Life-Cycle-Cost Analysis of using Low Impact Development Compared to Traditional Drainage Systems in Arizona: Using Value Engineering to Mitigate Urban Runoff

by

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ABSTRACT

The rate of urbanization has been impacted by global economic growth. A strong economy results in more people moving to already crowded urban centers to take advantage of increased employment opportunities often resulting in sprawling of the urban area. More natural land resources are being exploited to accommodate these anthropogenic activities. Subsequently, numerous natural land resources such as green areas or porous soil, which are less flood-prone and more permeable are being converted into buildings, parking lots, roads and underground utilities that are less permeable to stormwater runoff from rain events. With the diminishing of the natural landscape that can drain stormwater during a rainfall event, urban underground drainage systems are being designed and built to tackle the excess runoff resulting from urbanization. However, the construction of a drainage system is expensive and usually involves massive land excavations and tremendous environmental disturbances. The option for constructing an underground drainage system is even more difficult in dense urban environments due to the complicated underground environments, creating a need for low footprint solutions. This need has led to emerging opportunities for low impact development (LID) methods or green infrastructures, which are viewed as an environmentally friendly alternative for dealing with stormwater runoff. LID mimics the pre-development environment to retain the stormwater runoff through infiltration, retention, detention and evaporation. Despite a significant amount of prior research having been conducted to analyze the performance of runoff volume reduction and peak flow decrement of various green infrastructures, little is known about the economic benefits of using LID practices.

This dissertation fills the gap in the knowledge regarding the life-cycle-cost effectiveness of green infrastructure in current urban developments. This study’s two research objectives are:

(1) Develop a life cycle cost calculation template to analyze the cost benefits of using LID compared to the traditional drainage system

(2) Quantify the cost benefits based on the real-world construction projects

A thorough literature review led to the data collection of the hydrological benefits of using LIDs in conjunction with overviewing three real-world construction projects to quantify the cost benefits of LIDs.

I dedicate this dissertation to my amazing wife Diana, my loving parents Wenyou and Suqin and sister Ting. I am eternally grateful for your love, unwavering support, and continuing guidance. Without you this would not have been possible.

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1. INTRODUCTION

1.1 Research Background

Stormwater runoff, one of the most typical and destructive results of natural disasters, often results in significant impacts to an urban environment during a significant rain event. Of all-natural disasters, stormwater induced flooding frequently occurs, extensively, massively and destructively. A review of historic extreme rainfall impact for ten typical urbanized areas indicated that the impacts of stormwater are destructive, resulting in billions of direct economic losses, fatalities, damaged properties and residents' relocation. On September 8th, 2014, the Phoenix area was inundated following a historic rainfall event of 5.5 in. (139 mm) in 8 hours. It was estimated that this event resulted in approximately $18 million in direct loss and damage (Zhang and Ariaratnam 2018). The rate of urbanization has been impacted by global economic growth.

A strong economy results in more people moving to already crowded urban centers to take advantage of increased employment opportunities often resulting in sprawling of the urban area. More natural land resources are being exploited to accommodate these anthropogenic activities. Subsequently, numerous natural land resources such as green areas or porous soil, which are less flood-prone and more permeable are being converted into buildings, parking lots, roads and underground utilities that are less permeable to stormwater runoff from rain events. According to the projections of land cover change in the United States that were published on environmental protection agency (EPA) website, urban highly developed areas with impervious surface rate 80 to 100% of the total cover keep increasing throughout years. Figure 1 displays the simulation results of land use changes in Phoenix per the society development algorithm published on EPA website, and the results indicate that highly developed urban area will be increased to 40% in Phoenix by 2100 from 29% in 2010. The hypothesis for the selected algorithm assumes that social, economic and technological developments will be along with the historical patterns and the population in the United States will reach to 455 million by 2100 (EPA 2017). With the altered urban impervious rate from urbanization, runoff rates have been dramatically shifted.

The traditional method to tackle the excess runoff generated from land development is to build an effective drainage system. The drainage system consists of two major components: (1) stormwater conduit system; (2) stormwater storage system. The key to a well-designed drainage system is adequate to receive, convey and store the excess runoff. However, the construction of a drainage system is expensive and usually involves extensive land excavations and environmental disturbance. The massive excavation is not always the best choice in the dense urban city due to the limited underground space. A research question was raised about whether the application of sustainable stormwater mitigation strategies can alleviate the pressure on urban drainage systems and how cost beneficial they can be.

Three land development projects in the Arizona region, including the information on the drainage system and land cover type, have been reviewed. At the same time, the alternative LID design for each has been carried out to investigate the cost-effectiveness of applying LID. In this study, two LID strategies including extensive green roof (GR) and permeable interlocking concrete pavements (PICP) were considered for conducting the analysis.

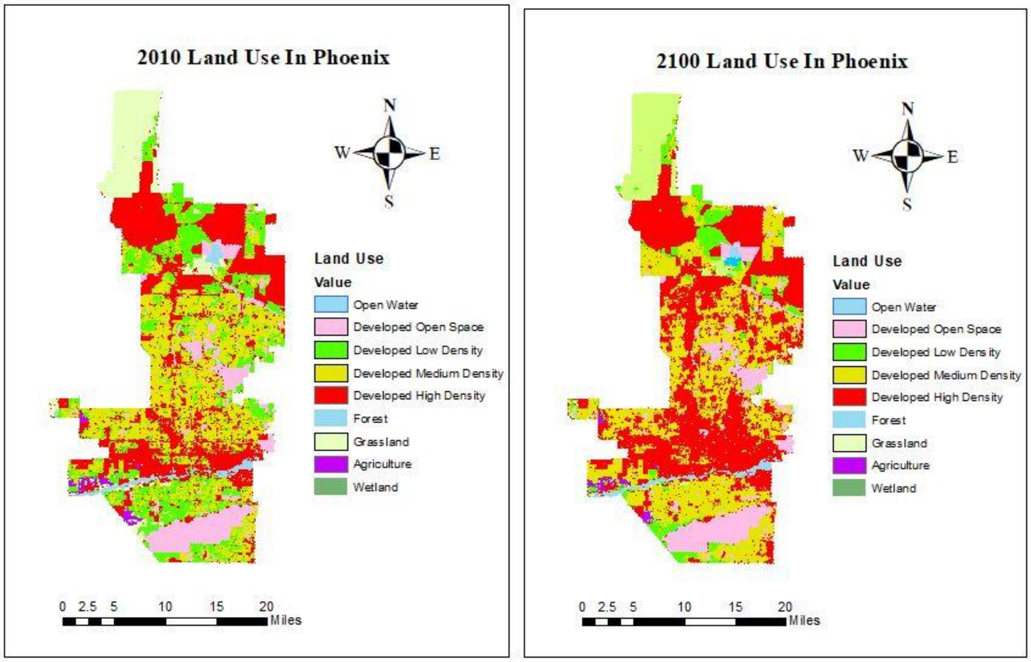

Figure 1: Land Use Changes in Phoenix From 2010 to 2100

1.2 Research Objectives

The primary objectives of this dissertation are twofold: (1) develop an LCC calculation template to analyze the cost benefits of using LID compared to the traditional drainage system, and (2) quantify the cost benefits based on the real world construction projects. This study hypothesizes that the application of LID not only can positively alleviate the pressure on drainage system but also be more cost-effective. The research results can assist stakeholders in understanding a valuable alternative to the traditional drainage system. This research study is separated into three phases:

Phases I involves building the body of knowledge about stormwater in an urban environment through literature review and meta-analysis. Efforts have been taken place to quantify the stormwater runoff impacts in urbanized cities, to investigate specific runoff control methods including the traditional methods and innovative methods, and to identify the runoff mitigation performance of the innovative methods.

Phase II is to perform the LCC effective analysis between two investigated LID methods and traditional stormwater storage system, determining the cost savings from applying LID strategies on the construction projects. The reason why two LID strategies were considered into the LCC analysis is attributed to the limit available construction cost information. Three construction projects built in the Phoenix metropolitan area were selected to perform the LCC analysis. The construction cost information for the traditional drainage system is gathered from the accepted bidding proposals, which was the winning bid out of 3~4 bidding proposals for each project.

Phase III acts as a continuous study for Phase II and adds the traditional stormwater conduit system into the analysis of cost benefits of using LID methods, creating a baseline for the cost effectiveness of the investigated LID strategies and offering insights to stakeholders an alternative to the traditional drainage system.

1.3 Dissertation Format

The dissertation is organized in five chapters. **Chapter 1** establishes the research background, problem statement, general objectives for the dissertation and provides a brief description of each phase of dissertations. Each of the three subsequent chapters represents an independent article that has been published or is being under peer-review for academic journals. Thus, each chapter owns an individual abstract, introduction, literature review, methodology, research results discussion and conclusions.

Chapter 2 discusses stormwater impacts in urbanized areas globally by reviewing historical stormwater events and mitigation strategies accompanied by runoff reduction performance that are considered simultaneously to relieve the stress on underground drainage systems. The meta-analysis performed in the study introduces the runoff reduction performance for selected six runoff mitigation method and in the meantime. The findings of this chapter were published in the *Journal of Sustainable Development*.

Chapter 3 analyzes LCC effective of two selected LID strategies based on three construction projects and quantifies the LCC savings on the traditional stormwater storage system, including stormwater retention basin and supplemented drywell system. The results from this chapter are in preparation and planning to submit to ASCE *Journal of Urban Planning and Development*.

Chapter 4 presents a comprehensive LCC comparison between two investigated LID strategies and the traditional drainage system, including a storage system and a conduit system. The results from this chapter create a baseline for cost-effectiveness of LID strategies regarding the drainage system in the construction industry. The findings from this chapter were submitted to Frontier Journals *Frontiers of Engineering Management*.

Chapter 5 summarizes the overall research findings, contributions and limitations of the dissertation and provides recommendations for future research. Following this chapter are the references.

2. META-ANALYSIS OF STORM WATER IMPACTS IN URBANIZED CITIES INCLUDING RUNOFF CONTROL AND MITIGATION STRATEGIES

2.1 Abstract

The rate of urbanization has been impacted by global economic growth. A strong economy results in more people moving to already crowded urban centers to take advantage of increased employment opportunities often resulting in sprawling of the urban area. More natural land resources are being exploited to accommodate these anthropogenic activities. Subsequently, numerous natural land resources such as green areas or porous soil, which are less flood-prone and more permeable are being converted into buildings, parking lots, roads and underground utilities that are less permeable to storm water runoff from rain events. With the diminishing of the natural landscape that can drain storm water during a rainfall event, urban underground drainage systems are being designed and built to tackle the excess runoff resulting from urbanization. However, the rapid pace of urbanization has profoundly affected the formation of urban runoff thus resulting in the existing underground drainage system being unable to handle current flow conditions. This paper discusses storm water impacts in urbanized areas globally by reviewing historical storm water events and mitigation strategies accompanied with runoff reduction performance that are considered simultaneously for the purpose of relieving the stress on underground drainage systems. It was found that the stormwater impact on ten selected typical urban areas were enormously destructive followed by billions of direct economy loss, fatalities, damaged properties and residents' relocations. Furthermore, the meta-analysis of selected six runoff mitigation methods indicated that the average runoff reduction percent ranged

from 43% to 61% under different rain events in various installed sites across different event years.

2.2 Introduction

Storm water runoff, one of the most common and destructive results of natural disasters, often results in significant impacts to an urban environment during a major rain event. Of all-natural disasters, storm water induced flooding occurs frequently, extensively, massively and destructively. Not only does flooding inundate residential properties and people, but it often impacts food, farmlands, local businesses, communication systems, transportation arteries, and critical underground utilities. Since the beginning of 21st century, significant flooding has occurred over 50 times around the world, displacing millions of people.

Storm water is referred to as rainfall or snowmelt that runs off impervious ground surfaces such as buildings, paved roads, parking lots and driveways and flows into manmade drainage infrastructures such as gutters, ditches, storm sewers, channels or streams (Penn and Parker 2011). Due to urbanization, the land exploitation rate has largely increased and consequently, surface vegetation covered areas and natural land preservation that could diminish the flooding impacts are removed and replaced with impervious material such as pavement and buildings. As a result, the discharge volume and frequency of runoff increases as runoff is unable to slowly filter into a land surface with higher imperviousness rate (Carson et al., 2010; Sun et al., 2013; Ohana-Levi et al., 2017). Furthermore, with poor maintenance and aged underground drainage systems, the actual drainage capacity may not even conform with the original design capacity. As runoff surges into drains, it often picks up motor oils, surface sediment, dirt and excess nutrients such as nitrogen and phosphorus through the drainage infrastructure. This deterioration in the quality of drainage infrastructure often results in clogging and fracturing induced by the carried pollutants. The effect is a decrease in the future performance of the drainage infrastructure. Often, the runoff increment due to urbanization has already surpassed the design capacity of the current drainage system. Many urban drainage systems have been struggling to handle excessive runoff. Subsequently, a question has been raised about whether the application of sustainable storm water mitigation strategies can alleviate the pressure on urban drainage systems and how good these are in terms of the performance of storm water runoff reduction. This paper discusses storm water impacts on urbanized areas through a review of historical incidents and runoff reduction strategies to improve storm water-resilience performance in urbanized areas. The runoff reduction performance associated with each strategy is discussed through the literature review. The predominant strategies for improving storm water runoff are defined follows:

Green Roof: Green roof is a runoff control strategy also referred to as eco-roof, living roofs, or garden roofs (Cutlip, 2006). The methodology for this strategy is to incorporate the planting of landscape onto building rooftops as shown in Figure 2. The primary objective of the finished roof is to absorb precipitation landed on the rooftop, temporarily store it and release it at a controllable speed facilitated by the water retention capabilities of planting soil (Graceson et al. 2013).

Figure 2: Green Roof in Tempe, Arizona

Blue Roof: Blue roof is designed to retain rainwater at the roof top and release excess rainfall through orifices weirs, or other outlet devices that slowly discharge storm water during or after a rainfall event (NJDEP, 2017) The mechanism of finished Blue roof is to control the runoff leaving the rooftop at a slower speed than conventional roofs, and eventually reducing the peak flow rate and storm water runoff volume. Blue roof can either be constructed on a new building or as a retrofit, to an existing building as a runoff control strategy (NJDEP, 2017).

Rooftop Disconnection: Rooftop disconnection is a relatively straightforward runoff mitigation strategy that simply diverts the roof runoff into the gutter of downspouts from an impervious surface to pervious surfaces such as grasslands, shrubs and other landscape. In this way, the redirected runoff can be infiltrated, filtered, and treated prior to draining into a storm water conveyance system (Sample, 2013).

Swales: Swales are engineered vegetated ditches that can provide a stable route for storm water runoff and a low-cost drainage option for highways, farms, industrial sites and commercial areas (Struck et al. 2007). Barrett (2008) concluded that if the soil is permeable and the initial moisture is low, infiltration achieved by swales can approach 50% in semiarid regions. In other words, nearly half of the received rainfall will be retained on site. Lucke (2014) conducted a field study to evaluate the hydraulic reduction performance of four different field swales. Results showed that around 50% of runoff can be infiltrated.

Permeable Pavement: Permeable pavement, also called pervious pavement, is an innovative method of paving vehicle and pedestrian pathways that allows water to pass through the surface into the underlying soil layer through voids in the pavement. Figure 3 illustrates a parking lot paved with permeable pavement. The aim of permeable pavement is to mimic the pre-development hydrologic condition in which the storm water can be effectively delayed, and runoff volume can be largely reduced (Eckart et al., 2017).

Figure 3: Permeable Pavement in Tempe, Arizona

Bioretention (or Rain Garden): Bioretention is another way to mimic the movement of water before urban development and release the water stress on urban drainage systems. A rain garden/bioretention is a shallow depression where native shrubs and flowers are planted. Figure 4 illustrates a typical bioretention used in Arizona. The main purpose is to temporarily hold and soak in rain water runoff that flows from rooftops, parking lots and driveways (Ahiablame et al., 2012; Selbig and Balster. 2010).

Figure 4: Bioretention in Tempe, Arizona

Drywell: Drywell is an underground facility that can collect runoff and recharge subsoil through an infiltration system (NJDEP, 2017). Drywell functions by combining water conveyance systems, such as vertical downspout or horizontal storm drain pipes, and water storage units, such as chambers or large dimension corrugate metal pipe, that are only used for storm water collection and storage.

Construction Wetlands: Constructed wetlands, also referred to as storm water wetlands, are designed for flood control purposes. Unlike a natural wetland, constructed wetlands perform fewer ecological functions. Despite that, constructed wetlands have achieved excellent performance in reducing runoff volume (Lenhart and Hunt. 2011).

2.3 Previous Research

2.3.1 Urbanization Impact on Storm Water Runoff

Urbanization is the transition outcome of the developing society, either from the economy development or science development, and consequently, leading to more people living in rural area moving to urban area. To accommodate the population density living in urban areas, existing land resources are being utilized and converted into living spaces, transportation routes and recreational areas. As the urban area expands horizontally, more land areas such as forests, wetlands, and even rivers, which are less prone to runoff, are transformed to buildings, roads, and parking lots. The changes of runoff formation due to urbanization can be classified into two types: 1) infiltration capacity change and 2) storage capacity change

2.3.1.1 Infiltration Capacity Change

Various studies have demonstrated the effects of changing land cover types in urban areas on soil infiltration of water. Continuous growth of natural terrain coverage for residential, industrial, commercial and parking spaces results in existing land cover and permeable soils being disturbed and consequently, larger voids in the soil are compacted and sealed. As a result, the infiltration ability of the land area is often significantly diminished. Water balance refers to the flow of water in and out of a hydrological system. With decreasing permeability of urban areas, excessive rainwater is transformed into surface runoff to accommodate water balance.

Efforts have been made by scientists to evaluate the changing infiltration rate during different stages of urbanization including forest zones, agricultural zones and urbanized zones. Pitt et al. (1999) analyzed 153 urban soils and found that typical infiltration values for non-compacted clays and silts were 170mm/hr., but only 10mm/hr. for compacted clays and silts. Similarly, typical infiltration values for uncompacted sand sample were 380 mm/hr., but only 46mm/hr. for compacted sands. Taylor et al. (2009) assessed the infiltration characteristics of soils in upper Waikato (New Zealand) under both pine forest and agriculture areas. The in-situ infiltration measurement revealed that the infiltration capacity of agriculture area (between 3 and 99 mm/hr.) was an order of magnitude less than the pine forest area (121-1207 mm/hr.) The high measured infiltration value indicated that a higher precipitation event is required to generated surface runoff. Nazir and Sharma (2015) conducted hydraulic conductivity study in five forest covers in India and estimated the infiltration rate under both disturbed and undisturbed forest cover. By using the double ring infiltrometer method, the study indicated that the maximum infiltration value found in these five sites after the first five minutes was 512±30.1 mm/hr. in undisturbed forest. However, in the same type of forest except disturbed, it was 312±43.2 mm/hr. It was observed that the infiltration capability of soil decreased with the soil disturbance.

Likewise, additional studies were conducted in determining the general percentage of runoff increase due to urbanization induced infiltration changes. Jaber (2008) described concerns that storm water could bring to an urbanized setting including increased runoff, increased soil erosion, and impaired water quality. In a city built with impervious materials such as pavement and concrete, the runoff rate would be largely increased. Comparing a 75% to 100% impervious cover in a city to natural ground cover, more than 55% of the precipitation would transform into surface runoff in an urban zone, while only 10% of the precipitation would be converted as runoff in a natural ground cover area. The increased runoff in an urban area is attributed to the fact that the infiltration rate of impervious materials is relatively low. Subsequently, excessive water cannot filtrate into the underground effectively but rather converts as surface runoff (Huong and Pathirana, 2013). Makovic et al. (2014) claimed that 80% of rainfall water soaked into the soil and becomes part of subsoil water in natural terrains, while this situation is opposite in urban areas, where at least 80% of rainfall forms as runoff to wastewater disposal systems or rivers and only 20% soaks into the soil

2.3.1.2 Storage Capacity Change

There are two relative terms to describe water storage, consisting of detention and retention. Detention means that moisture in the soil is detained as it makes its way into the groundwater or streamflow. Retention denotes that water is retained against gravitational forces and later conveyed into the atmosphere.

Forest soils are generally less dense than regular soil and have a greater capacity to store water. Anderson et al. (1976) reviewed soil-water storage experiments conducted by multiple scientists and researchers and tabulated the maximum soil-water storage under selected forest stands. The research results indicated that soil-water storage varies with root depth, soil texture, and types, ranging from 7-23 inches. Canopy interception, also known as retention capability, refers to the rainfall water retained by tree leaves and successfully evaporated. The rainfall that is not intercepted will fall as throughfall or streamflow on the forest floor. Hundecha and Bardossy (2004) modeled an afforestation scenario in the Rhine Basin in Southwest Germany and studied the land cover change effect on urban runoff. By comparing the runoff with the existing 40% forested scenario, containing more than 43% of agriculture, it was found that a 100% forested scenario would result in an average of 14% decrement in peak flow throughout the study season. Interception loss in forests was found to account for a substantial amount of loss in the total rainfall, Xiao and McPherson (2016) illustrated the surface water storage capacity of twenty tree species for a 40-yr period with different rainfall intensities and durations. The study indicated that tree leaves play a pivotal role in intercepting rainwater. During the leaf-on season, a 40-yr Japanese zelkova tree can intercept 85% and 62% of rainfall for 5 and 25-yr storm events, respectively. However, during the leaf-off season, interception drops to 26% and 25% for the same storm events.

Together with deforestation; however, urbanization has largely reshaped the drainage capacity of existing drain areas. In order to deal with the excess runoff, urban drainage infrastructures are designed to collect and transport urban surface runoff away from urban areas to the nearest water body or wastewater treatment plan for water recycling purposes (Zhou, 2014; Chocat et al., 2007). An ideal drainage system can effectively remove the runoff generated from streets, parking lots, rooftops, and other surface features at a rate faster than the rainfall accumulation rate. Litter and soil erosion in urbanized areas can clog drainage systems such as gutters, drain manholes and catch basins, thereby decreasing the resulting drainage capability. Wallace (2013) concluded that clogging damages the drainage system to the point that it loses its design capacity resulting in increased localized flooding. Furthermore, extreme weather is the key cause of urban flooding since the drainage systems designed or constructed years ago typically underestimated the rainfall severity and frequency, leading to less relief time and space for drainage systems under frequent rainfall events to maintain water balance in the hydrology system.

2.3.2 History of Storm Water Impacts in Urban Areas

Urbanization induced impacts on runoff is reflected by increased runoff rates and volumes, decreased infiltration, decreased groundwater recharge and base flow (Ahiablame et al., 2012). Meanwhile, the economic impact of urban runoff cannot be neglected. Table 1 presents details on urban runoff impacts in several major cities through examination of ten historical events from 2012 to 2017 that had major flooding. Displacement of residents and significant economic losses were experienced in each of these significant flooding events with failure of the urban drainage infrastructure being a common issue.

Table 1: Review of Historic Events about Stormwater Impacts on Urban Areas

Year	Time (MM/DD)	Location	Population (Million)	Flooding Reason	Precipitation Level	Impacts
2012	07/21	Beijing, China	21.8	- Extreme event - Failure of drainage system	Total 212mm Average 57.6mm	1. Affected 1.9M people and 10 fatalities 2. 95 waterlogging spots in urban area 3. 545 flights delayed
2012	10/28	New York, USA	8.6	- Severe precipitation - Failure of drainage system	Total 87mm	1. $32B US dollar loss 2. Total 53 fatalities 3. Subway system flooded and shut down
2013	10/08	Ningbo, China	5.8	- Severe event - Cascading effect due to flooding shuts off electricity and other utilities	> 500mm	1. 70% of urban area inundated 2. Affected 832K residents 3. ￥6.9B CNY economy loss
2014	09/08	Phoenix, USA	1.7	- 100-year event - Water pumping station under-design	Total 84mm	1. Massive inundation on Interstate-10 at 43rd average and 2 fatalities 2. Minimum $35.2M US dollar economy loss.
2016	06/30-07/6	Wuhan, China	10.9	- Natural landscape gone from urbanization - Drainage system under-design	Total 560.5mm	1. Affected 750K people, 14 fatalities 2. ￥2.2B CNY economy loss 3. 5848 buildings collapsed
2016	07/19-07/20	Beijing, China	21.8	- Failure of drainage system - Extreme rainfall event	Average 210.7mm 274mm in downtown	1. At least 75 fatalities 2. Public transportation shut off 3. 212 flights canceled
2017	05/07	Guangzhou, China	14	- Extreme event	Average 50mm Maximum 524mm	1. 172 buildings collapsed 2. 6925 residents relocated
2017	06/20-06/26	Quzhou, China	2.2	- Extreme event - Reservoir/dam under-design	Average 151mm Maximum 246mm	1. Affected 480K residents 2. ￥890M CNY economy loss
2017	06/23-06/28	Xiangxi, China	2.6	- Extreme event - Low elevation of inundation area	Average 50mm Maximum 200mm	1. Affected 460K residents 2. 3m urban flooding depth
2017	08/17-09/03	Houston, USA	2.4	- Anthropogenic climate change - Hurricane Harvey	Average 1016mm Maximum 1270mm	1. Affected 13M people and at least 88 fatalities 2. 203,000 homes damaged

2.3.3 Strategies for Better Storm Water-Resilience Performance

Low impact development (LID) consists of various storm water runoff mitigation practices that are aimed at preserving or mimicking natural drainage processes (EPA, 2012). Successful implementation of a LID can retain water and encourage it to soak into the subsoil rather than allowing it to freely flow into the street as runoff. Multiple storm water mitigation strategies are previously discussed.

2.4 Meta-Analysis

To gain a better understanding of the effectiveness of various mitigation strategies in reducing urban runoff, a meta-analysis was conducted. Data from previously published research was analyzed in terms of different mitigation methods. For this analysis, six runoff control and mitigation strategies were considered. It was found that runoff reduction performance of Green Roof is optimal with an average runoff reduction rate of 61.2% followed by Permeable pavement and Bioretention at 56.4% and 52.9%, respectively. Runoff reduction is calculated by using the water balance method to determine water differences between inflow and outflow and quantifying the percentage water retained or lost in a media. Two types of runoff were considered in this research including infiltration excess runoff and saturation excess runoff, which are the two typical scenarios used to represent runoff in an urban area. Infiltration excess runoff is formed once the rainfall intensity is larger than the water conductivity of contact surface including rooftops, roads, and parking lots. In this way, any excess water that the contact surface cannot infiltrate into the subsoil becomes runoff. For example, the rate of water flowing into a manhole or other drainage system has exceeded the system's ability to absorb or release it during an extreme event. For saturation excess runoff, the storage capacity of the drainage system has reached a threshold such that it cannot physically contain more water. For example, urban storm water that is collected by drainage systems such as gutters, catch basins, and underground pipes, must be treated by a wastewater treatment plant (WTP) prior to being released into a nearby water body. However, the runoff volume collected by the drainage system could be beyond the capacity of the WTP. Given that the daily treatment capacity is limited for each WTP, the treatment system may stop receiving untreated water considering the overload impact. Subsequently, runoff that is ready for treatment may have no place to go but to stay in the drainage system or urban surface.

Table 2 presents a comprehensive summary analysis of laboratory and field research of the various runoff control and mitigation strategies. Forty-four studies from 2001-2017 are analyzed demonstrating implementation in various countries and climates.

Table 2: Summary of Mitigation Performance for Alternative Methods

Mitigation Method	Site Location	Year	Average Runoff Reduction (%)	Infiltration Capability (mm/h)	Reference
Green Roof (14 Studies)	East Lansing, MI	2004	85	N/A	VanWoert et al. 2004
	Vancouver, Canada	2005	67	N/A	Connelly and Liu. 2005
	Brussels, Belgium	2006	54	N/A	Mentens et al. 2006
	East Lansing, MI	2007	80.8	N/A	Getter et al. 2007
	Pittsburgh, PA	2008	70	N/A	Bliss et al. 2008
	Austin, TX	2008	66	N/A	Simmons et al. 2008
	Vancouver, Canada	2010	29	N/A	Roehr and Kong. 2010
	Auckland, New Zealand	2010	82	N/A	Voyde et al. 2010
	Shanghai, China	2010	55	N/A	Roehr and Kong. 2010
	Southfield, MI	2011	68.25	N/A	Carpenter and Kaluvakolanu. 2011
	Storrs, CT	2011	51	N/A	Gregoire and Clausen. 2011
	Sheffield, UK	2012	50	N/A	Stovin et al. 2012
	Newport, UK	2013	44	N/A	Graceson et al. 2013
	St. Louis, MO	2015	50	N/A	Morgan et al. 2015
	Coventry, UK	1999	59.5	N/A	Bond et al. 1999

Permeable Pavement (11 Studies)	Athens, GA	2006	93	N/A	Dreelin et al. 2006
	Coastal Plain, NC	2007	100	N/A	Bean et al. 2007
	Sydney, Australia	2010	N/A	20+	Ball and Rankin. 2010
	Ontario, Canada	2011	43	N/A	Drake et al. 2014
	Australia and abroad	2013	81	N/A	Imteaz et al. 2013
	Beijing, China	2015	34.8	N/A	Yang et al. 2015
	Edinburgh, UK	2016	40	N/A	Alsubih et al. 2016
	Cleveland, OH	2018	34.5	N/A	Winston et al. 2018
	Songpa, Korea	2018	48	N/A	Shafique et al. 2018
	Peoria, IL	2016	30	N/A	Riemann. 2016
Rain Garden (Bioretention) (11 Studies)	Kinston, East NC	2008	53	N/A	Collins et al. 2008
	Southfield, MI	2008	N/A	102-508	Carpenter and Hallam. 2008
	Minneapolis, MN	2009	N/A	30-720	Asleson et al. 2009
	NC and MD, US	2009	35	N/A	Li et al. 2009
	Edison, NJ	2010	N/A	20-1500	Stander et al. 2010
	Seattle, WA	2010	61	N/A	Chapman and Horner. 2010
	Nashville, NC	2012	40	N/A	Brown. 2012
	Melbourne, Australia	2013	75	N/A	Imteaz et al. 2013
	Foshan, China	2015	67	N/A	Jia et al. 2015
	Cleveland, OH	2015	80	N/A	Jennings et al. 2015
	Guelph, Canada	2017	44	20-510	Maxwell et al. 2017
Grass Swale (4 Studies)	Various regions, US	2008	50	N/A	Barrett. 2008
	Los Angeles, CA	2008	52.5	N/A	Ackerman and Stein 2008
	Queensland, Australia	2014	52	N/A	Lucke et al. 2014
	Foshan, China	2015	42	N/A	Jia et al. 2015
Detention pond (4 Studies)	Nashville, TN	2001	67	N/A	Liptan 2001
	Tampa, FL	2001	30	N/A	Rushton. 2001
	Minneapolis, MN	2006	50	N/A	Hussain et al. 2006
	Piedmont, NC	2012	56	N/A	Line et al. 2012
Constructed Wetland (3 Studies)	Los Angeles, CA	2008	40	N/A	Ackerman and Stein 2008
	Coastal Plain, NC	2011	54	N/A	Lenhart and Hunt. 2011
	Ashby, VA	2017	43	N/A	Schwartz et al. 2017

2.4.1 Green Roof

VanWoert et al. (2004) performed two studies to find the water retention effect of various treatments on rooftops. The first study examined three rooftop systems including: 1) a standard commercial roof with gravel ballast; 2) extensive green roof system without vegetation; and 3) a typical extensive green roof with vegetation. The second study tested the influence of roof slope and depth of green media on water retention capability. It concluded that the mean percent rainfall retention for green roof with vegetation is approximately 82.8%. Another finding of the research was the confirmation that vegetated green roof not only can reduce the amount of runoff, but also extend the time before runoff occurs compared to a conventional commercial roof.

Connelly and Liu. (2005) conducted a research program to verify the performance of green roof and reduce the barriers toward its marketability. A green roof with 3” (75mm) of growing medium can mitigate 95% of rainfall runoff in the first day of observed rainfall events over 30 measured days. The rainfall for the first measured day was 0.48” (12.19mm) over a duration of 4 hours and 23 minutes. Overall, the tested green roof retained 67% of rainfall over the 30 measured days.

Mentens et al. (2006) found that the retention capability of green roof performed better during the summer than winter. Using a study about the application of green roofs in Brussels, the research results showed a 2.7% runoff reduction with just 10% of green roof coverage and 54% for an individual building. Getter et al. (2007) studied the roof slope effect on mean retention and concluded a mean retention of 76.4% at 25% slope, with the highest retention of 85.6% at 2% slope. Bliss et al. (2008) constructed and monitored a prototype green roof in Pittsburgh, Pennsylvania. The results indicated a 70% runoff volume reduction compared to a conventional roof in the same test building. Simmons et al. (2008) compared the performance of six different extensive GR designs vegetated with native species, to black roofs, and white roofs in Austin Texas. It was found that maximum run-off retention was 88% and 44% for medium and large rain events, respectively.

Roehr and Kong (2010) examined how distinct climatic conditions affect the runoff reduction of green roofs at three locations including Vancouver and Kelowna in British Columbia, and Shanghai, China. The results showed that that a typical green roof can reduce annual rooftop runoff by 29% in Vancouver, 55% in Shanghai and 100% in Kelowna. Voyde et al. (2010) presented field monitoring results from a 235m^2, extensive living roof (also referred to as a green roof) in Auckland, New Zealand. The results indicated that the living roof retained a median of 82% of received rainfall per rainfall event. Carpenter and Kaluvakolanu (2011) investigated the roof reduction rate in Michigan. Overall, the researched green roof retained 68.25% of rainfall volume and reduced peak discharge by an average of 88.86%. Gregoire and Clausen (2011) quantified runoff from a 248m^2 extensive GR in Connecticut. It was found that the green roof retained 51.4% of precipitation during the study period. Stovin et al. (2012) conducted a laboratory experiment over 16-month period. They concluded that water retention capability can vary over different seasons and different rainfall patterns.

Graceson et al. (2013) conducted research to study the relationship between water retention capability with different types of growing media. Data was observed over a one-year period to find the relationship. The study concluded that decks were able to retain 44% of rain falling directly on their surface. More specifically, sedum decks retained 40% and meadow decks retained 48% of the rain. Morgan et al. (2015) studied green roofs with various media depth (plants depth) by performing a similar water retention capability study in Missouri over an 18-month period. All the green roofs studied in this experiment retained approximately 50% of the precipitation over the study period.

2.4.2 Permeable Pavement

Bond et al. (1999) conducted over thirteen years of research experiments to analyze rainfall and runoff reduction by adopting permeable pavements. Average runoff volumes between 34% and 47% were observed. Using a water balance study, it was concluded that the average water retention capability in the study area was 59.5%. Research results not only indicated that permeable pavement performs well in rainfall runoff reduction, but also confirmed that permeable pavements are capable of degrading mineral oil contamination. Dreelin et al. (2006) compared the porous performance of an asphalt parking lot to a porous pavement parking lot of grass pavers in Athens, Georgia. The research results indicated that the porous parking lot produced 93% less runoff than the asphalt lot. In a study conducted by Ball and Rankin. (2010), effective imperviousness was reduced from 45% to 5% after the implementation of permeable pavement. The results found that a minimum of 1/6" (4mm) of rain was required to consider significant rainfall, while a rainfall intensity in excess of 20mm/hr. was necessary to generate surface runoff from a permeable road surface. Drake et al. (2014) evaluated the hydraulic performance of permeable pavement in Vaughan, Ontario and found that permeable pavement can reduce and completely capture overall storm water outflow volume by 43%.

Imteaz et al. (2013) presented data measurements regarding the performance of permeable pavements used in Australia. The research revealed an average of 81% of runoff reduction by using permeable pavement. Yang et al. (2015) manifested a design rainfall intensity of 150mm/hr. and found retention capabilities to vary within a range of 24.2% to 45.6% based on varying medium depth. Depth plays a significant role in controlling retention. According to an experiment conducted by Alsubih et al. (2016), the total rainwater volume temporarily retained in the experimental pavement structure ranged from 40% to 92% of the total inflow from different rainfall intensities. Winston et al. (2018) conducted research on the hydraulic performance of four permeable pavement sections revealing a volume reduction varying from 16% to 53% and peak flow reduction ranging from 69.7 to 100%. Shafique et al. (2018) evaluated the hydraulic performance of PCIP. The experiment revealed that PCIP had 30% to 65% of runoff reduction performance during various storm events.

Collins et al. (2008) compared runoff reduction between asphalt and pervious concrete in terms of rainfall depth and found the percent of runoff reduction in asphalt to be 34.6%, compared to 99.9% in pervious concrete. This translates to more than 60% percent of rainfall retained in pervious concrete compared to asphalt. Average percent volume reductions from rainfall were 35.7, 43.9, 66.3, 63.6, respectively for four types of permeable pavements analyzed.

2.4.3 Bioretention (or Rain Garden)

Li et al. (2009) studied six bioretention sites across Maryland and North Carolina to investigate the performance of rain gardens. Outflow and inflow data for each site were recorded to quantify performance. The results indicated that approximately 20% to 50% of runoff entering the rain garden was lost to exfiltration and evapotranspiration. Stander et al. (2010) conducted three experiments with different sizes of rain gardens including 2%, 4% and 6% of drainage area. The rain garden with 2% of drainage area undertook the maximum hydraulic loading compared to that with 6% drainage area. The study suggests that infiltration rates are not significantly different among different rain garden sizes. Maxwell et al. (2017) selected simple rain gardens as an alternative rainfall mitigation design for small-scale projects. In this research, they conducted five field studies to assess performance. The results indicated that simple rain gardens can retain an average of 44% of rainfall under a rain event of 1” (25mm).

2.4.4 Detention Pond

Rushton (2001) constructed an innovative parking lot in Tampa, Florida to demonstrate how a small modification in parking lot design can decrease the amount of storm water runoff. The research revealed that swales reduced on average 30% of storm water runoff at the study site. Liptan (2001) simulated the runoff volume reduction performance in 4 acres of impervious area. The simulated results indicated that applying detention pond could retain the 7 hour runoff volume by 67%. Hussain (2005) performed a field study to evaluate the water quality performance of dry detention pond. The retention efficiency was 50% from the investigated studies. Line et al. (2012) installed a detention pond in a drainage area of 6.6 acres with a 90% imperviousness rate and found that the runoff rate was almost half of that on a control site containing no storm water control measures.

2.4.5 Constructed Wetlands

Lenhart and Hunt (2011) constructed and monitored a storm water wetland. Twenty hydrologic and eleven water quality events were captured and evaluated. The research concluded that the constructed wetland was very effective in storm water control with a reduction of 80% in outflow peak and 54% in runoff volume. Schwartz et al. (2017) constructed a retrofitted storm water retention pond located in a highly developed headwater watershed near the Potomac River. The results showed that the pond could hold 43% of the average inflow during the study period.

2.5 Discussion of Meta-Analysis Results

The meta-analysis results indicate that all six runoff control and mitigation methods were effective for storm water runoff reduction. Runoff reduction performance varies with different scenarios and is usually published as a range. Averages of these ranges are presented in Table 2. The maximum reduction was found by applying Permeable pavement (Bean et al. 2007). More information about the reduction performance regarding all investigated methods can be found in Table 3. Figure 5 shows a boxplot distribution of runoff reduction performance for the analyzed mitigation methods. From Figure 4, the performance distribution using Green Roof shows a lower variability with half of the analyzed data having a consistent runoff control and mitigation performance ranging from 50% to 70%, which suggests that this application is more likely to produce a desired reduction performance. Permeable pavement is not as consistent compared to Green Roof, as indicate by the box plot having a larger variation and median runoff reduction of 45%, which is the lowest compared to the other five methods. Based on the meta-analysis, it can be concluded that Permeable pavement has a relative lower likelihood to produce a desired runoff control and mitigation outcome.

Table 3: Summary for Runoff Reduction Performance of Investigated Methods

Mitigation Method	Green Roof	Permeable Pavement	Rain Garden	Grassed Swale	Detention Pond	Constructed Wetland
Maximum Reduction (%)	85	100	80	52.5	67	54
Minimum Reduction (%)	29	30	35	42	30	40
Average Reduction (%)	61	56	57	49	51	46

Figure 5 indicates that all runoff control and mitigation methods are applicable; however, it is recommended to consider additional factors when selecting a specific method given the performance variation of using permeable pavement. Figure 6 illustrates the average percent reduction performance of all runoff control and mitigation methods by year analyzed. The overall average of 56.5% runoff control and mitigation rate for all analyzed methods reveals that more than half of the outflow from impermeable concrete, asphalt, rooftops, and roadways can be absorbed and retained by these methods.

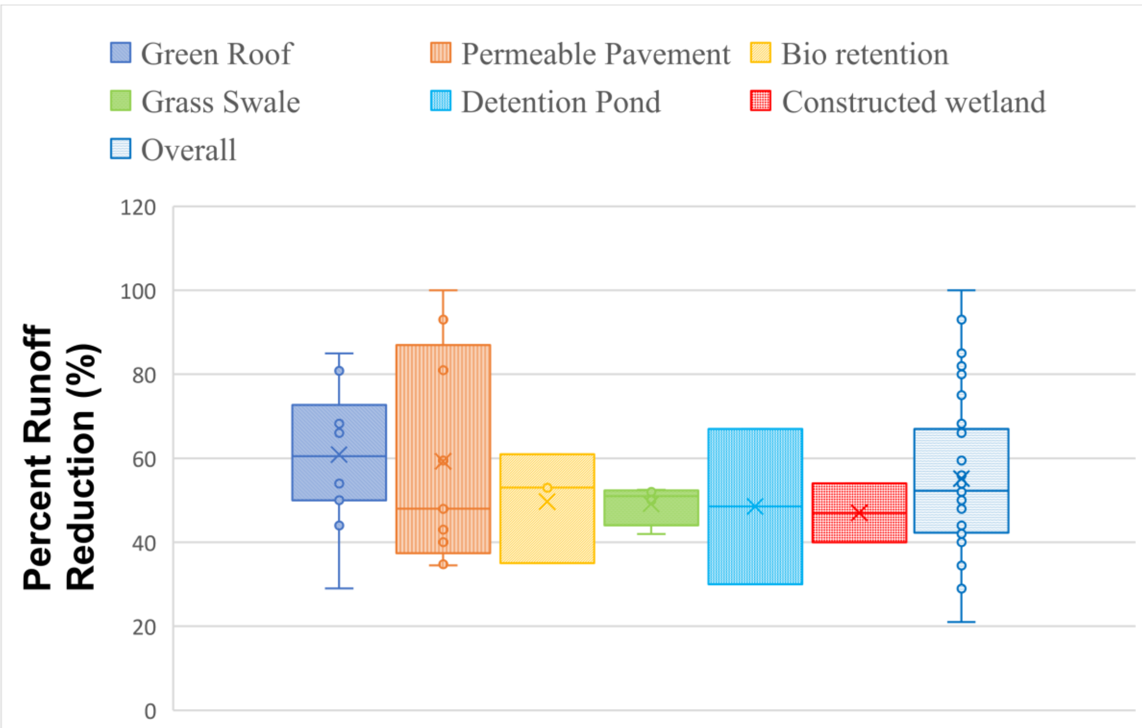

Figure 5: Box Plot of Percent Runoff Reduction for Alternative Strategies

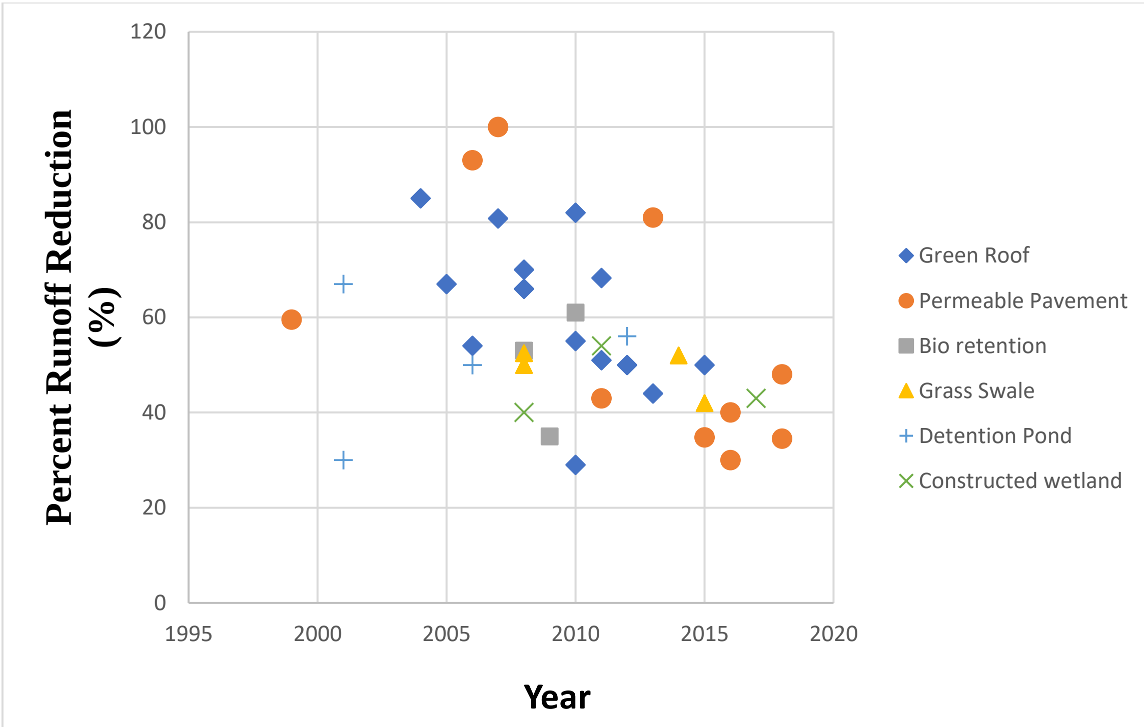

Figure 6: Average Runoff Reduction Using Alternative Strategies

2.6 Conclusions

A meta-analysis of past and current state-of-practice in storm water impacts in urbanized cities was presented in this paper to gain a better understanding of this important topic. A review of runoff incidents and impacts on urban area reveals the destructive effects of excessive urban storm water. A sampling of cities was selected for analysis based on population and geographical region as part of the meta-analysis. There is no indication that urban growth will slow down anytime soon, thus resulting in more urban impervious areas being built and consequently, more pressure placed on urban drainage systems during significant rain events. Expanding the urban drainage system is not the only way to help alleviate these impacts. Several runoff control and mitigation strategies described in this paper have proven to reduce runoff volume and relieve hydraulic pressure on urban drainage systems. It is anticipated that city planners or authority organizations will better understand the benefits of such sustainable storm water runoff control and mitigation methods. It is recommended that future research be conducted to obtain additional data for the performance of different runoff control and mitigation methods including emerging state-of-art strategies. Furthermore, it is recommended that research be conducted on the performance of multiple methods for a given application to better understand their connectivity.

3. COST-EFFECTIVENESS ANALYSIS OF LID COMPARED TO CONVENTIONAL STORMWATER STORAGE SYSTEMS IN ARIZONA

3.1 Abstract

Low Impact Development (LID), or green infrastructure, refers to a land planning and engineering design practice to tackle urban storm runoff. The nature of LID is to mimic the pre-development environment to retain the runoff through infiltration, retention, detention and evaporation. Despite a significant number of prior researches having been conducted to analyze the performance of runoff volume reduction and peak flow decrement of various green infrastructures, little is known about the economic benefits of using 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 discover the cost benefits of applying LID to meet the current drainage design requirements listed in the project documents. It was found that using LID can save an average of 23% LCC compared to a conventional stormwater storage system for 50 service years and 15.1% for 25 service years.

3.2 Introduction

Urban development usually takes flooding impacts on the natural environment into consideration in proposing new land development. Ironically, increasing urban flooding and decreasing consumable water resource appears at the same time in a traditional urban environment. A major reason for this irony is that the natural water cycle system has been interfered with from urbanization, which paves the cities with impermeable materials such as concrete and pavement, decreasing the urban infiltration capability while in the same time more groundwater resources are utilized for human activities. Urbanization induced stormwater impacts are not only reflected by an increased runoff volume rate, decreased infiltration capability, reduced groundwater recharge rate, but also an economic impact. A review of historic extreme rainfall impact for ten typical urbanized areas indicated that the stormwater impacts are destructively followed by billions of direct economic losses, fatalities, damaged properties and residents' relocation. On September 8^{th}, 2014, the Phoenix area was inundated following a historical event of 139mm (5.5 in.) in 8 hours. It was estimated that the incident resulted in approximately $18 million in direct loss and damages (Zhang and Ariaratnam, 2018). 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. The components of an integrated drainage system include routing pipes, catch basins, area drains, storm manhole, water storage system such as underground water tanks or detention basins and drywells, which is a method of discharging ponded water by subsurface injection and consequently to recharge the groundwater.

Precipitation in Maricopa County has been strongly influenced by variations in climate, changing from approximately annually 178mm (7 in.) in the Phoenix metropolitan area to more than 635mm (25 in.) in the mountain region of northern Maricopa county (Maricopa County, 2018). The precipitation occurrence in Arizona is divided into two seasons: summer (July to September) and winter (December to March). Especially during the summer period, in which the warm air creating the low-pressure surface zones and drawing moist air from the ocean and consequently, producing a monsoon period or a tropical storm. During the monsoon season, a constructed drainage system is the primary dependence to tackle the excess runoff generated from the urban environment and only during this period the threshold of the drainage capability is under the critical test since summer thunderstorm season would result in flash floods and make Arizona experience more severe weather than other states. (Hedding, 2018)

For the drainage system design, three types of design storm distributions are to be used in Maricopa County, 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 2-hour storm distribution is to be used for the design of stormwater storage facilities, the 6-hour storm distribution is used for flood studies and design of stormwater drainage facilities in Maricopa County of drainage areas less than 51.8km^2, and the 24-hour storm distribution is used to perform the flood studies for the area that is larger than 259km^2. (Maricopa County, 2013) For the research purpose, the projects selected in this research are small scale land developments and the rainfall distribution of 100 years 2 hours has been defined to design the stormwater storage facilities throughout all investigated ones according to the project description.

For urban development, such as residential, commercial or industrial, an on-site drainage system is a part of the critical developments that needed to be considered at all the time since the existing land environment is disturbed from the construction, which is shown from the changing runoff coefficient of post-development. The key to a well-designed drainage system is the effectiveness to receive and store the excess runoff in the proposed storage facilities such as underground water tanks or detention basins. The construction of stormwater storage facilities is expensive and usually involving extensive land excavations and soil disturbance as shown in Figure 7, which shows the construction crew installing the ø3.05m (120 in.) corrugated metal pipe (CMP). CMP is the underground stormwater storage facility that is commonly used in the Arizona region especially in the project with limited space, where the underground space is apt to be primarily utilized (Ariaratnam, 2017). The size of the stormwater storage facility is directly correlated with the landcover scenarios. With the more landscape coverage onsite, which is more permeable and tend to hold the received precipitation, the smaller size of the stormwater storage facility is needed. Adversely, with the majority part of the site covered with impervious material such as concrete and asphalt, the more substantial portion of the precipitation can be transformed as runoff and as a result, the bigger size of the stormwater storage facility is required. Aside from the stormwater storage facility, the drywell(s) as the auxiliary unit is required to build to drain the temporarily stored runoff. According to the drainage design manual in Arizona, the designed drywell(s) is required to remove away the stored runoff in 36 hours after the runoff event has ended (Maricopa County, 2013). Thus, in Arizona, an integrity stormwater storage system commonly consists of stormwater storage facilities and drywells.

The objective of this research is to perform a value engineering study on traditional stormwater storage systems and substitute it with the alternative sustainable design to determine the cost savings on the traditional stormwater storage system. As an alternative while sustainable method, Low Impact Development (LID) tends to become one of the most progressive ways in reducing stormwater runoff and managing the runoff quality. In this paper, three land development projects in Arizona region including the information of drainage system and land cover type have been reviewed while in the same time the alternative LIDs design for each of them has been performed to investigate the cost-effectiveness of applying LID. In this study, two LID strategies including extensive green roof (GR) and permeable interlocking concrete pavements (PICP) were considered to conduct the analysis. The cost information of capital investment and operation and maintenance (O&M) for the traditional drainage system has been retrieved from the accepted project proposals or through the interview with experienced project managers. The cost information for capital and O&M of the considered LID strategies was gathered through the interview with local engineers who are experienced in the land development with green strategies. The LCC analysis spreadsheets were built based on a previous study (Uda et al. 2013). For each of the three reviewed projects, three life cost analysis sheets were created included applying both GR and PICP, GR exclusively and PICP exclusively. All nine analysis was conducted to determine the cost savings on the stormwater storage system according to the runoff volume reduction through applying LIDs.

Figure 7: Construction Crew Installing the 120 in. CMP for Stormwater Storage

3.3 Methodology

The study is project orientated to apply the alternative LID designs for runoff impacts' mitigation 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 insight stakeholders and contractors with the cost-effectiveness of LID regarding building the stormwater storage system and drywell 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 tool called PlanSwift. Only the paved parking spaces with the specific dimension of 2.74m 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 the equation (see Equation 2) was used, which modifies the displayed equation (see Equation 1) being listed in Storm Water Policies and Standards for City of Phoenix.(COP, 2011)

$$V = C\frac{P}{12}A \tag{1}$$

$$V_r = (C_{lc} - C_r)\frac{P}{12}A \tag{2}$$

where V = design runoff volume (c.f.); V_r = runoff volume after applying LID (c.f.); C = weighted runoff coefficient shown in the project document; C_{lc} = runoff coefficients for different land cover type (roof = 0.95; asphalt pavement = 0.95); C_r = runoff volume reduction coefficient of LIDs; P = designed rainfall depth according to the location of the project (inches); A = onsite drainage area (sq.ft).

Rational Method as listed in Equation 1 is allowed for the estimation of stormwater peak flow, and runoff volume for the design of storm drains and retention stormwater storage facilities. The runoff coefficient (C) used in the rational 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 landcover type affect the runoff coefficient, but also the rainfall intensity or return period of the precipitation event. For example, the runoff efficient of different rainfall return period for the same land use scenario is different. Based on the stormwater design manual, the runoff coefficient is 0.75 under the 2-10 years return period for the business/commercial area while 0.9 under the 100 years return period for the same land type. (COP, 2011)

Similarly, the runoff reduction performance for the LID strategies is also related to the specific rainfall event. Given the purpose of the research is to determine the cost-effectiveness of the LID compared to the designed drainage storage system as shown in the project document. The designed rainfall event in the project document is selected in determining the runoff reduction performance of GR and PICP. For all reviewed projects, the precipitation event with total rainfall depth of 2.17-2.19 in. (55mm) is chosen to design the stormwater storage facilities. The literature review has indicated that GR can achieve an average of 61% volume runoff reduction and 56% for the permeable pavement across different project site, rainfall event and different construction craft. (Zhang and Ariaratnam, 2018). While for this research, specific design on the GR and PICP has been determined to perform the cost analysis. Thus, the runoff reduction performance for the design of GR and PICP has been reviewed under similar rainfall events.

The components of an integrity GR consist of vegetation layer, growing medium layer, and waterproof layer. GR is typically characterized as intensive (having 152.4 to 609.6mm of medium and large vegetation) or extensive (having 76.2 to 152.4mm of medium and smaller vegetation). The application of the extensive GR with 4 inches growing medium was considered in this research, and the extensive GR is an idea for efficient stormwater management and requires low maintenance need. To determine the runoff reduction performance, the preliminary reports regarding the designed rainfall events have been reviewed. Getter et al. (2007) analyzed the runoff from 12 extensive GR platform, and the research indicated that the extensive GR with 2% slope could retain 85.6% of heavy rainfall (>10.0mm) and delay the peak flow for an extended period. Carpenter and Kaluvakolanu (2011) did a field study to collect 6-month runoff data for a different type of roof with 4% roof slope including asphalt roof (for control purpose), vegetated extensive GR and a stone ballasted roof. The summarized runoff data suggested that the overall extensive GR can retain 68.25% of rainfall, 54.3% for rainfall event of total 32.26mm of precipitation and 35.4% for rainfall event of total 74.68mm of rainfall. Voyde et al. (2013) monitored the runoff reduction performance of a 235m^2 extensive GR for a year in Auckland, New Zealand. The field study result indicated that the extensive GR could retain a median of 82% of rainfall, 42% for the rainfall event with 55mm of total precipitation depth and 50% for the rainfall event with 30mm of total precipitation depth. Stovin et al. (2013) measured the runoff retention capability for the typical extensive GR configuration from UK locations and highlighted that the extensive GR could hold 59.1% of rainfall for the annual rainfall of 496mm. Thus, it was concluded that the typical extensive GR could hold an average of 55% rainfall for the designed precipitation event.

PICP consists of concrete pavers, permeable joint material, open-graded bedding course, open graded base reservoir and open graded subbase reservoir (Tyson and Tayabji, 2015). The benefits of using PICP include the paving materials require no time-sensitive site forming and are ready for traffic immediately upon completion. The strategy of PICP is to infiltrate the water to the underlying aggregate storage layers and dewater through an underdrain as required. For the research, the runoff reduction performance for the designated PICP under the designed rainfall intensity has been reviewed. Collins et al. (2008) performed the hydrological study for a permeable pavement parking lot through June 2006 to July 2007 to measure the difference in surface runoff volumes, total outflow volumes and time to peak. It was estimated that PICP could retain an average of 98.8% of rainfall with precipitation depth from 6mm to 50mm while average 80% of rainfall was converted as surface runoff from the event with total precipitation depth of 135mm. ICPI. (2008) published a report and claimed that the infiltration rate for PICP could be up to 1270mm/hr. with regular maintenance and runoff reduction can be as much as 100% from a 75mm rain event. Winston et al. (2018) conducted the hydrologic performance of four permeable pavement to determine hydrological benefits. The site studies conducted in Northeast Ohio have shown that the permeable pavement could substantially reduce stormwater runoff volume and peak flow rate. The experiment performed on the sites installed with PICP reveals that the PICP can retain 91.6% of total 602mm inflow and 75.8% of total 543mm inflow. Thus, it was estimated that the design PICP could retain a minimum 80% of rainfall for the designed rain event of 55mm.

Based on the runoff reduction performance regarding extensive GR and PICP, the runoff reduction volume given the designed precipitation can be modelled for the investigated construction projects and subsequently, the savings on the existing stormwater storage facilities and drywells can be evaluated.

3.4 Project Document Review

To gain a better understanding of the projects located in the Phoenix metropolitan area, three different types of projects have been reviewed: 1) commercial; 2) residential; and 3) multifunctional. Project data including roof area and parking lot area were retrieved from the measurements on the scaled project documents. The construction price for the drainage system was gained from the proposed and accepted bidding proposals, including the detailed breakdowns. Further supplementary data for the design of drainage systems, such as a weighted runoff coefficient, designed rainfall intensity or total depth, and on-site stormwater retain capability, was also obtained from the project description. Detailed descriptions for the project are defined in the following sections.

3.4.1 Case Study #1 – Multifunctional Building in Scottsdale, Arizona

The first project studied is a multifunctional building (see Figure 8) located in Scottsdale, Arizona and built in 2017. It 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 the 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 (NOAA ATLAS 14). The weighted runoff coefficient is 0.84, as per the project documents. It was estimated that the developed site would generate a volume of 226,049 c.f. (6401 m3) direct runoff and the constructed runoff retention basins could retain 263,443 c.f. (7463 m3), 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 (Maricopa County 2013).

3.4.2 Case Study #2 – Multi-Family Development in Phoenix, Arizona

This project consists of the construction of a 363-unit multi-family development (see Figure 9) and related site improvements in Phoenix, Arizona. The project, with 14.14 acres (5.72 ha) of development built in 2018, was installed with on-site underground retention basins of 120 in. (3.05 m) diameter corrugated metal pipe (CMP) to retain the pre-development versus the post-development runoff. The drainage system constructed for the project includes 120 in. (3.05 m) CMP, 48 in. (1.22 m) Rubber Gasketed Reinforced Concrete Pipe (RGRCP), various diameters of HDPE pipes, 18 units of nyloplast area drains, storm drain manholes, and five drywells to percolate the stored runoff into the underground retention basins. For the roofing system, 4.2 acres (1.7 ha) 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 1.26 acres (0.51 ha) of parking spaces were paved with 2 in. (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 2.24 in. (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 50,146 c.f. (1420 m^3), including the additional 25% safety storage design as per the design manual (COP 2011). The underground retention tanks could provide a total of 50,182 c.f. (1421 m^3) of retention capability and an onsite percolation rate of 0.1 c.f./sec as per the test, which required the installation of five drywells.

3.4.3 Case Study #3 – Resort-Style Apartment Building in Chandler, Arizona

The third project reviewed is a resort-style apartment building (see Figure 10) located in downtown Chandler, Arizona. The project with 5.54 acres (2.24 ha) of land development was built in 2018. Furthermore, 796 feet (242.6 m) of 96 in. (2.44 m) diameter CMP was installed to retain the runoff generated from the rain event of 2.16 in. (55 mm), which is the 100-year, 2-hour rainfall distribution event, according to NOAA ATLAS14. Meanwhile, various sizes of HDPE, catch basins, different sizes of area drains, and drywells were constructed to form the on-site drainage system, to protect the impacts of runoff from spreading. The designed runoff volume from the project was 39,976 c.f. (1132 m^3), based on the weighted runoff coefficient of 0.92 calculated in the project documents. Four drywells were designed to discharge the stored runoff in 36 hours as per the drainage design manual for Maricopa County. It was measured that 1.6 acres (0.65 ha) of the conventional flat roof was chosen to be the roof portion for the apartment project. 4in. (101.6 mm) thickness asphalt pavement was selected to construct the traditional parking spaces, which totalled approximately 0.71 acres (0.29 ha).

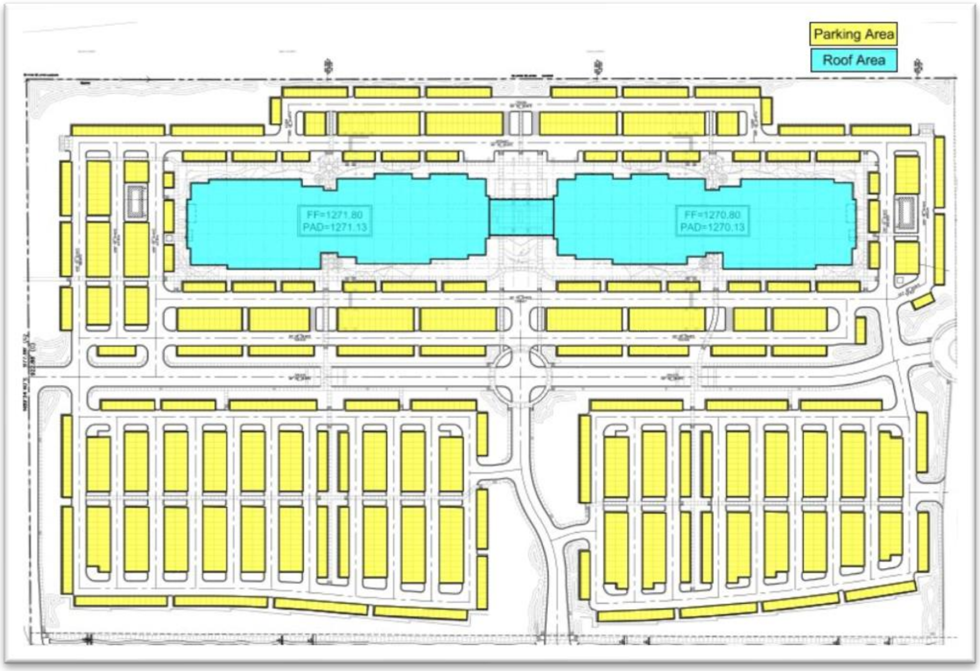

Figure 8: Case Study #1 Located in Scottsdale, Arizona

Figure 9: Case Study #2 Located in Phoenix, Arizona

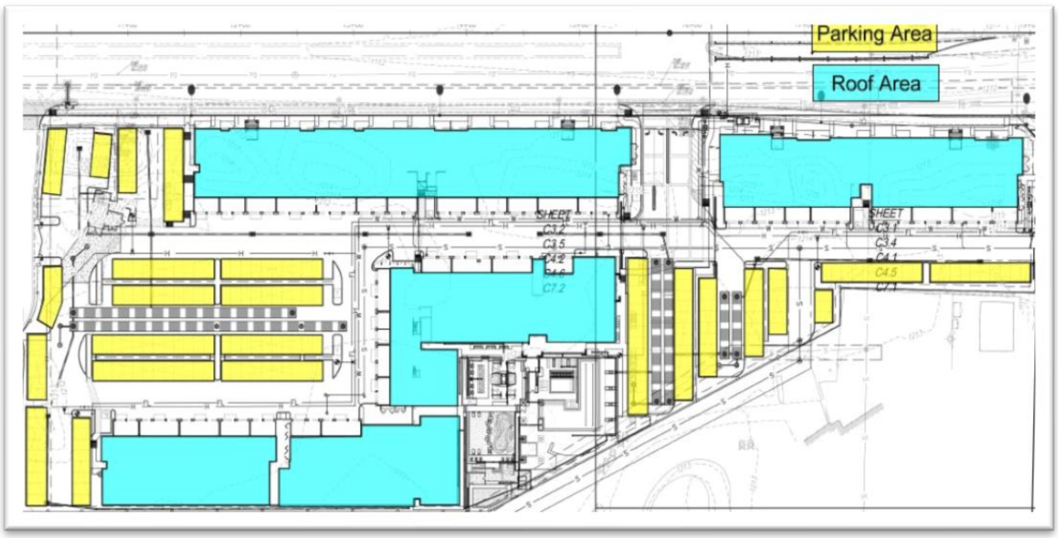

Figure 10: Case Study #3 Located in Chandler, Arizona

3.5 Cost Data Collection

All construction costs for the infrastructures, including the drainage system and LID, are based on local, Phoenix Metropolitan area items since construction-related costs tend to vary across different States. As previously mentioned, the construction price of the drainage system is gathered from the accepted project bidding proposals, while the construction price for LID was gathered from local project managers 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 about the cost analysis of applying green infrastructure/LID in Phoenix, AZ (COP 2018). For the LCC analysis, the maintenance cost was required not only for reaching the life expectancy, but also for continuously meeting the designed performance. Table 4 presents the detailed cost information.

Table 4: Detailed Cost Information

Variable	Retention Basin ($/c.f)	120" CMP ($/c.f)	96" CMP ($/c.f)	Drywell ($/EA)	Conventional Roof ($/sq.ft)	2" Thickness Asphalt ($/sq.ft)	4" Thickness Asphalt ($/sq.ft)	Extensive GR ($/sq.ft)	PICP ($/sq.ft)
Capital Cost	0.82	3.5	4.8	20,000	8	3.2	4.3	10.7	8
Annual Maintenance Cost	0.06	1	1	2000	0.16	0.2	0.2	0.1	0.2
Replacement Cost	0.5248	2.5	3.1	24000	6.4	2.0	2.5	8.5	6.8
Designed Life Span (Years)	30	30	30	30	30	25	25	40	30

All cost information listed in Table 4 were obtained from either bidding proposals or interview results to demonstrate the presented models. For example, the cost for 120 in. (3.05 m) diameter CMP and 96 in. (2.44 m) diameter CMP is listed as a total bidding price in the construction proposals, and the converted value was achieved by dividing the bidding cost by the provided stormwater retention volume. For the drywell, the capital and maintenance costs were provided by a project manager working for a local drilling company. 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 drywell system and reduce dewatering performance. The roofing price was gained from a general contractor who provided the most likely accepted price during the bidding process for constructing a typical flat white roof in Arizona. The capital cost of the asphalt paving varied depending on the thickness of asphalt, while the maintenance fee was like the bituminous treatment or fog coating, which lays another half inch thickness of coating material on top of the existing asphalt. The constructing price of PICP was gathered through a quotation from a local paving company specialized in PICP. The annual maintenance activities for PICP include joints cleaning and debris removal using an air vacuum machine. The authors are confident in the accuracy of the cost data for the Phoenix Metropolitan area.

3.6 Cost-Effective Analysis

The cost analysis is based on runoff volume reduction from applying LID strategies and consequently, savings on the stormwater storage facilities and supplemented drywells. For the analysis of 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 the capital cost. Equation 3 was used to project the LCC savings from applying LID strategies, and Equation 4 was utilized to project the savings rate. Net Present Value (NPV) was used to calculate the LCC for each project at various discount rates including 0%, 3% and 5%. The LCC projection results can be found in Figure 11.

$$S = C_T - C_{LID} \tag{3}$$

$$SR = \frac{S}{C_{LID}} \tag{4}$$

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 (%).

Figure 11: LCC Saving Rate from Applying LID for Each Project

3.7 Results Analysis

The results suggest that LCC savings from applying LID cannot be detected across all investigated projects. For example, using LID to the Multifunctional Building in Scottsdale, Arizona project is not cost efficient compared to the savings realized in Case Study #2 and #3. The reason for this could be the cheaper construction costs in building the above-ground retention basin. A face-to-face interview with a professional construction manager suggested that the construction of retention basins can be faster and less expensive using a scraper that can perform massive excavations and is exceptionally efficient for moving soil. However, the success of using a ground retention basin is limited to a larger project site. For a site with limited space, underground space must be utilized for the construction of stormwater storage facilities. As shown in case study #2 and #3, which have demonstrated the cost efficiency of applying LID on site. Using both LID designs, case study #2 and #3 mark an average of 23% life cycle saving for 50 service years and 15.1% for 25 service years. With GR only, it could lead to an average saving of 33.6% for 50 service years and 22% for 25 service years. Furthermore, applying PICP only for the case study #3 could save an average of 17% for the 50 service years and 15.8% for the 25 service years. Applying PICP only on the project in case study #2 was not cost efficient, because the thinner and cheaper asphalt was utilized on the parking lot for this project.

Calculating the average LCC saving rate provides an understanding of the cost benefits of using LID at the global project scales. While the saving rate is mainly associated with the initial construction costs. For more detailed cost savings of LID, it was determined that applying both LID methods on case study #2 (14.14 acres) can save an average of $1,070,700 for 50 service years and $469,360 for 25 service years. Moreover, it was determined that applying both LID methods on case study #3 (5.54 acres) can save an average of $580,619 for 50 service years and $267,272 for 25 service years. Furthermore, the average saving amount and rates are influenced by discount rates. For the case study #2 and #3, it was observed that both LCC saving amount and rate are the highest at the 0% discount rate and decreasing along with the increasing discount rates.

3.8 Conclusions and Recommendations

This study aimed to investigate the cost efficiency of LID regarding building drainage storage facilities and supplementary drywell systems. It concluded that applying LID could be cost beneficial in 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 infrequent rain events, applying LID not only brings the design stormwater mitigation capability but also delivers aesthetic benefits and increases property values. This research contributes to the body of knowledge by assisting stakeholders and contractors in understanding the cost benefits of LID better. However, research at the current stage is limited in analyzing the cost savings of stormwater storage facilities. Future research can focus on additional cost benefits including the size decrement for drainage conduit pipes, quantity reduction for water collection systems, and urban heat island alleviation from applying green infrastructures.

4. LIFE CYCLE COST SAVING ANALYSIS ON TRADITIONAL DRAINAGE SYSTEM FROM LOW IMPACT DEVELOPMENT STRATEGIES

4.1 Abstract

Areas, where natural vegetation covers have been converted to asphalt, concrete, or roofed structures, have experienced increased surface imperviousness and decreased natural drainage capability. To prevent the occurrence of waterlogging in developed sites, conventional drainage systems are built to mimic natural drainage patterns. 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 and are used to store and percolate the runoff, while conduit systems are a combination of catch basins and conduit pipes used to collect and transport the runoff. The construction of these drainage systems is costly; however, and may involve significant environmental disturbance. In this research, low impact development (LID) methods consisting of extensive green roof (GR) and permeable interlocking concrete pavement (PICP) are introduced for application 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 Phoenix, Arizona metropolitan area. The research results indicate that applying both LID methods to existing projects can save an average of 27.2% in life-cycle-costs (LCC) for 50-year service life and 18.7% in LCC for 25-year service life on the proposed drainage system.

4.2 Introduction

Urbanization has led to enormous challenges regarding stormwater management in cities. Converting vegetation covers into concrete pavement covers has reshaped urban permeability capacity, resulting in increased runoff volume and peak flow rates. Due to climate change affecting precipitation patterns, storm-affected areas are more likely to experience increased precipitation. Thus, drainage systems are becoming more vulnerable to flooding risks. To reduce potential development-induced flooding risks, drainage systems following the site grading design will be proposed.

Constructing traditional drainage systems is a standard method to reduce the flooding risks 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 and involve heavy construction machines and long work periods. The options for traditional drainage systems are becoming increasingly difficult to implement in dense urban environments due to the complex underground environments, thus creating a need for low footprint solutions. This need has led to emerging opportunities for 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 retaining the runoff close to its source. The hydrological benefits of the two LID methods investigated in this paper, extensive green roof (GR) and permeable interlocking concrete pavement (PICP), have been identified in past experiments (Zhang and Ariaratnam, 2018).

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

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

Based on the grading and drainage plan, the hydrological contribution area for each water collection point within the project area was delineated and segmented. Later, the weighted runoff coefficient for each contribution area was recalculated per the applicable area of extensive GR and PICP. The peak flow rate for each delineated drainage area was changed according to the modified runoff coefficient. Subsequently, the required conduit sizes for transporting the 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 size of drainage pipes (Maricopa County, 2018). The peak flow reduction performance regarding the specific rainfall event was determined by reviewing hydrological experiments performed by other scholars.

4.3 Literature Review

To fully understand the cost benefits, it is essential to identify the hydrological performance of the investigated LID methods. As a continuation of a previous research study that only considered the volume reduction benefits when applying LID methods, this paper adds the benefits of reduced runoff flow rate into the cost benefits analysis. To gain a better understanding of the hydrological advantages of extensive GR and PICP, published studies looking at flow reduction performance were examined. The runoff reduction performance is not only correlated to the land cover types but also the rainfall intensity or return period of the precipitation event. The following section describes prior research conducted for PICP and extensive GR to better understand flow rate reduction performance under the designed rainfall depth and intensity as shown in the project documents (100 years, 2 hours).

4.3.1 Permeable Interlocking Concrete Paver

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 observed 36 rainfall events, the parking lots installed with PICP saw an average reduction of 71% in peak flow, while the maximum peak flow reduction was 100% during some smaller events. For example, only 1.2% of rainfall volume was converted as surface runoff during a storm event of 6 mm to 50 mm of 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 and two different manufacturers of PICP were selected to examine the performance. The research results indicated that PICP could reduce peak flow rate by as much as 89% compared to traditional asphalt pavement during a rainfall of 51.6 mm 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 3.5 in. (90 mm) per hour and that runoff only occurred two hours after a rainfall event with an intensity of 5.39 in. (137 mm) per hour.

Braswell et al. (2018) examined the hydraulic performance of PICP built over low conductivity soil. The experiment took place 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 0.93 in. (23.6 mm) per hour and by 63% during rainfall with an intensity of 0.811 in. (20.3 mm) per hour.

Shafique et al. (2018) investigated the runoff mitigation performance of PICP in a populated area of Seoul, Korea and determined its runoff reduction performance and capability during different storm events. The research results claimed that 100% runoff was retained under rainfall with an intensity of 1.57 in. (40 mm) per hour and 30% to 50% of runoff was reduced under rainfall with an intensity of up to 4.72 in. (120 mm) per hour. The research concluded that the PICP system could capture all runoff during small storms with an intensity of less than 1.57 in. (40 mm) per hour.

4.3.2 Extensive Green Roof

Hakimdavar et al. (2014) examined how rainfall characteristics and GR scale impacts the peak and cumulative volume generated from extensive GR. The hydrological performance of three extensive GR in New York City was analyzed. The results indicated that extensive GR could reduce peak flow by an average of 63.5% under rainfall 1.97 in. (50 mm) in depth and with an intensity of 0.94 in. (24 mm) per hour.

Razzaghmanesh and Beecham (2014) presented the hydrological investigation of four medium-scale GRs that were set up in Australia. Over the recorded 226 rainfall events, the average runoff retention coefficient was determined to be 89% for intensive GR and 74% for extensive GR. The two-year experimental results also suggested that the average peak flow rate of extensive GR could be reduced by 78.7% for an average rainfall depth of 0.75 in. (19.1 mm) moreover, 44.3% for a rainfall depth of 0.89 in. (22.5 mm). Moreover, the peak attenuation of extensive GR was observed as 95.25% for a rainfall depth of 1.21 in. (30.8 mm).

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 medium, 10 cm versus 15 cm depth, and irrigation provided daily versus not at all. During the study period of May–October in 2013 and 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 0.03 in. (0.6 mm) to 1.79 in. (45.4 mm) and intensities that varied from 0.03 in. (0.6 mm) to 3.3 in. (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 1.71 in. (43.4 mm) because the initial soil was saturated and cannot hold more water. Despite the lower runoff reduction in certain samples, the authors affirmed that GR could achieve a 100% runoff reduction in both runoff depth and peak runoff rate during smaller rainfall events and drier initial soil moisture conditions.

4.4 Research Methodology

The objective of the current study was to perform an integrated cost comparison between LID methods and traditional drainage systems. As a continuation of a previous research, the current study considers not only the cost savings of the stormwater storage system, but also stormwater conduit pipe as LID methods lead to a reduced runoff flow rate. Three construction projects recently built in the Phoenix, Arizona metropolitan area 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 for the conduit pipes, and the grading plans for the sites was examined in this paper. To mitigate the influence of other construction variables on costs, the analysis presented maintains the original design on the drainage grading plan, depth and slope of the conduit pipes.

The first stage of the study involved locating the existing catch basins and associated conduit pipes. Conduit pipes transport runoff from impervious surfaces, such as roofs, parking spaces, paved streets, and sidewalks to the water collection system. The sizes of conduit pipes are correlated with the flow rate upstream, Manning’s roughness coefficient, and pipe slopes, as shown in Equation 8. To determine the upstream flow rate, watershed delineation and segmentation were performed to determine the hydrology contribution area for each catch basin. The watershed area for each catch basin was determined based on the grading drainage plans, the grade break lines, and the existing flow path plan in the construction documents.

The experimental results from the literature review were used to calculate the runoff coefficient for LID, as shown in Equation 5. Afterwards, the applicable area for extensive GR and PICP within each delineated watershed was outlined, and the modified runoff coefficient for each watershed was re-calculated using Equation 6. The initial runoff flow rate and modified runoff flow within each delineated watershed were calculated using Equation 7. The weighted runoff coefficient as listed in the project documents was utilized to determine the initial runoff flow rate. The runoff flow rate entering each catch basin was altered according to the modified runoff coefficient for each affected watershed, leading to different sizes of conduit pipes being required downstream. Flow accumulations from upstream to downstream were taken into consideration to determine the required pipe sizes accurately.

$$C_{i(lid)} = C_{i(lc)} \times (1 - PR) \tag{5}$$

where $C_{i(lid)}$ is the runoff coefficient for a specific LID method; $C_{i(lc)}$ is the runoff coefficient for the original land cover; and PR is the peak flow reduction rate for the investigated LID methods.

$$C_w = \frac{\sum C_i \times A_i}{\sum A_i} \tag{6}$$

where C_w is the weighted runoff coefficient; C_i is the runoff coefficient associated with different land cover type; and Ai is the area for different land cover type within each watershed (acre).

$$Q = C_w iA \tag{7}$$

where Q is runoff flow rate (cfs); i is precipitation intensity per NOAA ATLAS14 (inch/hour); and A is the watershed area (acre);

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

where D is the diameter of the conduit pipes (ft); n equals Manning's roughness coefficient; and S is the slope of the storm drain (ft/ft); Q is runoff flow rate (cfs);

Following the alternative design of the conduit pipes, an LCC for constructing the modified pipes was conducted. 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 sizes of conduit pipes. The net present value (NPV) was selected for the cost benefits analysis, as shown in Equation 9.

$$NPV = C_{capital} + \left|\sum_{t=0}^{n} \frac{M}{(1+i)^t} + \frac{R}{(1+i)^t}\right| \tag{9}$$

where $C_{capital}$ is the capital construction cost spent initially; 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.

4.5 Case Studies

4.5.1 Project Descriptions

4.5.1.1 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. To address the runoff generated onsite, a drainage system including 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. The conduit pipes used to direct the runoff were 252 m (825 feet) of 30” HDPE, 268 m (878 feet) of 24” HDPE, 310 m (1,014 feet) of 18” HDPE, 218 m (714 feet) of 15” HDPE, and 673 m (2,208 feet) of 12” HDPE. Based on the project description, conventional roof coverage accounts for 9% of the total project area, while the coverage rate for the asphalt parking spaces is 22.4%.

With the new construction, runoff from the 100 years and 2 hour storm events, totaling 55 mm (2.17 inches) rainfall with an intensity of 24 mm (0.94 inches) per hour, is drained to the retention basins and subsequently percolated to the subsurface to recharge the groundwater through the drywell system. Based on the grading plan and location of catch basins, a total of 39 watersheds were delineated, and 1073 m (3,519 feet) of associated conduit pipes were selected to perform the alternative design.

4.5.1.2 Case Study #2 – Multi-Family Development in Phoenix, Arizona

The second case study was a 5.72 ha (14.14 acres) multi-family development in Phoenix, Arizona that was built in 2018. To mitigate the increase in runoff caused by the development, a traditional drainage system was constructed including underground retention tanks, various sizes of conduit pipes, 20 MAG catch basins, 12” Nyloplast area drains, and storm-drain manholes. In this case, the conduit pipes consisted of 183 m (598 feet) of 24” HDPE, 280 m (917 feet) of 18” HDPE, 390 m (1,280 feet) of 12” HDPE, 615 m (2,016 feet) of 8” HDPE, and 607 m (1,989 feet) of 6” HDPE. Corrugated metal pipe

(CMP) with an inner diameter of 3.05 m (10 feet) was built to retain the post-development runoff. The designed rainfall depth for the project was 2.28 in. (58 mm) with an intensity of 1.1 in. (28 mm) per hour. The retention capability provided by the designed retention basin was 50,183 c.f. and five drywells were installed to de-water the stored runoff within 36 hours 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 2 inches (50.8 mm) thickness asphalt pavement was selected to construct the traditional parking spaces totaling approximately 1.26 acres (0.51 ha).

Based on the drainage and grading plans for the land development, 20 watersheds were delineated (see Figure 12), and 497 m (1,630 feet) of conduit pipes was selected for the alternative design (see Figure 13). Areas filled with different colors in Figure 12 represent different watersheds. While in Figure 13, triangle markers indicate the location of catch basins and different colored lines display the size differences of the conduit pipes.

4.5.1.3 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 on 2.24 ha (5.54 acres) of land development and was built in 2018. To reduce the impact of the runoff, an onsite drainage system was built including various sizes of HDPE, catch basins, underground retention basins, and drywells. 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. CMP with an inner diameter of 2.44 m (8 feet) was built to provide 1,132 m^3 of water retention capacity, and four drywells were proposed to discharge the stored runoff in 36 hours.

A conventional flat roof was chosen to be the roof portion and accounted for 29% of the project area. A 101.6 mm thickness asphalt pavement was selected to cover the parking spaces and accounted for 13% of the project area. To transport the runoff, 458 m (1,500 feet) of 12" HDPE and 577 m (1,892 feet) of 8" HDPE were installed. Based on the grading and drainage plan, a total of 17 watersheds were delineated, and 302 m (990 feet) of various sizes of HDPE was depicted between watersheds.

4.5.2 Watershed Segregation and Peak Flow Rate Comparison

To reduce cost variation caused by construction factors such as grading-induced cost increment, watershed segregation was performed based on the existing grading and drainage plan. The grade break lines were utilized to delineate the watershed on the ground surface, while runoff generated from the roof was associated with how the roof outflow point and 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, while Case Study #1 connects the roof drain to the catch basin directly through the conduit pipes. Construction variations like these 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 Equation 6.

The study presents the reduction in peak flow within each watershed for the three investigated case study projects. The differences between the initial flow rate and the modified flow rate are the hydraulic benefits of applying LID methods. Figure 15 illustrates the flow rate comparison within each watershed in Case Study #1 with the results indicating that applying LID methods can reduce 36.8% of the overall flow rate for the entire project.

Figure 15 presents the flow rate variations in the watersheds for Case Study #2, which exhibited an average reduction of 34.6% in the overall peak flow rate. Similarly, Figure 16 indicates reductions in peak flow rates for Case Study #3 with the results suggesting that applying 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 the different case studies, especially for Case Study #2, where a reduction in peak flow rate was observed in every delineated watershed (see Figure 15).

Figure 12: Watershed Segregation Per the Grading and Drainage Plan

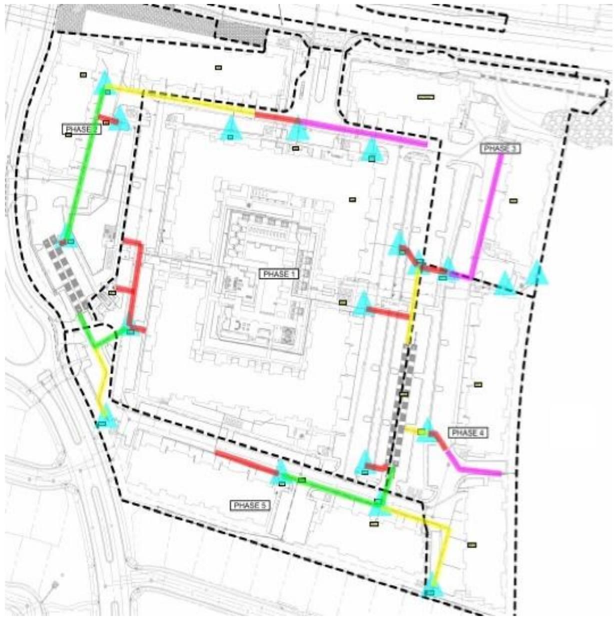

Figure 13: Catch Basin and Associated Conduit Pipes

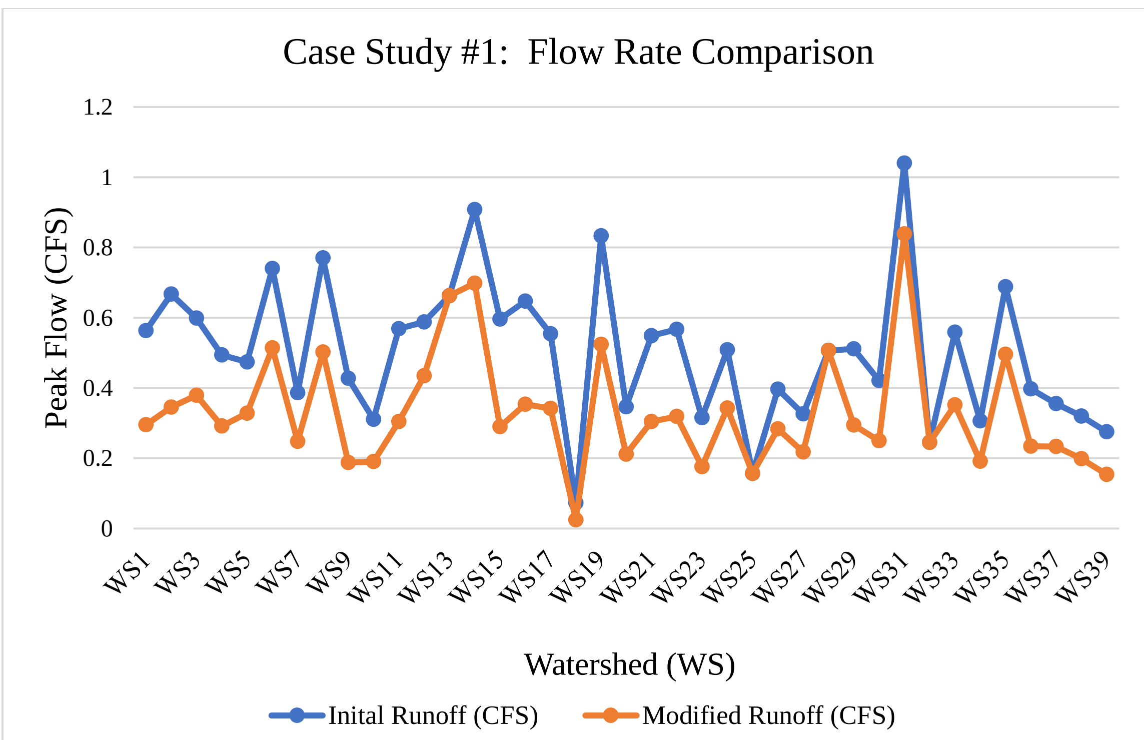

Figure 14: Runoff Flow Rate Comparison at Each Watershed (Case Study #1)

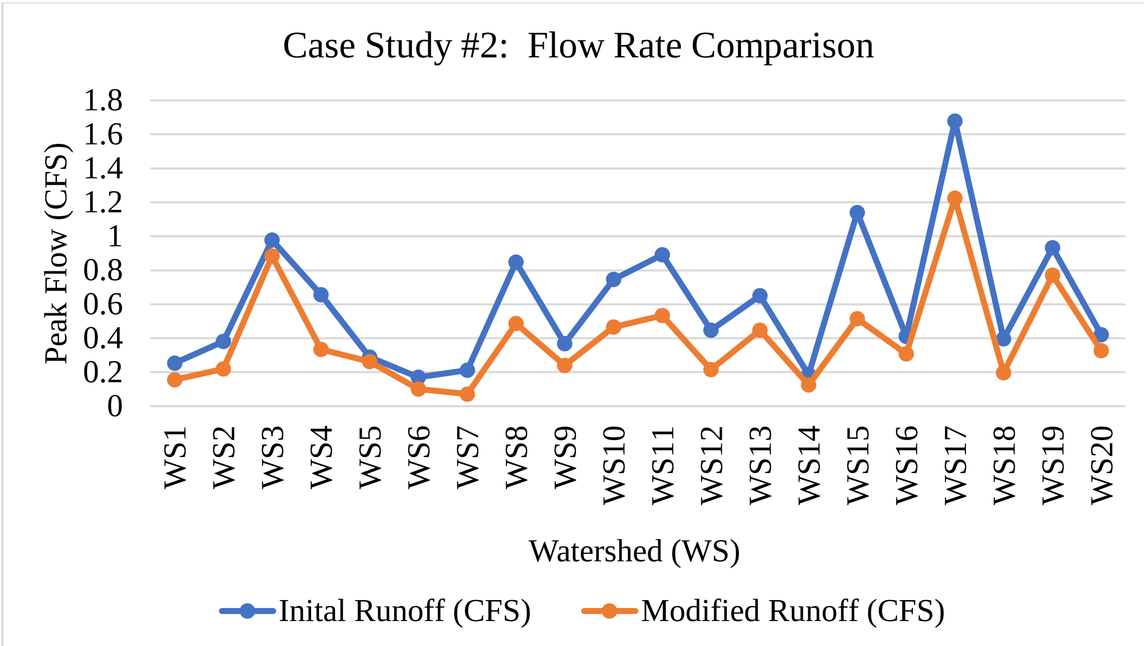

Figure 15: Runoff Flow Rate Comparison at Each Watershed (Case Study #2)

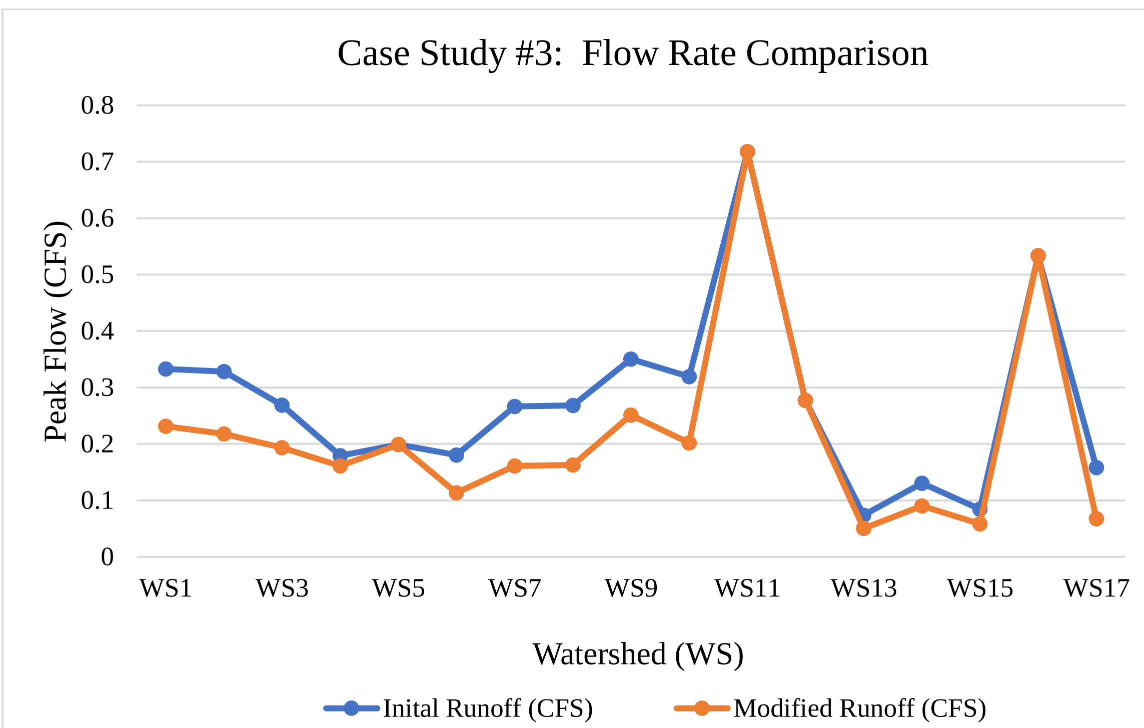

Figure 16: Runoff Flow Rate Comparison at Each Watershed (Case Study #3)

4.5.3 Alternative Design for Conduit Pipes

Observing the flow rate reduction within most watersheds initiated the alternative design of the existing conduit pipes. Flow accumulation at each catchment point was used to determine the combined flow rate for the downstream conduit pipes. Conduit pipes connecting watersheds were identified, and the associated pipe information, such as slope and Manning's roughness coefficient was collected. The flow directions between watersheds are presented in Table 5. The modified pipe sizes are calculated using Equation 8. Table 5 also summarizes the results from the alternative design of conduit pipes in the three case study projects and presents the accumulated runoff flow entering each watershed and the pipe sizes according to the changes in runoff flow.

Table 5: Summary for Alternative Conduit 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
	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
	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
Case Study #2	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

There was a notable decrease in peak flow rate due to the application of LID methods and the average reduction in pipe sizes in the investigated case studies was 2.5 inches (63.5 mm). The cost savings attributed to the reduction in existing pipe dimensions were analyzed with Table 6 presenting the LCC savings for different service years at different discount rates. It was estimated that the life expectancy for HDPE could reach 50 years and that the replacement cost is 20% more than the capital cost considering demolition costs. Maintenance activities for storm drainage conduits are not commonly performed as confirmed by a local project manager with over 30 years of experience in constructing drainage systems. This may be attributed to the fact that storm drainage systems do not typically general direct revenue, thus capital expenditures for underground pipes are spent elsewhere.

Table 6: Life-Cycle-Cost Savings Attributed to the Reduced Pipe Dimensions

Project	Service Years (Years)	LCC savings at different discount rate			Average Saving Rate
		0%	3%	5%	
1	50	$24,317.04	$16,517.73	$14,122.15	9%
	25	$11,053.20	$11,053.20	$11,053.20	
2	50	$33,375.01	$22,670.49	$19,382.58	33%
	25	$15,170.46	$15,170.46	$15,170.46	
3	50	$3,435.96	$2,333.93	$1,995.44	7%
	25	$1,561.80	$1,561.80	$1,561.80	

4.6 Results and Discussion

The primary purpose of this research was to analyze the LCC savings achieved by applying LID methods while meeting drainage requirements. To provide a comprehensive cost comparison, this study adds to previous research that identified the cost savings achieved by applying stormwater storage units and supplementary drywell systems, which percolate the stored runoff to the subsurface and recharge the groundwater. The research objective of the previous study was to consider the volume reduction benefits of extensive GR and PICP, which lead to a certain amount of runoff being retained onsite instead of relying on a traditional storage system. This reduces the required volume of the stormwater storage units thereby requiring fewer drywells. The current study considers not only the benefits of runoff volume reduction but also peak flow reduction, which modifies the required dimensions of the conduit pipes.

Various design scenarios were modelled using case studies and included PICP only, extensive GR only, and a combination of the two. Aside from considering various design scenarios, the study incorporated variables such as two different service years and various discount rates. Figure 17 illustrates the cost comparison results for case study #1 and shows that the cost benefits of LID methods are not always recognizable. The reason for these deficits is the cheaper construction costs incurred when building above-ground retention basins. The cost benefits of LID methods are; however, observed in case studies #2 and #3.

Figure 18 illustrates the LCC analysis results from case study #2. The results indicate that two simulation scenarios, including applying GR only and applying both strategies simultaneously, are optimum in reaching LCC savings. Cheaper construction cost for parking spaces in Case Study #2 result in lower cost savings of applying PICP only. The LCC analysis results for Case Study #3 are shown in Figure 19 and demonstrate the cost efficiency of applying LID methods in each scenario at various discount rates and service years.

The cost benefit findings are divided into two categories based on the drainage types: 1) projects installed with above ground retention basin; and 2) projects equipped with underground retention basin. The cost savings from applying LID methods are higher in the second drainage category, which can be seen in case study #2 and #3. By applying both PICP and GR, the alternative design in category two could deliver an average of 27.2% LCC savings for 50 service years and 18.7% for 25 service years. Meanwhile, using only GR leads to an average of 34% LCC savings for 50 service years and 22.4% for 25 service years. The reason why the saving rate is higher from applying GR only than applying both LID strategies is attributed to the different original construction cost, which is lower from applying GR only and higher from applying both LID strategies.

The average LCC saving rates reveal the cost benefits of using LID compared to traditional drainage system at different project scales, while the specific cost-saving amounts can quantify the importance of LID strategies for a different project. For the detailed cost saving amount in the designated projects, the comprehensive LCC comparison between LID and traditional drainage system demonstrates that applying both LID strategies on case study #2 (15.15 acres) can realize an average saving amount of $1,096,555 for 50 service years and $485,960 for 25 service years. For the case study #3, applying both LID strategies on case study #3 (5.54 acres) can save an average amount of $584,057 for 50 service years and $269,348 for 25 service years.

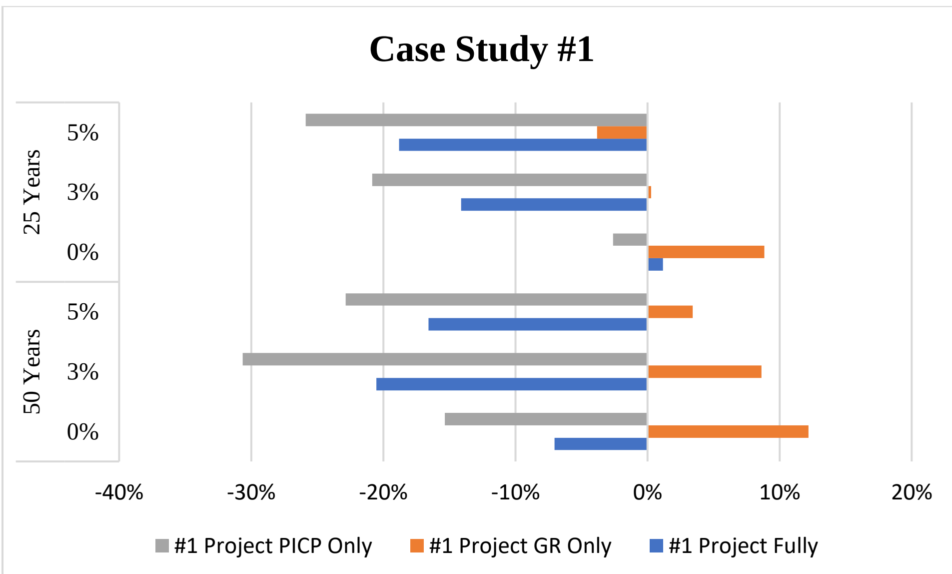

Figure 17: LCC Savings Rate on the Drainage System (Case Study #1)

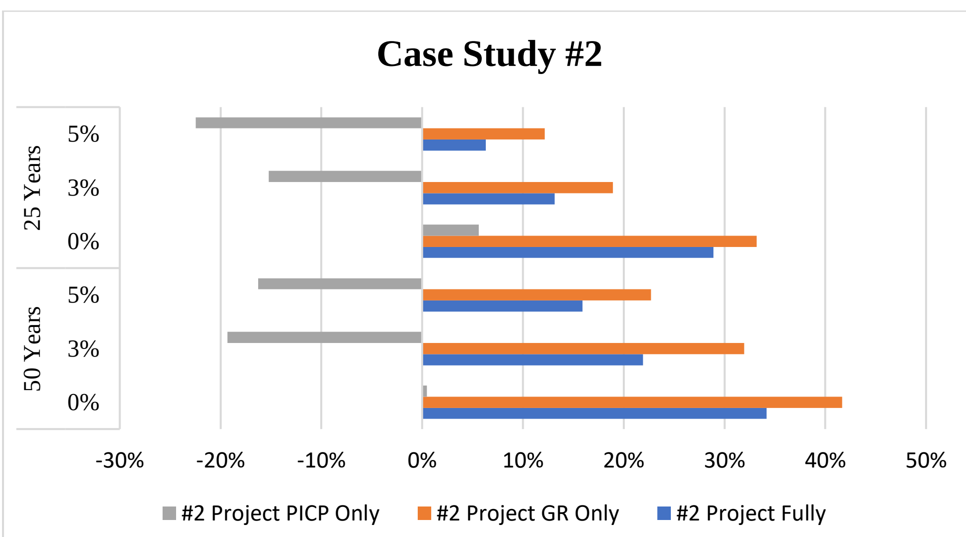

Figure 18: LCC Savings Rate on the Drainage System (Case Study #2)

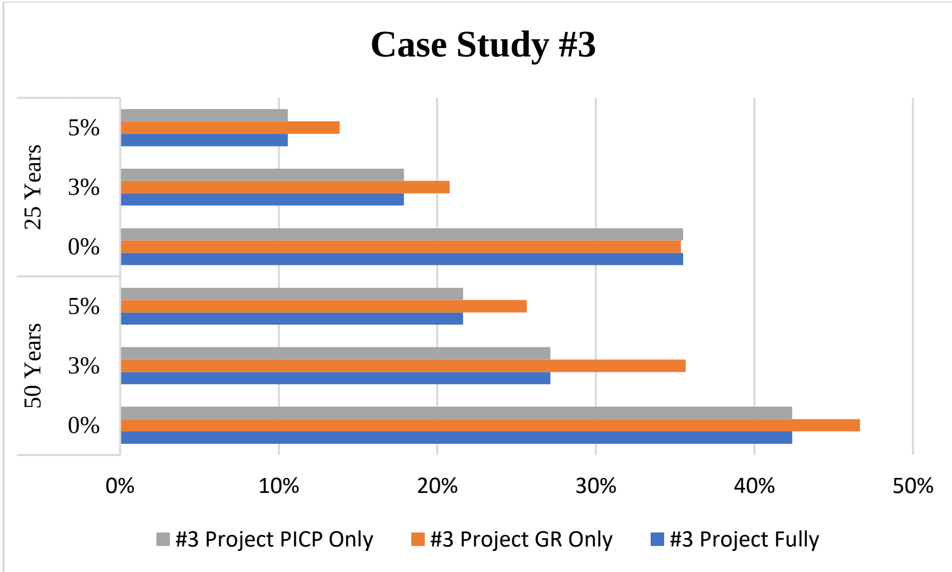

Figure 19: LCC Savings Rate on the Drainage System (Case Study #3)

4.7 Conclusions and Recommendations

This research aimed to insight stakeholders and contractors of the value of LID methods. LID methods are recognized as being effective at mitigating urban runoff volume and flow rate; however, there is a gap in the knowledge regarding the quantification of the cost benefits of applying LID methods in real-world projects. This paper bridges this knowledge gap by quantifying the runoff mitigation performance of extensive GR and PICP under design 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 were added in the analysis of LCC for both LID methods and traditional drainage systems.

The results of the presented research indicate that applying LID methods is beneficial for the designated drainage projects installed with underground retention basins.

By applying both PICP and GR, the alternative design in the designated drainage projects could realize an average of 27.2% LCC savings for 50 service years and 18.7% for 25 service years. Meanwhile, using only GR could realize an average of 34% LCC savings for 50 service years and 22.4% for 25 service years. For the detailed saving amount, it has demonstrated that applying both LID strategies on case study #2 (15.15 acres) can realize an average saving amount of $1,096,555 for 50 service years and $485,960 for 25 service years. For the case study #3, applying both LID strategies on case study #3 (5.54 acres) can save an average amount of $584,057 for 50 service years and $269,348 for 25 service years.

This research contributes to a better understanding of the cost-benefit of LID methods compared to traditional drainage systems based on application to three case study projects. Depending on different projects with various scopes and scales as selected in this research, the research findings could assist readers in understanding how cost beneficial of LID when applying on other similar projects. However, the cost benefits analysis presented in this paper was performed based on a general precipitation event. It is recommended that future research be conducted to analyze the cost benefits of LID under different rainfall events.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Research

The dissertation provides the first comprehensive LCC benefits analysis of LID strategies as alternatives to the traditional drainage system. This began with discussing stormwater impacts in urbanized areas globally by reviewing historical stormwater events and conducting a meta-analysis on the runoff mitigation performance of six LID strategies. Later, three completed construction projects in the Arizona metropolitan area were selected to perform an alternative LID design with a GR and PICP, to determine the cost-effectiveness of using LID to reduce the use of a conventional stormwater storage system. Next, the stormwater conduit system for these three completed construction projects was taken into consideration and to compare the LCC between the traditional drainage system and two LID methods under the designed precipitation events. The following section provides a summary of key findings to the body of knowledge, a discussion of limitations and recommendation toward future research.

5.2 Summary of Findings

A meta-analysis of past and current state-of-practice in stormwater impacts in urbanized cities was presented in this paper to gain a better understanding of this important topic. A review of runoff incidents and impacts on urban area reveals the destructive effects of excessive urban stormwater. A sampling of cities was selected for analysis based on population and the geographical region as part of the meta-analysis. There is no indication that urban growth will slow down anytime soon, thus resulting in more urban impervious areas being built and consequently, more pressure placed on urban drainage systems during significant rain events. Expanding the urban drainage system is not the only way to help alleviate these impacts. Several runoff mitigation strategies described in this paper have proven to reduce runoff volume and relieve hydraulic pressure on urban drainage systems. It is anticipated that city planners or authority organizations will better understand the benefits of such sustainable stormwater runoff control and mitigation methods.

The results of the thesis indicate that applying LID methods is beneficial for the designated projects installed with underground retention basins. By applying both PICP and GR, the alternative design in the designated projects could bring an average of 27.2% LCC savings for 50 service years and 18.7% for 25 service years. Meanwhile, using only GR could bring an average of 34% LCC savings for 50 service years and 22.4% for 25 service years. For the detailed saving amount in the designated projects, the comprehensive LCC comparison between LID and traditional drainage system demonstrates that applying both LID strategies on case study #2 (15.15 acres) can realize an average saving amount of $1,096,555 for 50 service years and $485,960 for 25 service years. For the case study #3, applying both LID strategies on case study #3 (5.54 acres) can save an average amount of $584,057 for 50 service years and $269,348 for 25 service years.

5.3 Limitations and Recommendations

This study contributes to the cost-benefit analysis regarding the use of LID methods compared to traditional drainage systems based on the selected construction projects. The other potential benefits of using LID methods also need to be explored, however. Such as the urban heat island alleviation from applying green infrastructures. Furthermore, the current cost benefits studies were conducted based on the designed precipitation event. Since the hydraulic performance of LID methods is correlated to the level of rainfall events, it is also recommended that future research can be conducted to analyze the cost benefits of LID methods under various rainfall events with different precipitation depth and intensity. Meanwhile, this study focused on one geographical location, Arizona, to decrease the variables when performing the cost analysis. Future research can be made in other locations across the United States based on the methodologies presented in this thesis. Therefore, a cost benefits guidance of LID can be made to help stakeholders and contractors when deciding if the alternative design is an optimum selection.

Another recommendation is to add more LID options in proposing land development and to quantify if LID options can completely replace the traditional drainage system. The options for traditional drainage systems are becoming increasingly difficult to implement in dense urban environments due to the complex underground environments, thus creating a need for low footprint solutions such as LID strategies. An approach to meet this objective is to depend on a hydraulic simulation tool for sustainable development purpose that also incorporates the database of cost benefits of various LID strategies. Addressing this recommendation will enhance the potential to build a sustainable environment for human needs and aspirations.

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