pipe, multiple Maricopa Association of Governments (MAG) 537 single/double catch basins, retention basins, and 15 dual drywells. For the roofing system, 1.3 ha (3.22 acres) of conventional flat roofing and gutter system was applied. Additionally, 3.09 ha (7.64 acres) of 101.6 mm thickness asphalt pavement was utilized throughout the parking lots. The project is designed to retain the 100-year, 2-hour storm event, which is a total of 55 mm of rainfall as per the National Oceanic and Atmospheric Administration [25]. The weighted runoff coefficient is 0.84 [4]. It is estimated that the developed site would generate a volume of 6,401 m^3 of direct runoff, while the constructed runoff retention basins could retain 7,463 m^3, which is for safety considerations. All generated runoff is expected to drain into the retention basin and subsequently percolate to the subsurface to recharge the groundwater through a drywell system. The drywell system is designed to discharge the stored runoff completely within 36 hours after the runoff event has ended [4].

3.2 Case Study #2: Multi-Family Development in Phoenix, Arizona USA

This project consists of the construction of a 363-unit multi-family development and related site improvements in Phoenix, Arizona as illustrated in Fig. 2. The 2018 project contained 5.72 ha (14.14 acres) of development and was constructed with on-site underground retention basins of 3.05 m (120 in.) diameter corrugated metal pipe (CMP) to retain pre-development versus post-development runoff. The drainage system constructed for the project included 3.05 m (120 in.) Corrugated Metal Pipe (CMP),1.22 m (48 in.) Rubber Gasketed Reinforced Concrete Pipe (RGRCP), various diameters of HDPE pipes, 18 units of Nyloplast® area drains, storm

Table 1. Background information (3 case studies)

Variables	Case Study 1	Case Study 2	Case Study 3
Weighted Runoff Coefficient	0.84	0.95	0.92
Rainfall Depth (mm)	55	57	55
Site Area (ha)	13.76	5.72	2.24
Roof Area (ha)	1.3	1.7	0.65
Parking Area (ha)	3.09	0.51	0.29
Onsite Storage Capability (m^3)	6,401	1,421	1,132
Drywell Counts (ea.)	15	5	4

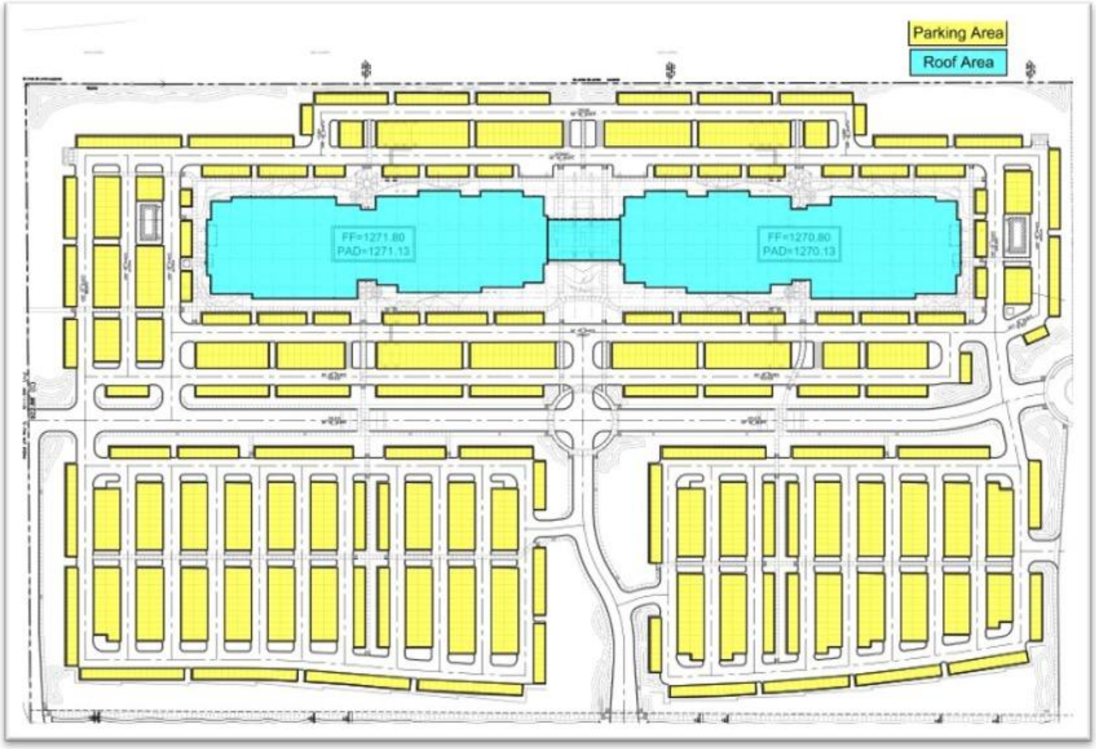

Fig. 1. Case study #1 site in Scottsdale, Arizona (Maricopa County)

drain manholes, and five drywells to percolate the stored runoff into the underground retention basins. For the roofing system, 1.7 ha (4.2 acres) of conventional flat roof with 2% slope and gutter system were built according to the construction documents. Asphalt pavement was utilized to construct the parking spaces on site. It was measured that a total of 0.51 ha (1.26 acres) of parking spaces were paved with 50.8 mm thickness of asphalt pavement. The runoff coefficient is 0.95 for both building and pavement and 0.45 for landscape. The designed precipitation depth was 57 mm (designed precipitation level for the event of 100-year, 2-hours). The drainage design for the project provided stormwater retention for the difference between the pre-development and post-development runoff volume in underground stormwater storage tanks. Stormwater runoff beyond the difference between the pre-development and post-development runoff volume was routed directly south of the site along with its historical pattern. Thus, the modified weighted runoff coefficient for the site was 0.5, as the difference between post development coefficient 0.95 and predevelopment 0.45. The required runoff volume generated from the project document was 1420 m^3, including the additional 25% safety storage design as per the design manual [2]. The underground retention tanks could provide a total of 1,421 m^3 of retention capability and an onsite percolation rate of 0.003 m^3/s as per the test, which required the installation of five drywells.

3.3 Case Study #3: Resort-Style Apartment Building in Chandler, Arizona USA

The third project reviewed is a resort-style apartment building located in downtown Chandler, Arizona as illustrated in Fig. 3. The 2.24 ha (5.54 acres) land development project was built in 2018. A total of 242.6 m of 2.44 m (96 in.) diameter CMP was installed to retain the runoff generated from the rain event of 55 mm, which is the 100-year, 2-hour rainfall distribution event according to [25]. Meanwhile, various sizes of HDPE, catch basins, different sizes of area drains, and drywells were constructed to form the on-site drainage system and to protect the impacts of runoff from spreading. The designed runoff volume from the project is 1,132 m^3, based on the weighted runoff coefficient of 0.92 calculated in the project documents. Four drywells were designed to discharge stored runoff within 36 hours as per the Maricopa County drainage design manual [3]. It was measured that 0.65 ha (1.6 acres) of the conventional flat roof was chosen to be the roof portion for the apartment project. A total of 101.6 mm thickness asphalt pavement was selected to construct traditional parking spaces, totaling to approximately 0.29 ha (0.71 acres).

3.4 Cost Data Collection

All construction costs for the infrastructure including the drainage system and LID, are based on the Phoenix Metropolitan area, as construction-related costs vary across different States. As previously mentioned, the construction costs of a drainage system were gathered from historical accepted project bidding proposals, while the construction price for LID was gathered from local design engineers who are experts in land development with green infrastructure methods. To fully collect the cost data, some prices such as maintenance and replacement for the green infrastructure were also cited from a recently published report regarding the cost analysis of applying green infrastructure/LID in Phoenix, AZ [26]. For the LCC analysis, the maintenance cost was required not only for reaching the life expectancy, but also for continuously meeting the designed performance. Detailed cost information is presented in Table 2.

All cost information listed in Table 2 were obtained from several awarded bids. It is admitted that the costs for different building items is varied depending on the construction company. All cost information collected in this study were either the average awarded prices or acceptable average prices a general contractor would submit during the bidding process. The gathered unit prices are converted to values applicable in the simulation. For example, the cost for 3.05 m (120 in.) diameter CMP and 2.44 m (96 in.) diameter CMP were listed as a total submitted bid price and the converted value was achieved by dividing the bid cost by the stormwater retention volume. For the drywell, the capital and maintenance costs were provided by contractors working for local drilling companies. The annual maintenance for the drywell was required since the debris and soils washed over after a rainfall event may clog the chamber of the

Fig. 2. Case study #2 site in Phoenix, Arizona (Maricopa County)

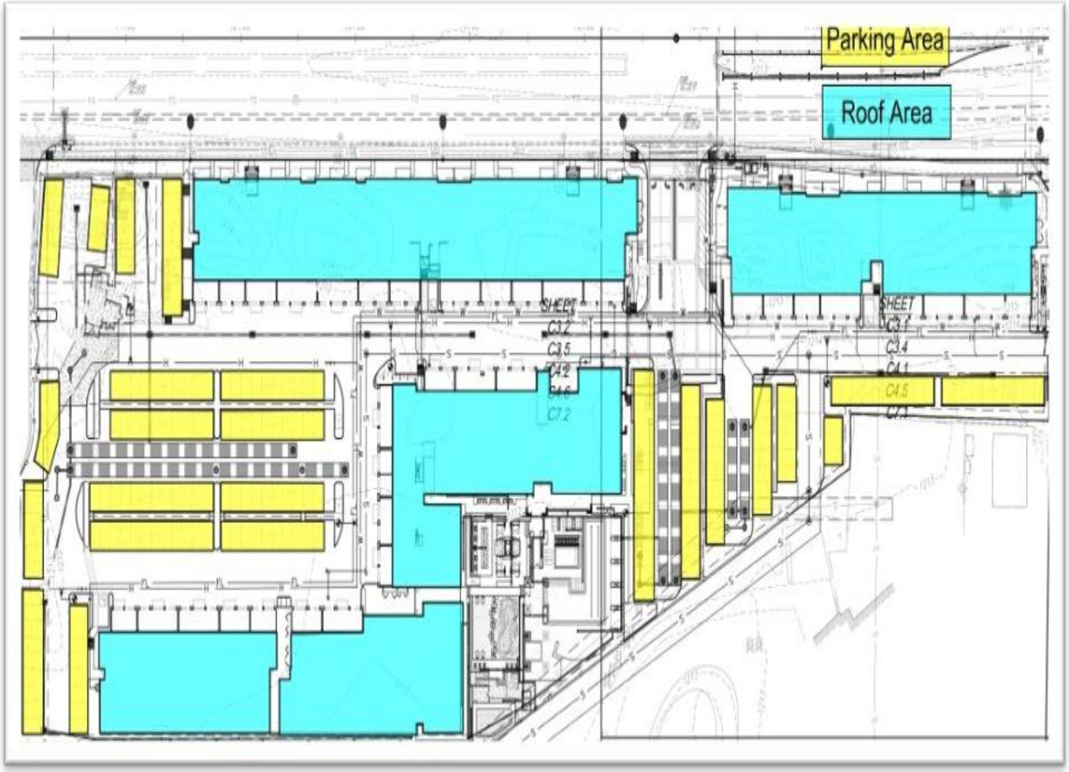

Fig. 3. Case study #3 site in Chandler, Arizona (Maricopa County)

drywell system and reduce dewatering performance. The roofing price was obtained from a general contractor who provided the most likely acceptable price during the bidding for constructing a typical flat white roof in Arizona. The capital cost of the asphalt paving varied depending on thickness, while asphalt maintenance involves bituminous treatment or fog coating, which gives another half inch thickness of coating material on top of the existing asphalt. The construction price of PICP was obtained through quotations from several local paving contractors who specialize in PICP. Annual maintenance activities for PICP include cleaning of joints and debris removal using an air vacuum machine. It is worth noting that all specific cost data remain confidential to protect the competitive bid process.

Table 2. Detailed cost information

Variable	Retention Basin ($/m^3)	120" CMP ($/m^3)	96" CMP ($/m^3)	Drywell ($/ea.)	Conventional Roof ($/m^2)	4" Thickness Asphalt (2") ($/m^2)	Extensive GR ($/m^2)	PICP ($/m^2)
Capital Cost	29.00	123.60	169.50	20,000	86.10	46.30 (34.40)	115.10	86.10
Annual Maintenance Cost	2.10	35.30	35.30	2,000	1.70	2.20 (2.20)	1.10	2.20
Replacement Cost	18.50	88.30	109.50	24,000	68.90	26.90 (22.00)	91.50	73.2
Life Span (Years)	30	30	30	30	30	25	40	30

3.5 Cost-Effective Analysis

The cost analysis is based on runoff volume reduction from applying LID strategies and consequently, savings on stormwater storage facilities and supplemented drywells. To analyze cost-savings from individual LID strategies, an additional two studies including GR only and PICP only were conducted for each project. For the LCC analysis, the annual maintenance and replacement costs were also considered in addition to capital costs. Eq. (3) was used to project the LCC savings from applying LID strategies, while the projected savings rate can be determined using Eq. (4). The LCC for each project was calculated using Net Present Value (NPV) at various discount rates of 0%, 3% and 5%. The LCC projection results for each of the three case study projects are presented in Fig. 4.

$$S = C_T - C_{LID} \qquad (3)$$

$$SR = \frac{S}{C_{LID}} \qquad (4)$$

where S = cost savings from applying LID ($); C_T = LCC of using the traditional stormwater storage facilities and drywells ($); C_{LID} = LCC of applying LIDs ($); SR = life cycle cost saving rate (%).

4. RESULTS AND DISCUSSION

Table 3 presents cost calculations for the 25 and 50 year service life span for the three case studies examined. Discount rates of 0%, 3%, and 5% were selected for calculating life cycle costs for the three strategies: 1) green roof + PICP; 2) green roof only; and 3) PICP only. Savings rates were calculated using Eq. 4 to determine cost savings of using LID strategies compared to traditional drainage storage facilities and supplementary drywell systems. The results reveal the highest cost savings are realized for the green roof + PICP (GR+PICP) strategy in case study #2 and #3.

The results presented in Table 3 and Fig. 4 suggest that LCC savings from applying LID cannot be realized across all of the case study projects. For example, LID for case study #1, the Multifunctional Building in Scottsdale, Arizona, is not cost efficient compared to the savings realized in case study #2 and #3. This is most likely as result of cheaper construction costs in building an above-ground retention basin. Discussion with construction industry professionals suggested that the construction of above-ground retention basins can be less expensive by using a scraper that can perform massive excavations and is exceptionally efficient in moving soil. However, the success of using an above-ground retention basin is limited to application on larger project sites. For a sites with limited space, it is preferred to utilize underground space to construct stormwater storage facilities.

The results presented in Table 3 and Fig. 5 suggest that highest savings rate of 40.88% is realized for the GR only option with 0% discount rate, while the highest cost savings differential is $1,924,874.79 for the GR+PICP option with 0% discount rate for a 50 year service life. These are similar when examining the 25 year service life. The PICP only option was not cost effective for the Multi-Family Development in Phoenix, Arizona because the project utilized thinner and cheaper asphalt on the parking lot. Furthermore, GR+PICP realized an average life cost cycle savings rate of 23.4% for 50 year and 15.6% for 25 year service life. Using GR only, an average savings rate of 31.3% was realized for 50 year and 20.7% for 25 year service life.

The results presented in Table 3 and Fig. 6 suggest the highest savings rate of 46.66% is realized for the GR only option with 0% discount rate, while the highest cost savings differential is $1,787,752.01 for the GR+PICP option with 0% discount rate for a 50 year service life for the Resort-Style Apartment Building in Chandler, Arizona. As with case study #2, these strategies are similar when examining the 25 year service life. The PICP only option showed positive savings rate and cost differential for all three discount rates in both the 25 and 50 year service life. For case study #3, the application of GR+PICP resulted in an average cost savings of 30.2% for 50 year and 21.2% for the 25 service life. Using GR only, an average savings rate of 36% was realized for 50 year and 23.3% for 25 year service life. Applying PICP only results in an average cost savings of 17% for 50 years and 15.8% for 25 year service life.

Table 3. Cost calculations for 25 and 50 year service life span

Case Studies	**Strategies**		**Service Life Span (50 years)**			**Service Life Span (25 years)**		
		Discount Rate	**0%**	**3%**	**5%**	**0%**	**3%**	**5%**
Case Study #1: Multifunctional Building	Green Roof + PICP	LIDs (C_{LID})	$11,599,294.06	$7,660,406.44	$6,265,574.22	$6,159,573.63	$5,554,850.54	$5,290,287.76
		Traditional Syst. (C_T)	$10,758,584.73	$6,071,965.32	$5,212,460.18	$6,220,874.92	$4,759,591.06	$4,284,247.00
		Cost Savings (S)	-$840,709.33	-$1,588,441.13	-$1,053,114.04	$61,301.29	-$795,259.48	-$1,006,040.75
		Savings Rate (%)	**-7.25%**	**-20.74%**	**-16.81%**	**1.00%**	**-14.32%**	**-19.02%**
	Green Roof Only	LIDs (C_{LID})	$3,353,466.05	$2,208,464.93	$1,914,249.21	$1,833,849.63	$1,734,028.53	$1,690,357.38
		Traditional Syst. (C_T)	$3,736,870.26	$2,381,697.00	$1,964,801.84	$1,984,485.56	$1,727,031.17	$1,614,396.40
		Cost Savings (S)	$383,404.21	$173,232.07	$50,552.63	$150,635.93	-$6,997.35	-$75,960.99
		Savings Rate (%)	**11.43%**	**7.84%**	**2.64%**	**8.21%**	**-0.40%**	**-4.49%**
	PICP Only	LIDs (C_{LID})	$8,245,828.01	$5,303,881.60	$4,207,086.21	$4,325,724.00	$3,820,822.01	$3,599,930.37
		Traditional Syst. (C_T)	$6,962,414.84	$3,666,837.39	$3,235,283.78	$4,204,833.01	$3,016,506.63	$2,660,579.86
		Cost Savings (S)	-$1,283,413.16	-$1,637,044.20	-$971,802.44	-$120,890.99	-$804,315.38	-$939,350.51
		Savings Rate (%)	**-15.56%**	**-30.87%**	**-23.10%**	**-2.79%**	**-21.05%**	**-26.09%**
Case Study #2: Multi-Family Development	Green Roof + PICP	LIDs (C_{LID})	$5,734,136.41	$3,755,405.72	$3,190,706.73	$3,105,436.21	$2,891,932.14	$2,798,525.36
		Traditional Syst. (C_T)	$7,659,011.20	$4,554,911.39	$3,678,426.07	$3,987,587.39	$3,256,950.90	$2,959,434.51
		Cost Savings (S)	$1,924,874.79	$799,505.67	$487,719.34	$882,151.18	$365,018.77	$160,909.15
		Savings Rate (%)	**33.57%**	**21.29%**	**15.29%**	**28.41%**	**12.62%**	**5.75%**
	Green Roof Only	LIDs (C_{LID})	$4,373,287.83	$2,880,080.68	$2,496,391.09	$2,391,541.21	$2,261,363.54	$2,204,411.57
		Traditional Syst. (C_T)	$6,161,039.83	$3,776,411.16	$3,042,713.33	$3,169,780.66	$2,673,713.98	$2,456,687.73
		Cost Savings (S)	$1,787,752.01	$896,330.49	$546,322.24	$778,239.45	$412,350.44	$252,276.16
		Savings Rate (%)	**40.88%**	**31.12%**	**21.88%**	**32.54%**	**18.23%**	**11.44%**
	PICP Only	LIDs (C_{LID})	$1,360,848.58	$875,325.04	$694,315.64	$713,895.00	$630,568.60	$594,113.79
		Traditional Syst. (C_T)	$1,353,971.37	$697,153.02	$573,647.83	$747,806.73	$528,410.63	$454,558.89
		Cost Savings (S)	-$6,877.22	-$178,172.03	-$120,667.81	$33,911.73	-$102,157.97	-$139,554.91
		Savings Rate (%)	**-0.51%**	**-20.35%**	**-17.38%**	**4.75%**	**-16.20%**	**-23.49%**
Case Study #3: Resort-Style Apartment Building	Green Roof + PICP	LIDs (C_{LID})	$2,431,955.83	$1,589,851.34	$1,341,830.63	$1,312,885.63	$1,216,412.87	$1,174,206.61
		Traditional Syst. (C_T)	$3,457,965.57	$2,018,220.82	$1,629,305.67	$1,776,898.39	$1,432,039.81	$1,296,384.55
		Cost Savings (S)	$1,026,009.74	$428,369.48	$287,475.04	$464,012.77	$215,626.93	$122,177.94
		Savings Rate (%)	**42.19%**	**26.94%**	**21.42%**	**35.34%**	**17.73%**	**10.41%**
	Green Roof Only	LIDs (C_{LID})	$1,666,594.66	$1,097,555.72	$951,337.35	$911,380.63	$861,771.86	$840,068.32
		Traditional Syst. (C_T)	$2,444,153.37	$1,489,097.11	$1,195,261.99	$1,233,675.19	$1,040,807.83	$956,429.49
		Cost Savings (S)	$777,558.71	$391,541.39	$243,924.63	$322,294.56	$179,035.97	$116,361.18
		Savings Rate (%)	**46.66%**	**35.67%**	**25.64%**	**35.36%**	**20.78%**	**13.85%**
	PICP Only	LIDs (C_{LID})	$765,361.17	$492,295.62	$390,493.28	$401,505.00	$354,641.01	$334,138.30
		Traditional Syst. (C_T)	$1,013,812.19	$529,123.71	$434,043.68	$543,223.21	$391,231.98	$339,955.06
		Cost Savings (S)	$248,451.03	$36,828.09	$43,550.40	$141,718.21	$36,590.97	$5,816.76
		Savings Rate (%)	**32.46%**	**7.48%**	**11.15%**	**35.30%**	**10.32%**	**1.74%**

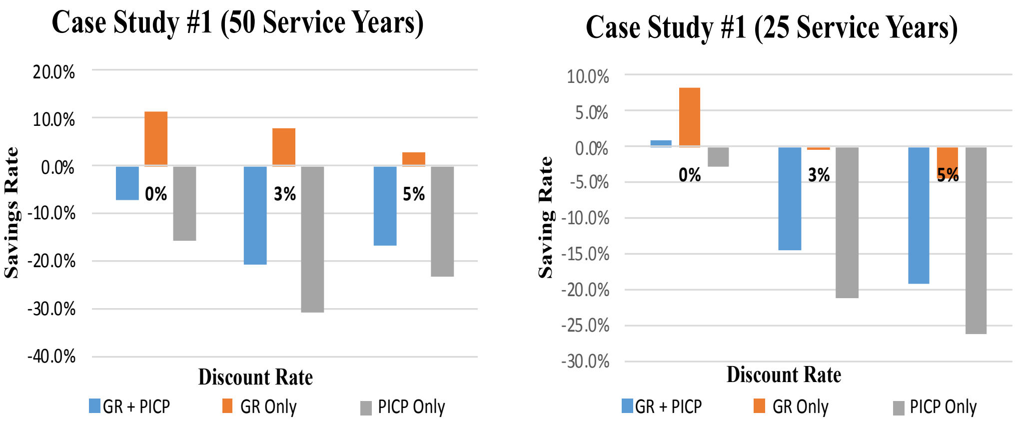

Fig. 4. LCC savings rate (SR) from applying LID for case study #1

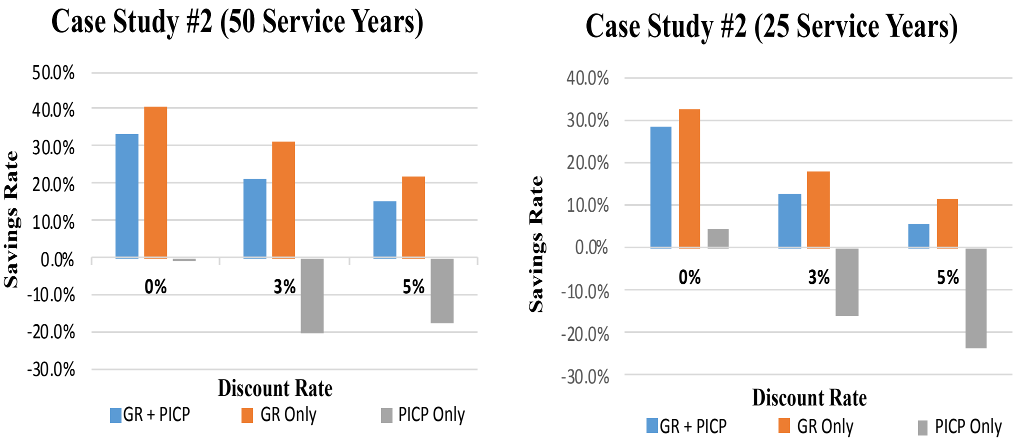

Fig. 5. LCC savings rate (SR) from applying LID for case study #2

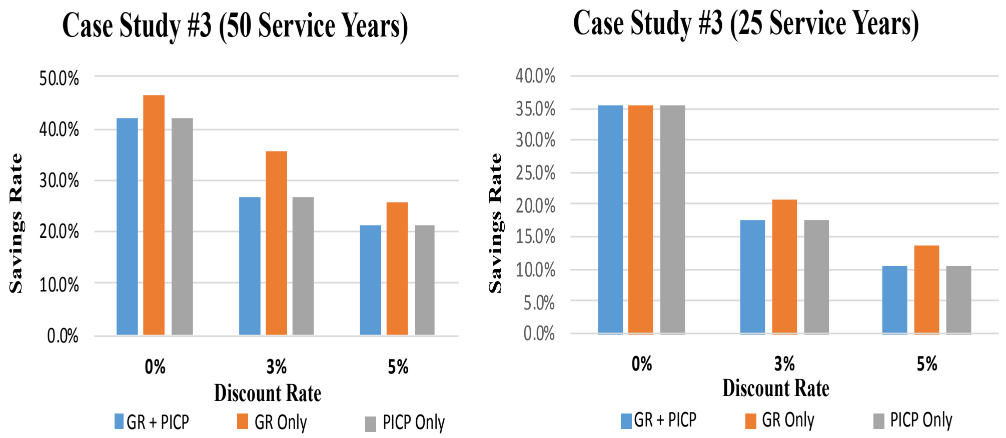

Fig. 6. LCC savings rate (SR) from applying LID for case study #3

Calculating the average LCC savings rate provides a better understanding of the cost benefits of using LID on the case study projects described in this paper. For more detailed cost savings of LID, it was determined that applying GR+PICP on case study #2 (14.14 acres) can save an average of $1,070,700 for 50 year service life and $469,360 for 25 year service life. Moreover, it was determined that applying GR+PICP on case study #3 (5.54 acres) can save an average of $580,619 for 50 year service life and $267,272 for 25 year service life. Furthermore, the average savings and rates are influenced by discount rates. For case studies #2 and #3, it was observed that both cost savings and savings rate are highest at the 0% discount rate and decrease with increasing discount rates. Also, as expected, the highest cost savings are realized with long service life.

5. CONCLUSIONS

The objective of this research was to investigate the cost effectiveness of adopting Low Impact Development (LID) such as GR and PICP for drainage storage facilities and supplementary drywell systems. The research found that LID is a cost benefit for construction projects with underground stormwater storage tanks. Compared to stormwater storage facilities, which only perform at their full function for a few months in Arizona due to infrequent rain events, applying LID not only promotes design stormwater mitigation capability but also delivers aesthetic benefits, environmental benefits, and increased property values over the long run. Using LID for case study #1 was found to be ineffective because of cheaper construction costs in building an above-ground retention basin. The construction of above-ground retention basins are typically less expensive because massive excavations can be performed using a scraper.

This research contributes to the body of knowledge by assisting stakeholders and contractors in better understanding the cost benefits of LID. Using GR+PICP, case study #2 and #3 realized an average of 23% and 15.1% life cost cycle cost savings for 50 year and 25 year service life, respectively. An average 50 year service life cost savings of $1,070,700 and $580,619 were realized for case studies #2 and #3, respectively. Moreover, an average 25 year service life cost savings of $469,360 and $267,272 were realized for case studies #2 and #3, respectively.

The research presented in this paper is limited to analyzing cost savings of stormwater storage facilities. It is recommended that future research focuses on additional cost benefits including optimal sizing of drainage pipes, quantity reduction of water collection systems, and urban heat island alleviation from application of green infrastructures. Also, recommended future research is recommended to analyze other *LID* as bioretention systems, filter drains with planting, and swales.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Zhang PF, Ariaratnam ST. Meta-analysis of storm water impacts in urbanized cities including runoff control and mitigation strategies. Journal of Sustainable. Development. 2018;11(6):27-40.
2. City of Phoenix. *Storm water policies and standards.* City of Phoenix City Code, , Phoenix AZ; 2011.
3. Maricopa County. Drainage design manual. Maricopa County Standards for Hydraulic Design. Maricopa AZ; 2013.
4. Suripin S, Sachro SS, Atmojo PS, Edhisono S, Budieny H, Kurniani D. Reducing stormwater runoff from parking lot with permeable pavement. E3S Web of Conferences, Semarang, Indonesia; 2018. August 14-15, 2018
5. Hu MC, Zhang XQ, Siu YL, Li Y, Tanka KJ, Yang H, Xu YP. Food mitigation by permeable pavements in Chinese sponge city construction. Water. 2018;10(2):172.
6. Lee JY, Moon HJ, Kim TI, Kim HW, Han MY. Quantitative analysis on the urban flood mitigation effect by the extensive

green roof system. Environmental Pollution. 2013;181:257-261.

7. Uda M, Van Seters T, Graham C, Rocha L. Evaluation of life cycle costs for low impact development stormwater management practices. Sustainable Technologies Evaluation Program, Toronto and Region Conservation Authority; 2013.
8. Maricopa County. Drainage policies and standards. Maricopa County Standards for Hydrology. Maricopa AZ; 2018.
9. Li L, Collins A, Cheshmehzangi A, Chan FKS. Identifying enablers and barriers to the implementation of the green infrastructure for urban flood management: a comparative analysis of the UK and China. Urban Forestry & Urban Greening. Elsevier. 2020;54.
   Available: https://doi.org/10.1016/j.ufug.2020.126770
10. Johnson D, Geisendorf S. Are neighborhood-level SUDS worth it? An assessment of the economic value of sustainable urban drainage system scenarios using cost-benefit analysis. Ecological Economics. Elsevier. 2019; 158:194-205,
    Available:https://doi.org/10.1016/j.ecolecon.2018.12.024
11. Ossa-Moreno J, Smith KM, Mijic A. Economic analysis of wider benefits to facilitate SuDS uptake in London, UK. Sustainable Cities and Society. Elsevier. 2017;28:411-419, Available: https://doi.org/10.1016/j.scs.2016.10.002
12. Nordman E, Isely E, Isley P, Denning R. Benefit-cost analysis of stormwater green infrastructure practices for Grand Rapids, Michigan, USA. Journal of Cleaner Production Elsevier. . 2018;200:501-510.
    Available: https://doi.org/10.1016/j.jclepro.2018.07.152
13. Alves A, Vojinovic Z, Kapelan Z, Sanchez A, Gersonius B. Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation. Science of the Total Environment. Elsevier. 2020;702.
    Available:https://doi.org/10.1016/j.scitotenv.2019.134980
14. PlanSwift®. Takeoff software for construction estimating. Construct Connect, Centerville, Utah; 2020. Available:www.planswift.com
15. Sena, A. Water Wednesday: Living roofs reduce energy use, stormwater runoff. U.S. Environmental Protection Agency (EPA). Washington DC; 2015.
16. Berghage R, Beattie D, Jarret R, Thuring A, Razaei F. Green roof for stormwater control. National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency (EPA). Cincinnati OH; 2009.
17. Getter KL, Rowe DB, Andresen JA. Quantifying the effect of slope on extensive green roof stormwater retention. Ecological Engineering. 2017;31(4):225-231.
18. Carpenter DD, Kaluvakolanu P. Effect of roof surface type on storm-water runoff from full-scale roofs in a temperate climate. Journal of Irrigation and Drainage Engineering. 2011;137:161–169.
19. Stovin V, Vesuviano G, De-Ville S. Defining green roof detention performance. Urban Water Journal. 2013;574-588.
20. Voyde E, Fassman E, Simcock R. Hydrology of an extensive living roof under subtropical climate conditions in Auckland, New Zealand. Journal of Hydrology. 2010; 394:384–395.
21. Tyson S, Tayabji S. Permeable interlocking concrete pavement. FHWA-HIF-15-007. U.S. Department of Transportation, Washington DC; 2015.
22. Collins K, Hunt WF, Hathaway JM. Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina. Journal of Hydrological Engineering. 2018;13(12): 1146-1157.
23. ICPI. Design professional fact sheet. Interlocking Concrete Pavement Institute. Burlington, Ontario, Canada; 2008.
24. Winston RJ, Dorsey JD, Smolek AP, Hunt WF. Hydrologic performance of four permeable pavement systems constructed over low-permeability soils in northeast Ohio. Journal of Hydrologic Engineering. 2018;23(4). Available: https://doi.org/10.1061/(ASCE)HE.1943-5584.0001627
25. Bonnin G, Martin D, Lin B, Parzybok T, Yekta M, Riley D. Precipitation – Frequency Atlas of the United States, Atlas 14, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce. Version 5.0, , Washington, DC. 2011;1.

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

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/63833