THE POTENTIAL OF GREEN INFRASTRUCTURE (GI) TO REDUCE URBAN RUNOFF IN PHNOM PENH CITY

CHANRACHNA NOU

A Thesis Submitted to the Graduate School of Naresuan University
in Partial Fulfillment of the Requirements
for the Master of Architecture Program in (Architecture - (Type A 1))
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has been approved by the Graduate School as partial fulfillment of the requirements for the Master of Architecture Program in Architecture - (Type A 1) of Naresuan University

Oral Defense Committee

.... Chair
(Associate Professor Sani Limthongsakul, Ph.D.)

.... Advisor
(Assistant Professor Dr. Sasima Charoenkit, Ph.D.)

.... Internal Examiner
(Assistant Professor Sirimas Hengrasmee, Ph.D.)

.... Internal Examiner
(Associate Professor Sarintip Tantanee, Ph.D.)

.... External Examiner
(Associate Professor Sani Limthongsakul, Ph.D.)

Approved

....
(Professor Paisarn Muneesawang, Ph.D.)

for Dean of the Graduate School

Title THE POTENTIAL OF GREEN INFRASTRUCTURE (GI) TO REDUCE URBAN RUNOFF IN PHNOM PENH CITY
Author CHANRACHNA NOU
Advisor Assistant Professor Dr. Sasima Charoenkit, Ph.D.

Academic Paper Thesis M.Arch. in Architecture - (Type A 1), Naresuan University, 2019
Keywords GI, Stormwater runoff, Tropical, Urban, Land-use

ABSTRACT

Land-use changes and the development of urbanization intensify the urban environment including stormwater runoff. An excess runoff overflow impervious surfaces, provokes local air and water pollution, soil erosion, and especially create floods. Despite the gray infrastructure which relies on the big size of drainage pipes, many cities around the globe are adapted to be resilient by integrating green infrastructure (GI) in either pre-development or as a retrofit to deal with these problems. Recently, the development of GI's concept is potentially coping with a highly urbanized area to resolve the disappearance of open spaces and green spaces on source control by using a variety of elements. Phnom Penh, a typical rapid urban development with a huge proportion of impervious urban surfaces, has been vulnerable to urban flood during the rainy season for almost two decades. The purposes of this research were to: 1) to investigate the performance of GI elements for reducing peak runoff rate in the urban area of Phnom Penh which has the tropical climate and 2) to examine the types of GI elements that are prominent for reducing runoff in different land uses. Three typical urban land uses in a center of Phnom Penh were investigated: residential housing, commercial, and mixed residential and commercial land-use. Two scenarios were designed: scenario 1 referred to non-GI and scenario 2 referred to the integration of GI elements. Due to the characteristic of these three typical urban land-uses, four GI elements include trees, bioswales, permeable pavements, and green roofs were implemented. The classification of land-use/land cover and the implementation of GI elements have proceeded on QGIS version 3.4.10 with support of the Google Satellite overlay-image. The Rational Method was used to estimate the peak runoff rate (Q) in both scneanrio2 and their overall outcomes were computed and analyzed in Ms. Excel.

The result demonstrates that the implementation of GI elements in these three urban land-uses is varied due to the different characteristics of land-use and the share of the existing land cover. Accordingly, the application of the various types of GI element and their potential of the runoff reduction is also different. Trees and permeable pavements are the best performance while bioswales show the least effective in these three land-uses. Green roofs have high performance in residential land-use and mixed-land-use, and at medium performance in a commercial land-use. The effectiveness of combined GI elements between the three areas is also obtained. The combined GI elements in mixed land-use had the most effective to reduce runoff, compared to the other two land-uses. In commercial and mixed land-use, the combined GI element is at high performance while it is low in residential land-use. The runoff reduction in entire central Phnom Penh consisted of three typical land-use, which approximately reduced by forth-ten (39.40%) of the total area when a half (49.39%) of GI is applied in the entire central Phnom Penh.

The study reveals that green infrastructure (GI) significantly reduces flood problems by alleviating the peak runoff rates in the typical urban land-use in a tropical city. It is efficiently used in Phnom Penh to cope with urban floods at high performance.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to Her Royal Highness Princess Maha Chakri Sirindhorn for providing me a scholarship to pursue a two-year Master's degree in Architecture, Faculty of Architecture, Naresuan University.

I would also like to dedicate my sincere thankfulness to my thesis advisor, Dr. Sasima Charoenkit for her dedication, valuable guidance, and patient reinforcement during the planning and development of the research. Her enthusiastic encouragement, advice, and motive support, in every circumstance, pushed me to progress and complete my research successfully.

My grateful acknowledgments are also extended to the research committees and the group advisors; Dr. Sirimas Hengrasmee, Dr. Sarintip Tantanee, Dr. Sani Limthongsakul, Dr. Sant Chansomsak Dr. Nattika Navapan, and Dr. Suwanna Rongwiriyaphanich for their assistance and constructive suggestions in carrying out the research. Their willingness to give their time so generously has been very appreciated.

Unforgettably, my very appreciation to various helpful people; Dr. Kampanart Piyathamrongchai, for his worthful contribution on teaching basic QGIS database; Ms. Duangjit Yatathe, for her aid and instruction during my academic year as a foreigner student; the academic and technical staffs in the Faculty of Architecture, for their precise time by providing me the facilities in processing documents; Cambodian and Thai seniors, for their generosity and comfort during my stay in Thailand.

Last and foremost, my special gratefulness to: my parents, for their wholehearted support and perceptive inspiration throughout my life; family and relatives, for their faith and cheer; and my best friends, for their kindness and steady bond in friendship.

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ABBREVIATIONS

A = Drainage area
Bios = Bioswales
BMPs = Best management practices
C = Runoff coefficient of land use/cover
C’ = Runoff coefficient of GI elements
°C = Degree celsius
cfs = Cubic feet per second
CGPs = Concrete grid pavers
cm = Centimeter
CSOs = Combined sewer overflows
CSS = Combined stormwater systems
EEA = European Environmental Agency
e.g. = For example or such as
GI = Green Infrastructure
GR = Green roofs
ha = Hectares
i = Rainfall intensity
IDF = Intensity-duration-frequency
i.e. = Specifically or namely
IFD Rainfall intensity–frequency–duration
in./hr. = Inches per hour
km^2 = Square kilometer
JICA = The Japan International Cooperation Agency
LID = Low Impact Development
LU/LC = Land-use/Land cover
m = Meter
mm = Millimeter

m^3/s = Cubic meter per second

n = Number of distinct land uses

PAs = Pervious asphalt

PP = Phnom Penh capital city, Cambodia

PP = Permeable pavements

PC = Pervious concrete

PICP = Permeable interlocking concrete papers

PRGPs = Plastic reinforcement grid pavers

Q = Peak runoff rate in scenario 1

Q’ = Peak runoff rate in scenario 2

GIS = Geographical information system

QGIS = Quantum Geographic Information system

S.I units = The international system of units

SUDS = Sustainable urban drainage systems

Tr = Trees

UK = United Kingdom

US EPA = United States Environmental Protection Agency

WSUDs = Water-sensitive urban designs

% = Percentage

< = less than in value

> = Greater than in value

= = Equal to in value

x = Multiplied by

- = Minus by

Σ = Summation

° , ' , " = Degrees, minutes, and seconds (DMS)

CHAPTER I

INTRODUCTION

1.1. Research background

The development of urbanization and land-use changes, from natural to a built environment, increases a portion of impervious covers. The construction of impervious covers such as buildings, sidewalks, streets, parking lots, puts pressure on the natural hydrological cycle by reducing rainwater infiltration and evapotranspiration and increases runoff volume, peak discharges and groundwater recharge (Lambin et al., 2001; Locatelli et al., 2017). In the study of the relationship between impervious cover and surface runoff by U.S. Environmental Protection Agency (2003), it is revealed that runoff increased from 10% to 55% by reducing water infiltration from 25% to 10% and evapotranspiration from 40% to 30% between natural ground cover and 70-100% of impervious cover (**Figure 1**) (EPA, 2003). Similarly, Lepeška (2026) found that runoff on 95% - 100% of impervious cover rose 64 times higher than the natural basin (Lepeška, 2016). Consequently, the extension of urban stormwater runoff volumes and flows rates provokes concern and poses negative impacts related to the increase in urban temperature, soil erosions, and flooding events that have impacts on wildlife and human health.

Most cities have relied on stormwater management systems based on conventional systems or gray infrastructure. These closed-systems are designed to quickly convey runoff through pipes from catchments to ponds, rivers, oceans, etc. However, it might not be effective during heavy precipitation events, where the flow can exceed capacity within the pipe network. Unlike the natural drainage system, runoff is infiltrated through several layers of soil, which removes particles or pollutants before discharging runoff to a natural water system. The conventional drainage system prevents this infiltration process to clean runoff, leading to poor water quality. To reduce the drainage burden, the combined sewer overflows (CSOs) have been developed to separately collect wastewater and stormwater. When CSOs occur, untreated or partially treated human and industrial waste, including toxic materials, debris, and stormwater are directly discharged into the receiving waters. Recently, the new alternative urban stormwater management approaches were developed globally. A range of urban stormwater management strategies including green infrastructure (GI) has been proposed and implemented to deal with the above problems (Hunt, W. F. et al., 2010; Yang & Cui, 2012).

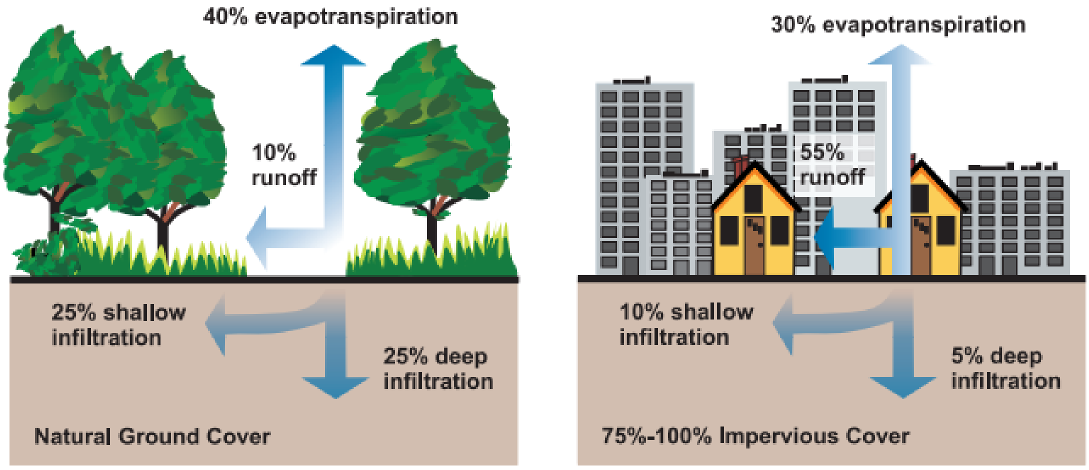


Figure 1 Relationship between the impervious cover and surface runoff in both natural ground cover and 70 - 100% of impervious cover.

Source: U.S. Environmental Protection Agency, Protecting Water Quality from Urban Runoff, page 1.

Green Infrastructure (GI) enhances multifunctionality in spatial planning by providing multiple ecosystem benefits (Agouridis et al., 2011). GI manages stormwater through onsite runoff and mimics the natural hydrological behavior of pre-developed urban environments(Hillary Rudd, 2002; Keeley et al., 2013). It allows drained water to be infiltrated through vegetation and underground layers as shown in Fig. 1. GI provides several environmental benefits, such as urban heat effect mitigation (Norton et al., 2015), air and water quality improvement (Attila Tóth, 2015), energy and climate change adaptation (Jayasooriya et al., 2017), human mental health and well-being enhancement (Coutts & Hahn, 2015). GI is considered as a cost-effective solution compared to gray infrastructure (Yang & Cui, 2012).

Green Infrastructure (GI) links vegetated areas with other physical features/built environments by creating a network of green and blue spaces that are woven into the urban environment (Viola, F. et al., 2017). GI appears in a variety of forms: retention ponds, constructed wetlands, detention ponds, trees, rain gardens, bioswales/vegetated swale, green roofs, permeable pavements, and rainwater harvesting (Mazer, Greg et al., 2001)**.** They were used to decrease the frequency and intensity of flooding events by slightly lowering the duration of peak flow, decrease the volume, and remove water pollutants in the processes of canopy interception, retain and infiltration, and evapotranspiration of runoff (McFarland et al., 2019). A study of potential GI by Martínez et al. (2018) found that GI optimally reduced peak runoff, runoff volume and pollutant by 28%, 60%, and 33 %, respectively (Martínez et al., 2018).

The capacity of GI elements in capturing urban runoff is varied due to different climates. One of the case studies in temperate monsoon climate, Mei et al. (2018) conducted an integrated assessment of various GI options for flood mitigation in an urbanized watershed in China. Their results showed that the implementation of the combination of the four GI elements (green roofs, permeable pavements, bio-retention cells, and vegetated swales) reduced peak flow rate of 80.62% (Mei et al., 2018).

Furthermore, in Houston, Texas, United States, GI elements like permeable pavements, vegetated swales, rain barrels, stormwater planter boxes, rain gardens, and additional trees were implemented on a neighborhood scale to minimize floods. They annually captured 56 billion litter of stormwater (Saraswat et al., 2016). In Colombia, the use of bio-retention cells for expanding green spaces in the sub-catchments, infiltration trenches as the opened drainage for playing fields and recreational areas; porous pavement to reduce stormwater runoff, and vegetative swales can improve the water quality in 46.2 km²-catchment. The combined GI elements can reduce flood volume by up to 60 % (Martínez et al., 2018). In New York City, the mean percentage of runoff capture for ten bioswales during 185 rain events increases from 59 % to 73 % (precipitation less than one inch) (Zhu et al., 2018).

Generally, the implementation of each Green Infrastructure (GI) element has been created by considering its overall effectiveness at three scales: the watershed, city, and site (McFarland et al., 2019). For the city scale, the application of GI elements as a retrofit solution is used to resolve the rapid disappearance of open spaces and green spaces (Copeland, 2016; McMahon, 2002). GI elements should be carefully selected to apply in different land uses. In an urban environment, there are different land uses that have different land covers. For example, residential areas feature a fine grain consisting of a variety of housing types, streets, and parking lots. Commercial areas can be a courser pattern of larger-scale buildings and parking spaces. Differences in building sizes, street characteristics, and open space network should be an influential factor in determining the suitable GI elements for each land use.

1.2. Statement of the problems

A large proportion of the existing studies of GI has been found in a variety of climate regions but the only small number of studies in the tropical climates. It has reported that 51.02% of studies carried out for a temperate climate and less than 10 % of studies were undertaken in tropical climate (Parker & Zingoni de Baro, 2019). With the high intensity of annual rainfall that was observed in tropical countries, flooding and flow quantity control are the main objectives that a stormwater management plan should focus on this climate zone (Rivard et al., 2006). Especially in developing countries, flooding problems are more aggravated than in developed countries since the rapid urbanization process and land-use change, and poor drainage infrastructure has been causing urban flooding in the urbanized areas.

Phnom Penh; a tropical city in Cambodia, annually suffers from stormwater runoff issues due to an increase in population and urban development (Yen et al., 2017). The gross amount of rainfall or storm events makes a larger scale of the flood plain in Phnom Penh. In 2011 and 2013, Phnom Penh experienced extreme flooding caused by a combination of abnormal monsoon rains, successive typhoons, and rising water levels in the Mekong River, posing impacts over 17,000 families in the 2011 floods, and over 3,500 families in the 2013 flood (Baker et al., 2017). Normal Monsoon rains, flood level reaches 1.5 m in some parts of Phnom Penh during the rainy season (Doyle, 2012). Besides, the inefficiency of drainage system management coupled with poor land-use management strategies extremely causes serious environmental problems, including floods on the lowland area in Phnom Penh (Retka, 2018). Moreover, there were few researches have been conducted on urban planning in Phnom Penh. Very few GI studies have been conducted for this capital city. Consequently, it is a crucial opportunity to estimate runoff reduction by the use of GI implementation in Phnom Penh.

In term of GI implementation, the relationship between land-use types and GI elements are necessary to investigate the overall performance of GI. The characteristic of the different land-use types, including the proportion of impervious covers, types, and the size of different land covers, should affect the selection of GI elements. Besides, The analysis showed that residential, transportation units and commercial and industrial units are the top three of the hazardous regions (very high, high medium, and low risk) in the urbanized area of Phnom Penh, approximately 70 % of core city per district (Development, 2019). For these reasons, the selection of GI elements for a suitable replacement in existing impervious cover types in different land-use types; residential, commercial, and mixed residential and commercial land-use is necessary.

1.3. Research scopes

The extent of this study has the following scopes:

- Land-use type: three different urban land-uses in Phnom Penh city are used to investigate the performance of GI. Residential area, commercial area, and mixed land uses of residential and commercial areas are selected for this study because they are the typical land-uses for cities. The results can be useful for other developing cities;
- Software for analysis: Quantum Geographic Information system or QGIS is an open-source software developed from GIS (Geographic Information system). QGIS is used to carry out the dynamic of land-use as it allows for Land use/Land cover (LU/LC) analysis. The software is considered feasible and effective.
- Quantification: Rational Method is a simple method suitable for runoff estimation in the relatively small catchments. It is widely used to estimate the peak surface runoff rate for the design of drainage structures.

1.4. Research questions

There are two research questions as follows:

- To what extent GI is effective in reducing runoff volume in the tropical climate?
- What are the suitable GI elements for runoff reduction in different land-use types of Phnom Penh?

1.5. Research aims

Regarding the reduction of stormwater runoff performed by GI, the major objectives of this research are:

- To investigate the performance of GI elements for reducing peak runoff rate in the urban area of Phnom Penh which has a tropical climate.

- To examine the types of GI elements that are prominent for reducing runoff in different land-uses.

1.6. Research significant

This study is significant because it investigates the potential use of GI for urban runoff reduction in a tropical climate. The findings of this study should contribute to the body of knowledge in the application of GI in a tropical city as follows:

- The performance of GI in reducing runoff in Phnom Penh will be estimated.
- The comparison of GI performance in different climate zones.
- Potential GI elements for different land uses of Phnom Penh should be identified.
- GI application for residential, commercial, and mixed land uses can be formulated and suggested for other cities that have similar characteristics.

1.7. Keywords

Five main keywords need to understand in this study: GI, stormwater runoff, tropical climate, urban, and land use. Their definition and term-use were defined below:

1.7.1. Green infrastructure (GI)

Green infrastructure (GI) has been defined in many ways:

- United States Environmental Protection Agency (US EPA):

"... cost-effective, resilient approach to managing wet weather impacts that provides many community benefits…, green infrastructure reduces and treats stormwater at its source while delivering environmental, social, and economic benefits." (EPA).

- European Environmental Agency (EEA), 2011:

"…The term is used for a network of green features that are interconnected and therefore bring added benefits and are more resilient ..." (European Environment Agency, 2011).

- Benedict, McMahon, Fund, & Bergen, 2012:

"…an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions sustains clean air and water, and provides a wide array of benefits to people and wildlife." (Benedict et al., 2012).

- European Commission, 2013:

"… broadly defined as a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem institutional blocks and protect biodiversity in both rural and urban settings." (2013).

In this study, GI is a term used as the green technology consisting of vegetation and non-vegetation components for runoff reduction to mitigate urban floods. There are many types of GI elements, such as Trees, Bioswale, Permeable pavements, and Green roofs.

1.7.2. Stormwater runoff

Stormwater refers to any precipitation that includes rain, storm, melting snow. In general, there are two patterns of stormwater. In a natural landscape without development, stormwater is absorbed into the ground or falls into bodies of water. In contrast, in an urban landscape, stormwater falls onto impervious surfaces such as roads, sidewalks, rooftops, or parking lots and is not soaked up by the ground. As a result, the flow of water over these surfaces, stormwater runoff carries water pollutants as sewage overflows and drains into local waterways, such as rivers, lakes, and streams, before eventually making its way into the ocean. Therefore, stormwater runoff is defined as the flow of water that occurs when excess stormwater is generated during precipitation and snowmelt.

1.7.3. Tropical

Three types of tropical climate are classified as Tropical Rainforest or Equatorial (Af), Tropical Monsoon (Am) and Tropical Wet and Dry or Savannah (Aw). According to Köppen Climate Classification, the principal regions with a tropical climate are the Amazon Basin in Brazil, the Congo Basin in West Africa, and Indonesia. The three types of tropical are described below:

- Tropical Rainforest or Equatorial (Af):

Rainfall is heavy in all months. The total annual rainfall is often more than 2,500 mm. Humidity is between 77% and 88%. There are seasonal differences in monthly rainfall but temperatures of 27°C (Average temperature: 18 °C). The summers are warm and very humid.

  - Latitude Range: 10° S to 25° N.
  - Global Position: Amazon Basin; Congo Basin of equatorial Africa; East Indies, from Sumatra to New Guinea.

- Tropical Wet and Dry or Savannah (Aw):

A seasonal change occurs between a very wet season and a very dry season. It gets a little cooler during this dry season but will become very hot just before the wet season. The average temperature is 16 °C with annual precipitation of 2.5 mm.

  - Latitude Range: 15° to 25° N and S
  - Global Range: India, Indochina, West Africa, southern Africa, South America and the north coast of Australia

- Tropical Monsoon Climate (Am):

Tropical Monsoon Climate appears in two distinct patterns. The first pattern features wet and dry seasons, with less pronounced dry seasons. Regions with this pattern of Tropical Monsoon Climate typically have significant amounts of rain falling during the wet season, usually in the form of frequent thunderstorms with a less pronounced dry season. The second pattern is similar to the first one, but extraordinarily rainy wet seasons and more pronounced dry seasons. The annual rainfall is greater than 1,000 mm and the dry season is followed by a sustained period of extraordinary rainfall. Areas that experience Tropical Monsoon Climate are affected by monsoon winds that blow in and from the sea during summer and bring with them the seasonal rain. These occur in both hot and cooler areas but are most commonly found in parts of Asia.

1.7.4. Urban

There are lots of different definitions of defining the meaning of ‘Urban’ such as population size, population density, type of economic activity, physical characteristics, level of infrastructure, or a combination of these or other criteria. Here are some of the possibilities:

- Landscape: Urban areas are densely-settled places, built-up settlements with bricks-and-mortar continuity.
- Population and Density: Urban areas are clustered, dense, settlements with populations above a certain size.
- Functional: Urban areas are places characterized by urban ways of living, urban ways of relating to other people, of urban economic activities, of urban forms of identity and social organization. It is called "functional" because we are talking about how things work or function.

In the term use of Phnom Penh, ‘Urban’ refers to a highly dense population characterized by contiguity in built-up development or highly built-up surfaces include building blocks. It is in administrative boundaries with increased international comparability of the economic, social, and environmental performances of metropolitan areas.

1.7.5. Land-use

Land-use is the function of land as it is used for both public and private lands. It is categorized according to economic, cultural activities, and certain purposes, including recreational, transport, agricultural, residential, and commercial land use (Saadeh et al., 2019). Under the typology, land that is not being used by humans for any purpose is often designated as being ‘wild’ or ‘natural’ land. Land that is only lightly used by humans, with little disturbance of the natural processes that take place on it is often designated as ‘semi-natural’.

1.8. Research framework

The research framework of this study is divided into five chapters:

- Chapter 1: Introduction
- Chapter 2: A literature review
- Chapter 3: Research methodology
- Chapter 4: Results

- Chapter 5: Discussion and conclusion (limitation of the study and future study)

A specific description of each chapter is called out to be further described.

1.9. Summary

Any types of land-use, with a great amount of impervious surface, generally make a large volume of runoff. The replacement of impervious surfaces by the GI elements potentially reduces runoff. Due to a small number of GI studies targeting a tropical city, this study aims to investigate the potential of GI application for runoff reduction by using Phnom Penh as a case study. The capital city of Cambodia has experienced urban flood problems and has different land uses which are similar to many cities situated in the tropical climate. The next chapter will provide a theoretical background of GI's performance in runoff reduction.

CHAPTER II

LITERATURE REVIEW

This section is a comprehensive description of key issues. Basic information such as location and geography, climate, rainfall, water level, and history and characteristic of flooding in Phnom Penh are first described. After that, studies and researches that relevant to land use/land cover in Phnom Penh, GI elements are reviewed. Finally, Quantum GIS (QGIS) and Rational Method are introduced as a tool for calculating runoff volume.

2.1. Overview of the study area

2.1.1. Cambodia

Cambodia situates between latitudes 10° and 15°N, and longitudes 102° and 108°E, in the southern portion of the Indochina Peninsula in Southeast Asia. It has a total area of 181,035 square kilometers, including 24 provinces and 27 cities. The country is bordered by Thailand, Laos, and Vietnam (**Figure 2**). It is also located in the Mekong delta, mountains, and Gulf of Thailand coastline. Highlands to the north-east and the east merge into the central highlands and Mekong Delta lowlands of Vietnam. About two-thirds of the country is occupied by a central plain of fewer than 100 m of altitude.

The international river the Mekong traverses the country from north to south-east, where the low-lying plains extend into Vietnam and reach the South China Sea at the Mekong Delta region. Sap River originates from Sap Lake located at the center of the Kingdom and flows to the Mekong (JICA, 2016). It entirely lies within the tropics and dominated by monsoons, tropical wet, and dry. The country's forest cover is about 8.742.401 ha, equivalent to 48.14 % of total area, and the average annual loss rate from 2014 to 2016 is about 0.67 %, equivalent to 121.328 ha compared to the total country's area (Lee et al., 2015). The latest data obtained from the National Institute of Statistics (2019) shows that the current population is approximately 16 million with a density of 86 pers./km² and 1.4 % of the annual growth rate in 2019.

Figure 2 Administrative map of Cambodia.

Source: The Nations Online Project (https://www.nationsonline.org/maps/cambodia-map.jpg)

2.1.2. Phnom Penh

1) Location and geography

Phnom Penh, the capital city of Cambodia, located in the south-central region of the country and surrounded by Kandal Province. It sits on the banks of the intersection of four rivers; Sap river, Upper and Lower Mekong rivers, and Bassac rivers. Tonle Sap River flows from Sap Lake to the Mekong at Phnom Penh, where Mekong river splits to Bassac River. A vast range of watershed of these four rivers is annually flooded in the rainy season, and the Sap River flows backward into Sap Lake (JICA, 2016). With a total area of 678.46 km², it divided into 12 districts (**Appendix 1**); a core city covers eight districts within four urban districts as shown in **Figure 3**. These four urban districts are the most urbanized area and situated in central Phnom Penh. The city's population is about 2 million with an annual growth rate of 3.2% in 2019 (reference). This city is known as the city with urban development that is closely related to the water system.

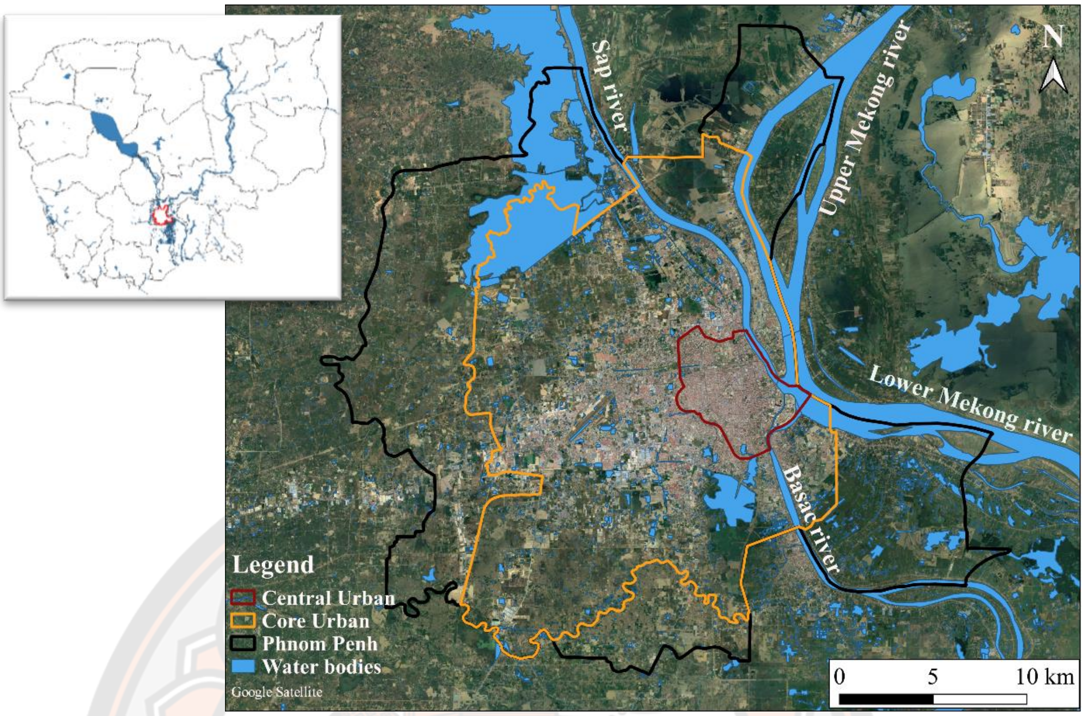


Figure 3 Map of central urban, core urban of Phnom Penh.

Source: Adapted from Open Development of Cambodia (ODC).

Phnom Penh is also defined as a non-forest cover where its topography is relatively flat in the administrative area and locates on the alluvial plain of Mekong downstream (Lee et al., 2015). It is vulnerable to flood since it located on the lowland, and it built on the high river embankments then continually expanded to the lower part from the river embankment, which is lower than the flooded elevation. The surveys showed that 30% of the capital area is lower than eight meters, 45% lower than nine meters, and 60% lower than 10 meters river elevation (Lee et al., 2015). The center of the capital is surrounded by the natural levee and ring dike, and its suburbs form low wetlands and some places are flooded in the rainy season.

2) Climate

Phnom Penh is entirely governed by monsoons and characterized by two major seasons: wet (May – October) and dry (November – April). The south-west monsoon brings heavy rains and high humidity from mid-May to early October, while the north-west monsoon lasts from early November to March, bringing drier and cooler air (The World Bank Group 2011). The annual average temperature is 28 0C, with an average maximum temperature of 38 ^{0}C in April and an average minimum temperature of 17 0C in January (Mei et al., 2018). The annual average of humidity is 77%, ranging from 70% to 80% (JICA, 2016).

3) Rainfall

The average annual rainfall recorded between 2000 and 2010 was 1,500 mm; the minimum annual rainfall was 1,171 mm (in 2006) and the maximum was

2,147mm (in 2000). There is 80% or more of the annual precipitation is concentrated in the rainy season (JICA, 2016).

Rainfall intensity was estimated using short-time duration rainfall data observed from 1980 to 1997 at Pochentong Station in the JICA study, “The Study on Drainage Improvement and Flood Control in the Municipality of Phnom Penh, 1999”. The last estimation was in 1997, thus the review of rainfall intensity and model hyetograph using data rainfall data is conducted by JICA in 2013.

Observed rainfall data was collected from the Ministry of Water Resources and Meteorology (MOWRAM). The rainfall gauging station (**Figure 3**) used to be the Pochentong Station which did observation from 1981 but was moved to Khmuouh where hourly rainfall data was observed by automatic record system from June 2012. However, hourly rainfall data is not enough in the observation period. Hence, a probable rainfall analysis was developed by ‘The Study on Drainage and Sewerage Improvement Project in Phnom Penh Metropolitan Area’ (2016), JICA.

Table 1 shows the probable rainfall derived from the daily rainfall data in 1981-1997 and 1981 -2013. This probability of daily rainfall analysis revealed that there was no large difference. The available hourly rainfall data in Phnom Penh is limited and as fewer data found in web sites (as shown in **Footnote 1** and **Footnote 2**) and they are mostly in daily, monthly, annually recorded.

Table 1 Probable rainfall of daily rainfall and hourly rainfall between two periods: 1981 to 1997 and 1981 to 2013.

Year	**Daily rainfall (mm/day)**		**Hourly rainfall (mm/h)**
	1981 to 1997	1981 to 2013	1981 to 1997
2	87.8	90.1	44.8
5	112.3	109.6	63.2
10	128.4	125.4	75.4
30	152.9	154.5	-
50	164.0	170.3	-

Source: JICA (2016)

4) Water level

Figure 4 shows a meteorological and hydrology observed in gauging stations in Phnom Penh. Pochentong Station is used for meteorology to survey temperature, humidity, rainfall, evaporation, sunshine, and wind, according to the observed data from 1985 to 2013. But this station was moved to Khmuoch from 2012. Gauges in Phnom Penh port, Chrauy Changva, and Chaktomuk were used to measure only water level (JICA, 2016).

Figure 4 Location of Meteorological and Hydrological Observation Sites

Source: The Study on Drainage and Sewerage Improvement Project in Phnom Penh Metropolitan Area (2016), JICA.

The highest water level of Bassac River and Sap River is generally recorded from August to October. The highest water level of the Bassac River is 9.84 m (2011) and the lowest level is 7.47 m (2010). On the other hand, the water level during March to May is very low (1.2 m). The difference in water level between the dry season and the rainy season is about 6 to 8 m. According to the interview with the Ministry of Water Resources and Meteorology (MOWRAM), river discharge of the Upper Mekong River is 32,000 m^3/s and maximum river discharges to Sap River and Bassac River are about 8,000 m^3/s and 1,500 m^3/s respectively. Peak discharge of Mekong River is recorded in June to October and the backflow from Mekong River to Sap River occurs in this season. Peak river discharge of over 16,000 m^3/s is estimated from August to November (JICA, 2016).

5) Flooding history and characteristic

Urbanized area in Phnom Penh is protected from flooding arising from an overflow of Mekong and Sap river by Kop Srov Dike in the northern part; Tumpun Dike at the southern part and natural levees along the Mekong/Sap river (Figure 5). These dikes were expected to cope with the risk of flooding overflow from the Mekong and Sap river (JICA, 2016).

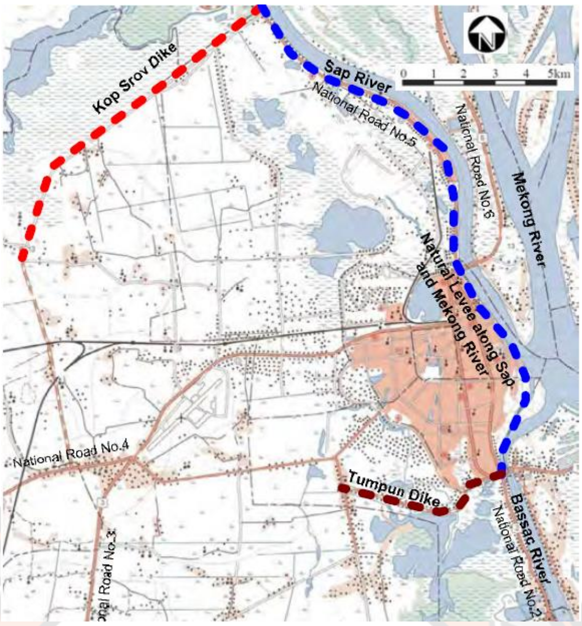


Figure 5 Dikes protecting from flooding to Phnom Penh

Source: The Study on Drainage and Sewerage Improvement Project in Phnom Penh Metropolitan Area (2016), JICA.

Meanwhile, many big natural lakes surrounding downtown have been filled utilized for construction purposes due to urbanization. Over the last decade, six lakes in Phnom Penh have been filled for land development after being leased to development companies by the Cambodian government. As rainfall is a critical issue in the rainy season, the replacement of water storages functioned as natural reservoirs, retention pond and buffer zones for water flow lead to the acceleration of flooding extents (Doyle, 2012).

The Japan International Cooperation Agency (JICA) has worked on drainage system by enlarging the existing drainage pipes or/and installing more drainage pipes to reduce flood in some areas of the city. But it cannot eliminate all of Phnom Penh's drainage problems or to prevent future floods in areas developed without flood protection (Doyle, 2012). Drainage improvement in the area on the northern side of Wat Phnom and most parts of Tuol Kok District have lagged behind other areas. Inundation in these areas still occurs several times a year in the rainy season (JICA, 2016). A social interview conducted by JICA to survey 100 households in 12 districts. The result showed that fifty-eight households have an experience of inundation around their house. The depth and duration of inundation reach mostly up to shin and knee and duration lasts for 2-3 hours (JICA, 2016).

The gross amount of rainfall or storm events makes a larger scale of the flood plain in Phnom Penh. Flood characteristics in this city caused by two patterns; Monsoon rains, flood level reaches 1.5 m in some parts during the rainy season; and Mekong river floods, with the depth more than 10 m between dry and rainy seasons and last for weeks (Doyle, 2012). In 2011 and 2013, Phnom Penh experienced extreme flooding caused by a combination of abnormal monsoon rains, successive typhoons, and rising water levels in the Mekong River, impacting over 17,000 families in the 2011 floods, and over 3,500 families in the 2013 flood (Baker et al., 2017).

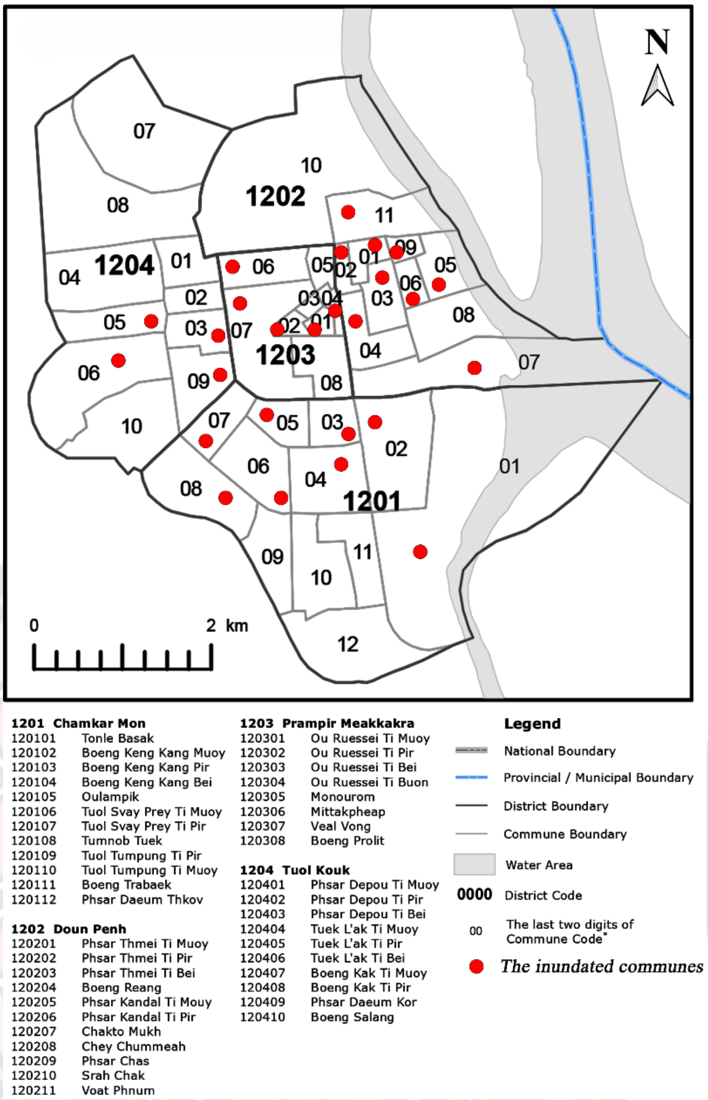
2.1.3. Urban flooding

There are four urban districts located in the center of Phnom Penh: Chamkar Morn, Doun Penh, Prampir Meakara, and Tuol Kork. A few studies had been conducted in central Phnom Penh as it is annually flooded during the rainy season. Based on the map of Urban Voice, it notifies the serious flooding road during the rainy season in 2013 in these districts (**Appendix 1**). Some locations were flooded for several days while other areas have flooded for over one week. Wen et al., (2016) resemble observed inundation areas in Chamkar Morn, Doun Penh, Prampir Meakara. The inundation in the north of the Royal Palace was reproduced as the most seriously damaged areas. These areas are located in the north of Royal Palace (the most serious area), on Oknha Tep Phan, south Preah Yrasak Paem, the market around road 163, and road 358 (Wen et al., 2016).

Caldentey et al. (2016) estimated surface runoff and discharge in Chamkar Morn district, partly cover three communes: Tuol Svay Prey ti Muoy, Tuol Svay Prey ti Pir, and Tumnob Teuk. By using an extreme rainfall event in September 2014 with an intensity of 109.8 mm. Their result showed that maximum surcharge ranges from 0.15-7.08 m^3/s and lasts almost 3 hours with the depth from 0.2 m to 0.5m (Caldentey et al., 2016). Similarly, Heng et al. (2017) conducted a questionnaire survey in four districts: Chamkar morn, Doun Penh, Prampir Meakara, and Tuol Kork. Particularly, Chamkar Morn district was used as a sample to analyses the characteristic of flooding conditions. Their results showed that the duration of flood/overflow of 1.5–3.0 h and the maximum overflow surcharge of 3.18–7.08 m^3/s (Heng et al., 2017). Besides, Sothea et al. (2012) determined peak runoff in these four districts, divided into 52 sub-catchments, by using three storm events: July 2008 (392 mm), August 2008 (76.6 mm), and September 2008 (27 mm). Their results point out that the greatest peak runoff for all sub-catchments occurred reaching 183.3 m^3/s, 16.6 m^3/s, and 1.8 m^3/s for the simulation of the large, medium, and small storm events, respectively (Sothea et al., 2012).

Yim et al. (2016) investigated runoff from rainfall events for May 2014 and 3 design storms of rainfall; 2-years, 5-years, and 10-years return periods. Their result illustrated that runoff was greatest in sub-catchment Wat Phnom (9 -16.5 m^3/s) and Phsar Thmei ti Pir (6 - 11.5 m^3/s) (Yim et al., 2016).

Figure 6 comprises the inundated communes in central Phnom Penh that combined from previous studies (Caldentey et al., 2016; Heng et al., 2017; Sothea et al., 2012; Wen et al., 2016; Yim et al., 2016).



Code	Name
1201	**Chamkar Mon**
120101	Tonle Basak
120102	Boeng Keng Kang Muoy
120103	Boeng Keng Kang Pir
120104	Boeng Keng Kang Bei
120105	Oulampik
120106	Tuol Svay Prey Ti Muoy
120107	Tuol Svay Prey Ti Pir
120108	Tumnob Tuek
120109	Tuol Tumpung Ti Pir
120110	Tuol Tumpung Ti Muoy
120111	Boeng Trabaek
120112	Phsar Daeum Thkov
1202	**Doun Penh**
120201	Phsar Thmei Ti Muoy
120202	Phsar Thmei Ti Pir
120203	Phsar Thmei Ti Bei
120204	Boeng Reang
120205	Phsar Kandal Ti Mouy
120206	Phsar Kandal Ti Pir
120207	Chakto Mukh
120208	Chey Chummeah
120209	Phsar Chas
120210	Srah Chak
120211	Voat Phnum
1203	**Prampir Meakkakra**
120301	Ou Ruessei Ti Muoy
120302	Ou Ruessei Ti Pir
120303	Ou Ruessei Ti Bei
120304	Ou Ruessei Ti Buon
120305	Monourom
120306	Mittakpheap
120307	Veal Vong
120308	Boeng Prolit
1204	**Tuol Kouk**
120401	Phsar Depou Ti Muoy
120402	Phsar Depou Ti Pir
120403	Phsar Depou Ti Bei
120404	Tuek L'ak Ti Muoy
120405	Tuek L'ak Ti Pir
120406	Tuek L'ak Ti Bei
120407	Boeng Kak Ti Muoy
120408	Boeng Kak Ti Pir
120409	Phsar Daeum Kor
120410	Boeng Salang

Figure 6 Map of inundated communes in central Phnom Penh.

Source: Adapted from JICA, Wen et al. (2016), Caldentey et al. (2016), Heng et al. (2017), and Sothea et al. (2012).

2.1.4. Land-use

Generally, a lack of sufficient data is inevitable for the developing countries. Likewise, in Penh Penh, land use data or most of the urban relative development data is not accessible by the public. It is, therefore, necessary to develop the land use map for the study.

1) The master plan of Phnom Penh

Urbanization is the underlying reason for Land-use change, leading to an increase of impervious surface and increasing surface runoff. Land-use map and summary of Land-use types in 2004 and 2035 were reported in “White Book on Development and Planning of Phnom Penh” in 2007 (**Appendix 1**).

Table 2 shows the summary of the land-use types and the surface ratio of Phnom Penh in 2004.

Table 2 Summary of Phnom Penh's Land-use types and surface ratio in 2004.

Land-use types	**Percentage (%)**
Natural	21.86
Agriculture	50.78
Administration	0.21
Education	0.99
Equipment	2.34
Industrial	1.34
Service	0.15
Transport	0.74
Highway	6.03
Open Urban	2.26
Urban	13.31

2) Land-use classification from other studies

Several studies have been focused on LU/LC in Phnom Penh with different times of observation. A study by Lim & Sasaki (2016) used a topographic map in 2002 and Google earth with time slider moving to 2005 to define land-use in Phnom Penh (LIM & SASAKI, 2016). They classify it into five types:

- Urban or built-up: residential, commercial or service, industrial, transportation, communication, utilities and other urban lands such as garden, waste dumps, etc.;
- Agricultural land: Cropland, pasture, orchards and other agricultural lands, etc.;
- Forest land: deciduous, evergreen forest land and mixed forest land
- Water: stream, canal, lake, reservoir, bay, and estuary
- Wetland: forest wetland and non-forest wetland

Their results showed that Phnom Penh has been increasingly urbanized. Its urban development needs more attention to reduce the negative impacts related to urban flooding and for better future land use planning. (LIM & SASAKI, 2016).

The urban-growth related to land-use around Phnom Penh between 1973 and 2015 were reviewed by Mialhe et al. (2019). The city's growth over the last 42 years was multiplied by eight (3,000 ha to 25,400 ha) and a surge in natural wetland reclamation occurred between 2006 and 2015 with an annual urban growth rate of 5.1%. Finally, the annual increasing rate of land use in Phnom Penh fluctuated between 5% and 10% between 1973 and 2015. The statistics of urban sprawl in Phnom Penh are therefore comparable to those of other large cities in Southeast Asia that have undergone rapid and recent changes. The final classification scheme shows ten land covers classes: agriculture, bare soil, built-up areas, development areas (e.g. ongoing building sites), seasonally flooded areas, mixed vegetation, water, permanent wetlands, and undefine (Mialhe et al., 2019).

Earth Observation for Sustainable Development (EO4SD) (as defined in **Footnote 3**) released a report for urban projects integrated the application of satellite data for urban development of developing countries. The report contains information about EO4SD-Urban service operations provides the full geospatial dataset of Phnom Penh in July 2016 i (Development, 2019). In the report, LU/LC distribution and its structure in the years of 2002/2003 and 2017 are provided for core urban and peri-urban areas of interest, as well as distribution and typology of the road network and flood hazard. **Figure 7** shows the Geographic position of Phnom Penh urban (core city, as defined in **Footnote 4**) and peri-urban (the whole is 886 km²) district in 2017.

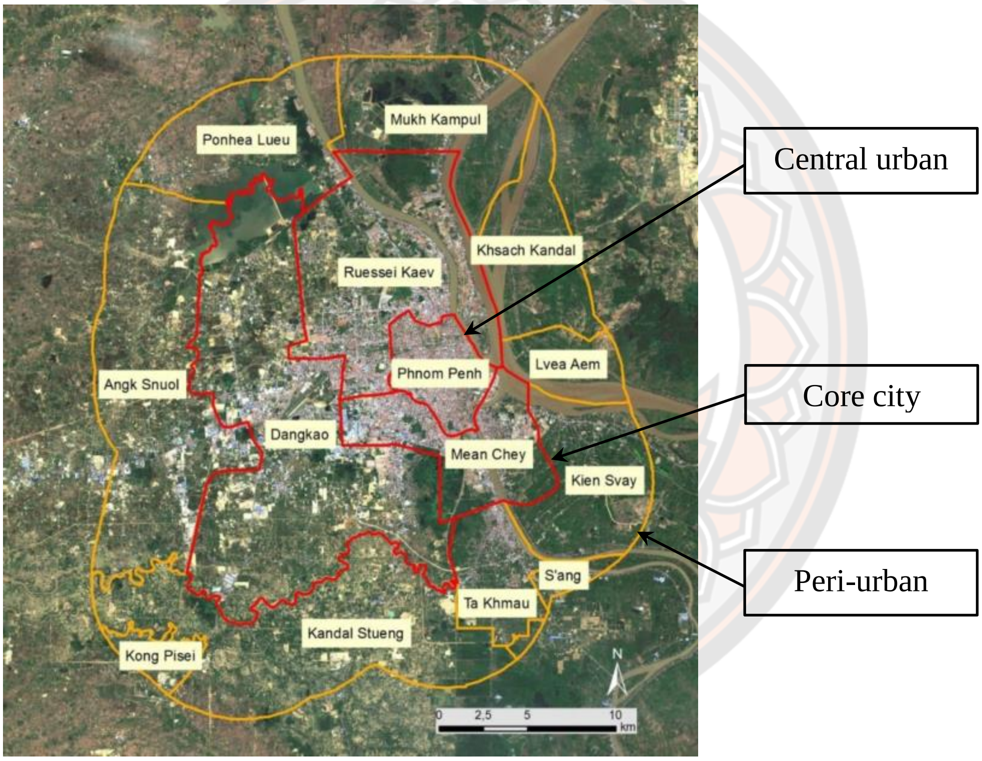


Figure 7 Geographic position of Phnom Penh central urban and core city (red) and peri-urban (orange) district in 2017.

Source: ESA EO4SD-Urban report (Development, 2019)

Land-use/Land cover (LU/LC) classification by using the very high resolution (VHR) data. **Figure 8** shows the maps of land-use in urban (left) and central urban (right) in 2017. These maps derived from the ESA EO4SD-Urban report (2019) which gives data of LU/LC types and surface coverage of urban Phnom Penh (**Table 3**). Many types of LU/LC were classified, but mixed land-use was absent in this report.

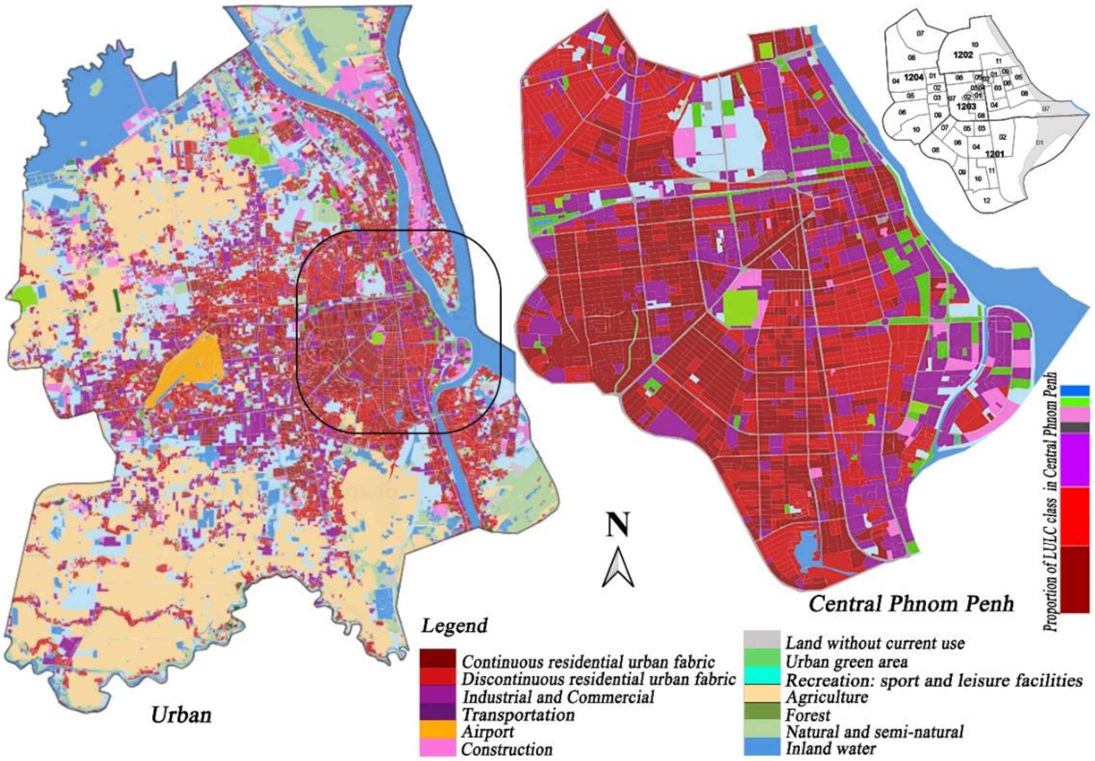


Figure 8 Map of land use level III and IV of central urban and urban in Phnom Penh (2017).

Source: Adapted from ESA EO4SD-Urban report (2019) and JICA.

Table 3 Land-use types and surface coverage of Urban Phnom Penh in 2017.

Land-use	**ID**	**Surface**	**Percentage**
Unit		(Km²)	(%)
Residential urban fabric: Continuous residential urban fabric Discontinuous residential urban fabric	1100	80.2	21.4
Industrial and Commercial	1210	31.11	11.54
Transportation	1220	4.59	0.28
Airport	1240	3.32	0.889
Construction	1330	13.88	3.72
Land without current use	1340	49.62	13.29
Urban greenery and recreation: sport and leisure facilities	1400	4.7	1.251
Agriculture	2000	91.66	24.56
Forest	3100	0.96	0.256

Table 3 (Cont.)

Land-use	**ID**	**Surface**	**Percentage**
Unit		(Km²)	(%)
Natural and semi-natural	3200	26.55	7.09
Bare land	3300	1.06	0.285
Water	5100	53.6	14.34
Total		**373**	**100**

Table 4 shows the land-use types in the central urban area of Phnom Penh. The proportion of LU/LC in the central urban area mostly covered by three land covers including continuous residential urban fabric, discontinuous residential urban fabric, and industrial and commercial. By using commune code from JICA and these three main covers, it is finally can be classified by using color codes the ESA EO4SD-Urban report (2019). The details for classifying were explained below:

- Residential land-use (Res): residential urban fabric includes continuous residential urban fabric and discontinuous residential urban fabric displayed by red and dark red colors respectively.
- Commercial land-use (Com): industrial and commercial (purple) and transportation (dark purple) that consist of a proportion of more than 1/2 of the total area in each commune;
- Mixed residential and commercial land-use (Mix): a mixture of two land-use types that classified above. The proportion of each land-use type is half and half.

Table 4 Land-use types in central urban, Phnom Penh 2016.

1201: Chamkar Morn district			**1202: Doun Penh district**		
Code	Area (km²)	Type	Code	Area (km²)	Type
01	4.65	Com	01	0.165	Mix
02	0.997	Res	02	0.107	Res
03	0.292	Res	03	0.314	Mix
04	0.658	Res	04	0.416	Res
05	0.303	Res	05	0.409	Mix
06	0.589	Res	06	0.147	Res
07	0.350	Res	07	1.50	Mix
08	0.786	Mix	08	0.729	Com
09	0.470	Res	09	0.101	Res

Table 4 (Cont.)

1201: Chamkar Morn district			**1202: Doun Penh district**		
Code	Area (km^2)	Type	Code	Area (km^2)	Type
10	0.626	Res	10	3.15	Com
11	0.459	Res	11	0.644	Com
12	0.971	Res			
1203: Prampir Meakara			**1204: Tuol Kork**		
Code	Area (km^2)	Type	Code	Area (km^2)	Type
01	0.0851	Mix	01	0.324	Mix
02	0.0872	Res	02	0.205	Res
03	0.0488	Res	03	0.306	Res
04	0.0828	Res	04	0.908	Mix
05	0.139	Mix	05	0.425	Res
06	0.387	Mix	06	1.17	Res
07	0.969	Com	07	1.59	Mix
08	0.401	Res	08	1.68	Res
			09	0.468	Res
			10	0.887	Res

Note: The total area of each commune is derived from ‘citypopulation (2008)’

As a result, the surface coverage and percentage of the three land-use are obtained. Residential, commercial, and mixed residential and commercial have the coverage area of 12.2468 km^2 (1224.68 ha, 42.24%), 10.142 km^2 (1014.2 ha, 18.94%), and 6.6071 km^2 (660.71 ha, 38.82%), respectively.

2.2. Green infrastructure elements

Green infrastructure (GI) elements appear in a variety of forms: retention ponds, constructed wetlands, detention ponds, trees, rain gardens, bioswales/vegetated swale, green roofs, permeable pavements, and rainwater harvesting. Otherwise, the most common GI elements applied in several cities are trees, bioswales, permeable pavements, and green roofs. To understand more about these elements, their component, types, and performance for stormwater reduction are described.

2.2.1. Trees

1) Components

Trees (Tr) is the most common GI in the urban landscape. Trees composed of leaves and branches, trunk, and tree pits soil/mulch surface (if tree pits are presented) (Elliott et al., 2018; Grey, Livesley, et al., 2018).

2) Types

The amount of runoff reduction significantly depends on trees species interacting with different climates (Huang et al., 2017). Monsoonal dry forest species are more tolerant to harsh conditions of cities with equatorial wet climates. Deciduous tree species are more common than evergreen species. They are mostly native to Southeast Asia, Africa, and South America. They, therefore, have a high transpiration rate to maximize photosynthesis during the wet season (Kjelgren et al., 2008). Particularly, forests in Cambodia consist of evergreen, semi-evergreen, deciduous, swamp, mangrove (Baker et al., 2017). In tropical rainfall seasonality driven systems, tree species exhibit different strategies depending on their ability to access/store soil water (Singh & Kushwaha, 2016). Coniferous trees intercept 30% of rainfall more than Deciduous trees because of tree properties (leaf, bark, and branch) in a continental climate (Zabret & Šraj, 2015). In a semi-humid continental monsoon climate, conifers intercept from 26.7 – 62.6 % of rainfall which is higher than deciduous trees; an interception rate of 25.2 – 50 % (Liu, Xiaowen & Chang, 2019). In the coastal Mediterranean climate, mature evergreen trees intercept rainfall up to 66.5 % (Xiao & McPherson, 2002) and from 49.1 – 60.9 % of evergreen coniferous trees (Asadian & Weiler, 2009).

3) Performance for stormwater reduction

Trees play a substantial role in reducing stormwater runoff, rainwater intensity and delaying through three processes: rainfall interception (canopy, stemflow, and throughfall) (Huang et al., 2017), infiltration, and evapotranspiration (Asadian & Weiler, 2009; Berland et al., 2017; CWP, 2018) as shown in **Figure 9**.

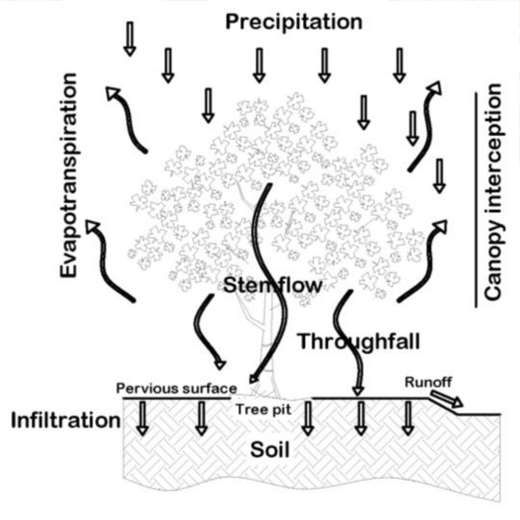


Figure 9 Typical water cycling of trees.

Source: Adapted from (Ekhuemelo, 2016; Wilmoth et al., 2019)

a) Rainfall interception (canopy, stemflow, and throughfall)

Rainwater losses through canopy interception when rainwater is directly captured by tree canopies (leaves and branches) without reaching the ground. This means that tree canopy can delays water reaching the ground by temporarily storing water on tree leaves and stems. Interception loss (canopy) is calculated by gross precipitation subtract a sum of stemflow (water that runs down at a tree’s stem or bole to the ground surface) and throughfall (water that passes through a tree’s canopy or drips off tree surfaces onto the ground) (Berland et al., 2017; Klaassen et al., 1998). In other words, canopy interception loss determined by a sum of water stored in tree canopies and evaporated from tree surfaces (Klaassen et al., 1998). For deciduous species, mean storage depths were four times greater for the leaves (0.97mm) than the stems (0.25mm) (McPherson et al., 2017) because of the leaflets and the stems. Huang et al. (2017) found a very small amount of total of stemflow experimented to white oak and Norway with 0.04% and 0.01% of total precipitation, respectively (Huang et al., 2017). Sometimes, rainwater loss through stem flow is assumed to be negligible because of its minor component of the water balance for mature canopies like conifers (Asadian & Weiler, 2009). The observed reduction in throughfall intensity by tree canopies serves in two purposes; delays water reaching the ground by temporary storage of the water on the tree; protects the mineral soil surface from the energy of raindrops reaching the ground at maximum velocity. High throughfall intensities occur consequently when the drip becomes bigger on dampen crown.

b) Infiltration (tree pits and soil)

The reduction of surface water runoff is not solely due to direct interception but also to the presence of the infiltration which much of the rainfall drains (Armson et al., 2013). Infiltration is the amount of stormwater that permeates into the soil surface through tree pits. Tree pits can be used to restore natural flow control, even in low infiltration soils and dense urban environments (Grey, J Livesley, et al., 2018). An individual street tree pit on the sidewalk can reduce the infiltrating rate of up to 66% (Elliott et al., 2018). The investigations in urban areas conducted at five sites in Manchester, UK, from January to September 2011, found that trees and tree pits could reduce runoff from asphalt with the maximum of 62- 66% (Armson et al., 2013; Elliott et al., 2018).

c) Evapotranspiration

Evapotranspiration can help to reduce runoff through roots, small pores on the underside of leaves, and vapor to the atmosphere. It depends on leaf area and mature size, stomatal conductance, and the health and condition of the trees (Scharenbroch et al., 2016). To manage soil moisture during the days or weeks between storm events, create additional capacity in the soil during storm events (Berland et al., 2017). Some amount of the intercepted water evaporates into the atmosphere and some infiltrates into the ground, decreasing peak flows and the total amount of urban runoff. Evapotranspiration is also one of the key losses in the urban hydrologic cycle and it fluctuates from different climate zones where trees are rooted in; the rate is higher in summer (Huang et al., 2017). The tree canopy layer can evaporate approximately 6.5–27% of the total rainfall of the tree canopy (Kirnbauer et al., 2013). **Table 5** summarizes the runoff reduction of trees from other studies.

Table 5 Trees perform in stormwater runoff reduction.

Tree types	Compositions	Rainfall (mm)	Canopy interception	Infiltration	Evapotrans-piration	Location	References
D. Liquidambar styraciflua (434)		3119 (7 years)	17-27% 3-3.1 m³/tree			on 1.6 Acre parcel urban tree, Hamilton, Ontario, Canada, 7 years of study (2002-2008)/ mean temperature	(Elliott et al., 2018)
D. Platanus x acerifolia (92)			6.5-11.1% 8.1-8.5 m³/tree				
D. Acer saccharinum (120)			6.5-11.1% 4.8-5m³/tree				
Evergreen or deciduous	-Sandy clay between 100 and 300 mm -Clay = 100 mm max depth -Trench: surface area=6m², with the edge=1.5m, depth = 600mm	789.8 mm		5.2 %- 43.7% (mean 18.3 ± 2.1) trench		4 residential suburban streets in Melbourne, Australia	(Kirnbauer et al., 2013)
Deciduous and evergreen trees, (126)	DBH = 1.4 m	480 - 2000 (monthly)			46-72 %	Parking lots, Chicago	(Scharenbroch et al., 2016)

Table 5 (Cont.)

Tree types	Compositions	Rainfall (mm)	Canopy interception	Infiltration	Evapotrans-piration	Location	References
Evergreen-deciduous (lagerstroemia)	DBH = 6.0±1.9			25.0±5.8 mm/min		Bangkok, Thailand/ Tropical monsoon dry season	(Kjelgren et al., 2008)
Asia wet evergreen (Pterocarpus)	DBH = 6.9±1.9			12.3±1.5 mm/min			
American dry-wet evergreen (Swietenia)	DBH = 8.1±2.0			20.0±5.5 mm/min			

Note: DBH is Diameter at breast height
The number in parentheses in the column of ‘tree-type’ is the total number of trees

2.2.2. Bioswales/vegetated swales

Bioswales (Bios) or vegetated swales are vegetated channels designed with underlying engineered structures to capture and treat stormwater runoff. They are most commonly used in residential roadways, in and around parking lots (Shafique & Kim, 2017), close to the buildings (collect runoff from downspouts) (Thiagarajan et al., 2018)

1) Component

The components of Bioswale include vegetation, substrate, and soil (**Figure 10**) (Mazer, Greg et al., 2001). The diversity of vegetation can deduct the amount of water through evapotranspiration and infiltration. Shrub species are the best option to plant on the slope of a swale or on a raised platform, where their roots can easily reach moisture in the soil. Either engineered soil or sandy loam is usually used for better flow in the system with a lateral slope to improve the functionality in terms of harvesting stormwater from adjacent areas and to convey it through the filter media and the underdrain system (MacAdam, 2012; Martínez et al., 2018). NRC suggests constructing Bioswale in locations with a mild slope (no greater than 5%) due to the risk of erosion. However, engineered soil mixture should consist of the maximum 5% of clay content to hourly pass 12–26 cm of rainwater. Also, the side slopes should be 4:1 (with a maximum slope of 3:1) to provide the most effective result (NACTO, 2013).

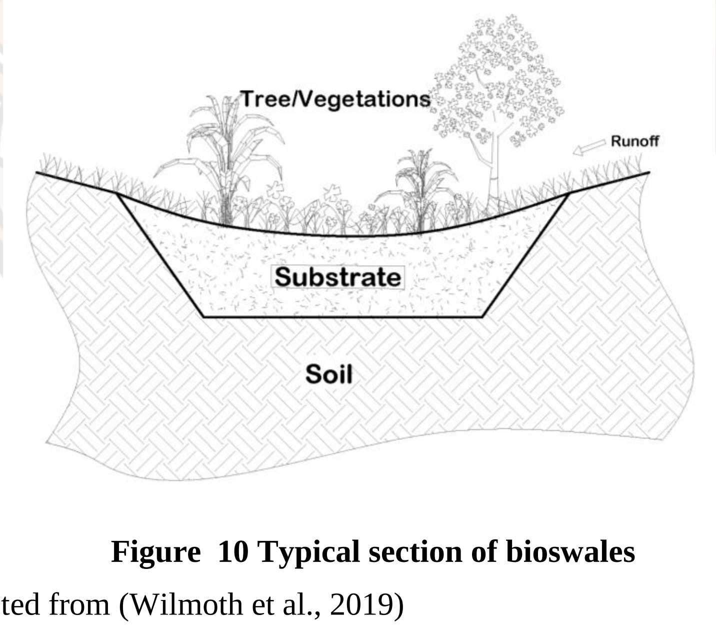


Figure 10 Typical section of bioswales

Source: Adapted from (Wilmoth et al., 2019)

2) Type

Bioswales are divided into two types; wet and dry bioswale. Both swales are used to capture water quantity and quality. It can be seen alone or nearby parking lots, roads, and roofs where runoff transfers into the swales. Bioswales are also known as grass swales, biofiltration swales, biofilters, or bio-retention cells. These systems can be used and adapted based on system requirements and desired conditions in urban areas (Shafique & Kim, 2017). The desired type of Bioswale alters to the need for rainwater storage requirements and location (size). Small-scale bioswales can be used to retrofit under constrained field condition and it varied to hydrologic conditions, different design attributes, and other environmental factors (Shrestha et al., 2018).

3) Performance for stormwater reduction

Bioswales are commonly used to collect runoff from roofs, sidewalks, and streets. They are best suited for large impervious areas like parking lots, driveways, and sidewalks. The factors that influencing runoff reduction include the depth and duration of rainfall events, storage depth, and length of the swales (Davis et al., 2012)**.** The ability to reduce stormwater runoff of bioswales integrating with engineered soil and trees is up to 88.8% from a parking lot in the Mediterranean climate (Xiao & McPherson, 2011). In a humid continental climate, stormwater volume was captured by Bioswale from 48 – 96 % of storm events (Shrestha et al., 2018). **Table 6** describes stormwater runoff reduction of bioswales from previous studies.

Table 6 Bioswales perform in stormwater runoff reduction.

Vegetation	Compositions	Runoff reduction (%)	Rainfall (mm)	Location/ Climate	Reference
2 Shrubs (crown diameter=0.43±0.03m) 4 trees (evergreen, DBH=1.37m)	-W x D x L =1 x 1 x 9 -Slope = 3 % -Engineered soil mix (75% native lava rock and 25% loam soil) -Geotextile fabric (0.3 m deep) -Pipe size: 5.1 cm	99.4	446 (100-year storm event)	California, USA /Mediterranean with hot, dry summers and cool, wet winters,	(Xiao et al., 2017)
Platanus x Acerifolia 'Bloodgood' (young and Small deciduous)	-W x D x L = 2.4 x 0.9 x 10.4 -Slightly sloped -Mulch (5.1 cm to 7.6 cm deep on the surface cover) -Clay loam -A fine graded nonwoven -Geotextile (top and bottom of soil) -Pipe size: 5.1 cm	88.8	446 (50 storm events=563.8)	Parking lot/ Mediterranean, summers are sunny, hot, and dry while winters are wet	(Xiao & McPherson, 2011)
Grass	-W x D x L = 1.2 x 0.9 x 42 m -Triangular in shape with 4:1 H: V side slopes -Sandy soils -Washed stone (2.3 to 38 mm stone size pea gravel covered -Underdrain (0.2 m diameter)	85	146 and 82.6	Brunswick County in Bolivia, North Carolina (NC), USA/39 events during the 12 months study period (February 2014–February 2015)	(Purvis et al., 2019)

Note: Dimension of swale: Width (W) x Depth (D) x length (L) in meter (m)

2.2.3. Permeable pavements

Permeable pavements (PP) offer plenty of environmental benefits including stormwater infiltration as it allows stormwater from rooftops or adjacent parking to percolate through the pavement and underlying layers. The implementation of Permeable pavements is available on sidewalks, parking lots, pedestrians, driveways/roads, residential or side streets, etc. to minimize runoff volume.

1) Components

Rather than using the traditional pavement, permeable pavements allow stormwater to percolate through various layers. Permeable pavements are typically composed of permeable surface, aggregate (base and sub-base) layer, and soil layer. Other optional materials that can be used to separate layers is geotextile fabric and an underdrain pipe. They may be added to discharge the overflow to a nearby storm drain (Kayhanian et al., 2019).

2) Type

Permeable pavements appear in many forms, including, pervious concrete (PCs) and porous asphalt (PAs). Other types of permeable pavements are block pavers with mixed design material like concrete and plastic; either side joint with fine sand or glasses planted in open surface (e.g. permeable interlocking pavers: concrete (PICPs), concrete grid pavers (CGPs), and plastic reinforcement grid pavers (PRGPs). These pavements are able to reduce urban runoff, mitigating as well as negative impacts of urbanization by providing stormwater on-site control system (Ko & Madduri, 2014).

a) Pervious concrete

Pervious concrete (PCs), as shown in **Figure 11**, is the most common type of permeable pavements used in sidewalks and parking lots. It is a mixture of Portland cement, water, coarse aggregate or gravel (single-sized coarse/ grading between 15-35%). Pervious concrete consists of the upper pervious concrete layer, aggregate base, sub-base course, geotextile (optional), and sub-grade soil.

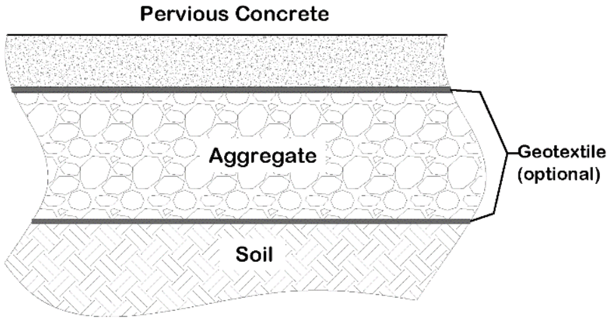


Figure 11 Typical section of pervious concrete

Source: Adapted from (Scholz & Grabowiecki, 2007)

b) Porous asphalt

The layer system of porous asphalt is similar to pervious concrete (**Figure 12**). Porous asphalt surface usually has a mixture of both fine and coarse aggregate bound together by a bituminous binder. The interconnected void space allows stormwater to flow through the asphalt and enter a crushed stone aggregate bedding layer and base that supports the asphalt while providing storage and runoff treatment. When properly constructed, porous asphalt is a durable and cost-competitive alternative to conventional asphalt.

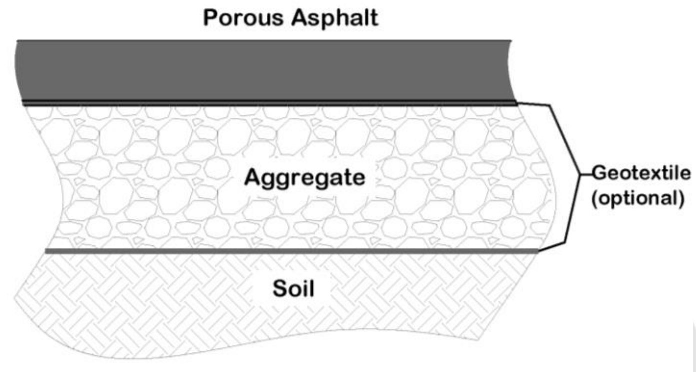


Figure 12 Typical section of porous asphalt

Source: Adapted from (Scholz & Grabowiecki, 2007)

The void space can be increased typically up to 15 to 20 % by reducing the amount of fine aggregate. The thickness of the asphalt depends on the traffic load, generally ranges from 7.5 to 18 cm. Porous asphalt can be used for municipal stormwater management programs and private development applications. The runoff volume and rate control, pollutant reductions allow municipalities to improve the quality of stormwater discharges. The use of porous asphalt can potentially reduce additional expenditures and land consumption for conventional collection, conveyance, and detention stormwater infrastructure.

c) Permeable interlocking pavers

Permeable interlocking pavers (**Figure 13**) are especially found as concrete pavers (PICPs), concrete grid pavers (CGPs), and plastic reinforcement grid pavers (PRGPs). PICPs are solid concrete blocks that fit together to form a pattern with small aggregate-filled spaces in between the pavers that allow stormwater to infiltrate. These spaces typically account for 5 to 15 % of the surface area (Agouridis et al., 2011). PICBPs as the same as PICPs except for the material which is brick instead of concrete (Agouridis et al., 2011).

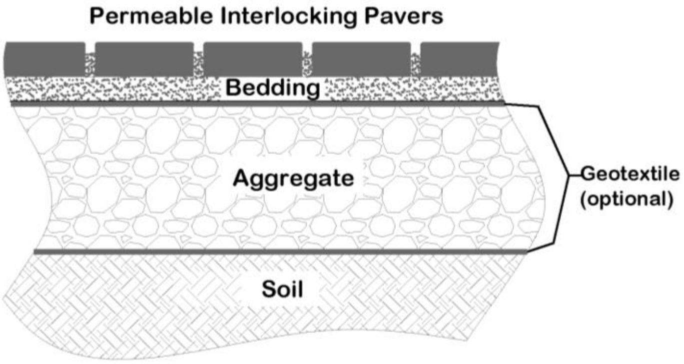


Figure 13 Typical section of permeable interlocking paver

Source: Adapted from (Hein et al., 2010)

Permeable interlocking concrete pavement (PICPs) as illustrated in **Figure 14 (a)** are generally designed with paving shapes that include small apertures in the paving surface or spacing lugs (Mullaney & Lucke, 2014). A typical PICPs main layer is concrete pavers (80 mm), bedding course (40-50 mm), base (100-150 mm), subbase (300-500 or varies on the structural and water storage requirements). Hydrological performance of each layer is relevant: bedding course with filling the joints promotes rapid infiltration between the pavers; the aggregate sub-base beneath a pervious paving structure can store large quantities of water before slowly releasing it into the subgrade below; geo-fabrics are used keep base and the bedding layers separate (Hein et al., 2010; Mullaney & Lucke, 2014)

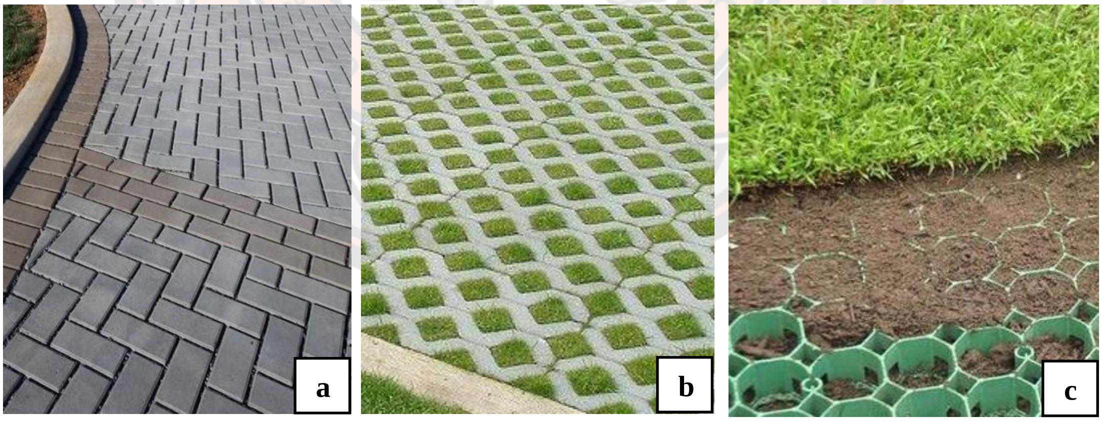


Figure 14 Typical permeable pavers: a. PICPs, b. CGPs, c. PRGPs

Source: **a**. from Techo-Bloc (2019), **b**. from Indiamart (2014), **c.** from External Works (2019).

Concrete grid pavers (CGPs), **Figure 14 (b)**, have larger openings than PICPs, **Figure 14 (c)**, they are not designed for use with a stone reservoir but instead can be placed directly on the soil or an aggregate base. As such, the infiltration rate of PICPs is much higher than that of CGPs (Agouridis et al., 2011). Typical grass is filled in the open spaces, although small aggregate can be used as well, to improve the process of infiltration to the underlying soil.

3) Performance for stormwater reduction

Losses of stormwater in permeable pavements are most likely attributed to three mechanisms: storage in the subbase, evaporation of base-course, and exfiltration into subgrade soils (Fassman & Blackbourn, 2010). In some circumstances, it may also include the capacity of underground storage tanks (Kayhanian et al., 2019). The thickness of these components is one of the key factors to reduce runoff as stormwater is stored and slowly recharged into the local groundwater system and result in surface runoff volume and peak reduction (Collins et al., 2012). Aggregate layer (base and sub-base) can capture and store stormwater, as a detention pond, until stormwater infiltrates into the native soil and eventually into the groundwater (Jayasooriya & Ng, 2019). The infiltration capacity of the soil is, therefore, an important design factor because it affects the performance of the system (Saadeh et al., 2019). Zhu et al. (2018) suggested that soil’s permeability of asphalt road has great influence in the whole permeable pavements systems to reduce runoff coefficient and flood peak flow. Sand is an ideal material for permeable pavements which can be applied to all occasions (Zhu et al., 2018) while native soil that contains silt/clay content less than 40% and clay content less than 20% is as effective as well-drained subgrade (Jayasooriya & Ng, 2019). However, soil with a minimum permeability rate of 0.5 inches per hour is also suitable for the construction of pervious concrete. Jayasuriya & Kadurupokune (2010) found that the percentage of runoff reduction from the conventional asphalt pavement varied between 45% to 55% for peak discharge and 50% to 60% for runoff volume reduction (Jayasuriya & Kadurupokune, 2010). The porous lot can produce 93% less runoff than the asphalt lot (Dreelin et al., 2006). **Table 7** provides details of the stormwater runoff reduction of permeable pavements found in the literature.

Table 7 Permeable pavements perform in stormwater runoff reduction.

Type	Compositions	Rainfall (mm)	Runoff reduction (%)	Location	References
Porous asphalt	- Porous asphalt - Base - Graded gravel or gravel (31.5-37.5 mm) 15 cm - 30 cm - Permeable geotextile - Subgrade	114.74		Sidewalk, Nanjing, China/	(Zhu et al., 2018)
		107.02			
		81.2 - 94.11			
Pervious concrete PC	- Pervious concrete layer (15 cm) - Aggregate bedding layer 5 cm (a washed ASTM no.78 stone); - Base coarse layer 23 cm (a washed ASTM no. 5 stone) - 10 cm underdrain- grade to drain at 0.42% slope - Situ soil	183 & 135 (2 storms)	43.9 (average)	Parking lots, a city of Kinston public service complex in eastern North Corolina	(Collins Kelly et al., 2008)
Permeable interlocking concrete pavers PICP (12.9 % open surface area and opening filled with no. 78 stone)	- PICP surface layer (8 cm) - Aggregate bedding layer 10 cm (A washed ASTM No.78 stone); - Base coarse layer 25 cm (A washed ASTM No. 5 stone) - 10 cm underdrain- grade to drain at 0.42% slope - Situ soil		66.3 (average)		

Table 7 (Cont.)

Type	Compositions	Rainfall (mm)	Runoff reduction (%)	Location	References
Concrete grid pavers CGP	- CGP surface layer (8 cm) - Sand 2.5cm - Aggregate bedding layer 10 cm (A washed ASTM No.78 stone); - Base coarse layer 22.5 cm (A washed ASTM No. 5 stone) - 10 cm underdrain- grade to drain at 0.42% slope - Situ soil		63.6		
PICP Permeable interlocking concrete pavers 120 m²	- PICP paver 75 mm - Pea gravel 75 mm (No. 57 stone) - Washed gravel 200 mm (No. 57 stone) - PVC drainpipe - Loamy soil - Slope 0.4 %	1,070 mm (largest event 88 mm) 10 months	100	Coastle plain of North Corolina	(Bean et al., 2007)

2.2.4. Green roofs

Characterized by vegetation on the top of buildings, Green roofs (GR) are the recent GI element for stormwater runoff reduction**.** Green roofs (GRs) have been proved to be innovative stormwater management measures by restoring natural states, enhancing interception, infiltration, and increasing evapotranspiration fluxes (Viola, F. et al., 2017)**.**

1) Components

Green roofs are customarily made up of four layers: vegetation, substrate, filter fabric, and drainage plate. The thickness and materials used in each layer will affect the capacity of water retention. Engineered soil is mixed with neat soil, perlite, organic fertilizer, and crushed expanded clay aggregate (Razzaghmanesh & Beecham, 2014)**.** The substrate contained perlite and peat can retain more water and effectively minimize the roof runoff (Lee et al., 2015; Stovin, 2010). Filter fabric is a protecting layer, preventing particles such as vegetation debris, and soil fines entering and clogging the beneath drainage layer. This fabric is also considered as a root-barrier membrane for vegetation in this typical roof (Kosareo & Ries, 2007)**.**

An optional water retention fabric, under the substrate layer, allows extra water to retain for the benefits of the plants; and for keeping the substrate layer moist. Storing extra water can increase the ability of Green roofs in reducing runoff (Rowe, 2006)**.**

2) Types

Green roofs are classified into two main types: extensive (**Figure 15**) and intensive green roofs (**Figure 16**). The classification is determined by a depth of substrate and vegetation types (Kosareo & Ries, 2007)**.**

a) Extensive green roofs

Extensive green roofs are a lightweight reservoir where water can be retained in the vegetation and substrate layer (Sims et al., 2016)**.** Extensive green roofs have a substrate depth of less than 150 mm (Kosareo & Ries, 2007; Mentens et al., 2006)**.** Vegetations with shallow roots are commonly grown like a small herbaceous plant, ground covers, grasses, small shrubs, and drought-tolerant succulents such as sedum (most favored use because it can tolerant to cold and longer dry climate (Gong et al., 2018; Volder & Dvorak, 2014)**.** Substate can be natural soil or engineered soil. To accompany the water flow in extensive Green roofs, having slope design is a good technical way to limit up to 45^0 (Mentens et al., 2006)**.**

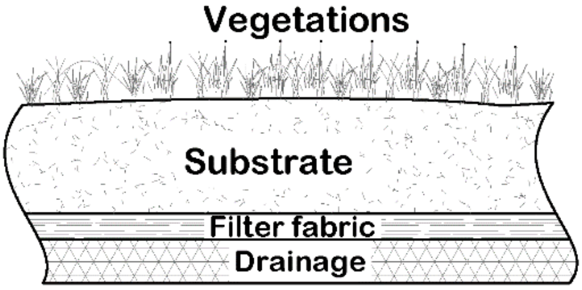


Figure 15 Typical section of extensive Green roofs.

Source: Adapted from (Connop, 2013)

b) Intensive Green roofs

The intensive green roofs have a thicker substrate, more than 150 mm. The intensive green roofs are designed similar to extensive roofs. Thus they require deeper substrate layers (Armson et al., 2013; Szota et al., 2019). A range from 150 to 350 mm and 150- 1200 mm of the substrate is suggested by Kosareo & Ries (2007) and Mentens (2006) respectively (Kosareo & Ries, 2007; Mentens et al., 2006). Constructing with these deep substrates, a wide variety of vegetation includes grasses, trees, shrubs, and perennial herbs that can be grown (Uhl & Schiedt, 2008). A larger quantity of runoff can be able to retain, yet in need of maintenance in the form of weeding, fertilizing, and watering (Kosareo & Ries, 2007). Its application is generally limited to the flat roof (Stovin, 2010) or roots with a slope of less than 1:100 according to structural design requirements (Mentens et al., 2006).

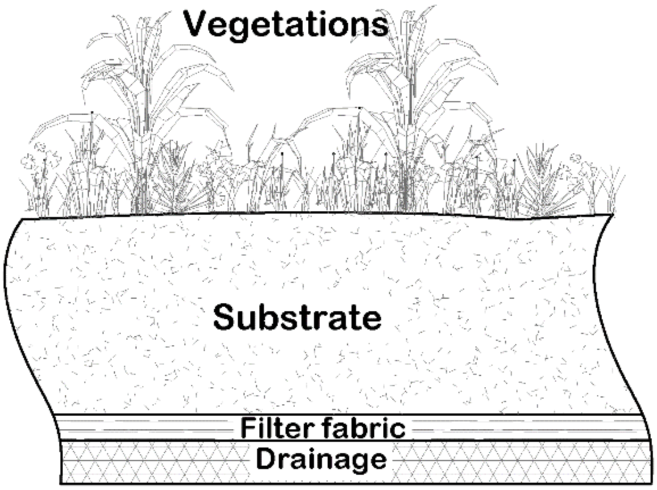


Figure 16 Typical section of intensive Green roofs

Source: Adapted from (DeNardo et al., 2003)

3) Performances

The hydrological process of green roof layers involves intercepting, retaining, and evaporating rainwater to the atmosphere (Viola, Francesco et al., 2017). Vegetation in green roofs intercept rainfall, among water taken up; either stored in plant tissues or transpired back into the atmosphere, some infiltrate to substrate; absorbed and retained in pored space. The ideal substrate comprises a balance of lightweight, well-drained material, has adequate water and nutrient holding capacity, and will not break down over time (Kosareo & Ries, 2007). Filter fabric allows water to pass through while preventing particles such as vegetation debris, and soil fines entering and clogging the beneath drainage layer. The drainage system moves the access water out. The important factors that affect the effectiveness of the green roofs are the substrate's thickness, type of vegetation cover, the slope of the green roofs, and the size of rainfall events (Golden & Hoghooghi, 2018; Liu, Xin & Chui, 2019).

Regarding the climate, green roofs are likely to perform better when rainfall and evapotranspiration exhibit the same seasonality during the hydrological year (humid subtropical climate). The role of climatic condition, namely annual rainfall, the potential of evapotranspiration, seasonality cycles, drive the maximum capacity of retention of green roofs when rainfall and temperature are in phase (Viola, F. et al., 2017). In the Northern temperate climate, Southfield, Michigan indicated that green roofs were highly efficient in capturing small storm events and were able to retain 68.25% of rainfall volume (Carpenter & Kaluvakolanu, 2011). The retention values of extensive (100 mm) and intensive (170mm) Green roofs were 11 % and 77 % in the US, Canada, New Zealand, China, and Europe (Ebrahimian et al., 2019). For tropical climates, the average percentage of rainfall diverted into evapotranspiration is even higher, about 49.9% for extensive Green roofs (90 mm) and 57.2% for the intensive ones (450 mm) (Viola, F. et al., 2017). **Table 8** shows the stormwater runoff reduction of green roofs from other literature.

Increasing stormwater runoff reduction associates with the retention performance of Green roofs (Sims et al., 2016). It is determined through quantification of the volume of precipitation that is retained in the substrate. The main factors affecting retention performance are substrate hydraulic conductivity, substrate depth, and rainfall depth (Volder & Dvorak, 2014).

Table 8 Green roofs perform in stormwater runoff reduction.

Substrate depth	Vegetations	Runoff reduction (%)	Rainfall (mm)	Location/ Climate	References
50 mm	Succulent species	28	512.2-665.6	Auckland, New Zealand/ winter and middle of autumn	(Castiglia Feitosa & Wilkinson, 2016)
100 mm	Succulent species	29			
	Sedum linear	17.51-24.85 (with storage layer)	Average 1770 (annual)	Shenzhen-China/ wet and dry season	(Li et al., 2019)
150 mm	Sedum linear	68	1100-1300 (annual)	Chongqing, China/ Subtropical monsoon climate, mean annual temperature 17.5-18.7 ^{0}C	(Zhang et al., 2015)
170 mm	grasses and weed	65.7	1249.6	Manchester/ wet summer	(Speak et al., 2013)
200 mm	Sedum	42.8-60.8%	42.5 mm (17h rainfall)-16 mm (14h rainfall)	Seoul, South Korea	(Zhang et al., 2015)
200 mm	Succulent species	32	512.2-665.6	Auckland, New Zealand/ winter and middle of autumn	(Castiglia Feitosa & Wilkinson, 2016)
400 mm		36			
800 mm		40			
1600 mm		60			

2.3. Quantum Geographic Information system (QGIS)

The rapid development of computer technology makes it possible for both scientific communities and scholars to make use of databases such as Quickbird, RapidEye, and Landsat, which provide data at a very high, high, and medium spatial resolution, respectively. These databases are used to carry out LU/LC analysis with the integration of geographical information systems (GIS) for understanding and defining land use and land cover dynamics and predicting land use in the future.

A geographic information system (GIS) is a computer system for capturing, storing, checking, and displaying data related to positions on Earth’s surface. GIS can show many different kinds of data on one map, such as streets, buildings, and vegetation. This enables people to more easily see, analyze, and understand patterns and relationships.

Quantum Geographic Information system (QGIS) is an open-source cross-platform and free desktop geographical information system application, and feasible. It is an ArcGIS alternative that used to analyze and edit spatial information, composing and exporting graphical maps. QGIS supports a wide variety of raster and vector layers; vector data is stored as either point, line, or polygon features. It enables users to assess and edit special information, in addition to creating and making available graphical maps. Many studies of land use detention have made extensive use of satellite image processing through Landsat data.

2.4. Rational Method

To estimate peak runoff, alternative methods are available. They include unit-hydrograph technique, empirical method, and semi-empirical method. However, the use of a particular method depends upon the available data and desired objectives. Specifically, the Rational Method is known as a simple and effective for runoff estimates from small drainages with large amounts of impervious area (Pennington, 2012). Based on data available, this method is suitable for estimating runoff peak rate in Phnom Penh.

2.4.1. Equation

Rational Method is originally proposed by Mulvanyin in 1850, to determine peak runoff rate in urban or suburban from a selected period of uniform rainfall intensity. It is an empirical linear equation. It applies to either U.S. or S.I. units for the parameters defined in the **Eq 1** and **Eq 2**, respectively. The method is appropriate for small urban watersheds with drainage areas less than 200 acres or 80 ha (20 acres for some sources) with generally uniform surface cover and topography. Application of the Rational Method is based on runoff potentials of the watershed such as the average intensity of rainfall (i) for a particular length of time (the time of concentration t_c), and the watershed drainage area (A) (Garcia, 2016).

$Q = CiA$ for U.S units **(Eq 1)**

Where,

Q = peak rate of runoff (cfs),

C = runoff coefficient,

i = average rainfall intensity (in./hr.),

A = drainage area (acres).

Or

$\mathrm{Q} = \frac{1}{360}\,CiA$ for S.I units **(Eq 2)**

Where,

Q = peak rate of runoff (m^3/s),

C = runoff coefficient,

i = average rainfall intensity (mm/hr.)

A = drainage area (ha)

2.4.2. The time of concentration (t_c)

The time of concentration doesn’t appear directly in the Rational Method equation. It is needed, however, for the determination of the design rainfall intensity to use in the Rational Method equation. For a given watershed, T_c represents the time required for rainfall landing on the farthest point of the watershed to reach the watershed outlet (Garcia, 2016).

In practice, the amount of runoff varies depending on the conditions of the catchment at the time that the event occurs. If the design rainfall falls on a dry catchment the resulting peak runoff will be lower than that for the design. Conversely, if the catchment is wet, the resulting peak runoff will be higher than that for which the works have been designed. After it starts to rain, the rate of runoff will progressively increase until it reaches a peak.

2.4.3. Runoff coefficient (C)

Different portions of a watershed have different degrees of perviousness. The impervious parts of the catchment do not allow incoming rainfall to infiltrate through them into the ground immediately and the permeable covers readily allow infiltration until they get saturated. The value of the runoff coefficient (C) is between 0 and 1, defining the proportion of rainfall that turns into the runoff. The value of the runoff coefficient encompasses the effects of infiltration, interception, evapotranspiration, and retention by a certain type of surface’s perviousness. An appropriate value of the runoff coefficient should be carefully selected for calculations.

The runoff coefficient, C, is a dimensionless ratio intended to indicate the amount of runoff generated by a watershed given an average intensity of precipitation for a storm. As the intensity of runoff is proportional to the intensity of rainfall, calibration of the runoff coefficient has depended on comparing the total depth of runoff with the total depth of precipitation (**Eq 3**).

$$C = \frac{R}{P} \qquad \textbf{(Eq 3)}$$

Where,

R = Total depth of runoff;

P = The total depth of precipitation

Many hydraulic design manuals are used to identify the runoff coefficient (C). Accordingly, a hydraulic design manual of the Texas Department of Transport (Garcia, 2016) has much diversity of C values that can be chosen for the urban watershed in different land-use types.

Table 9 summarizes the runoff coefficient (C) values for the urban watershed in different land-use types. The values are derived from 'Hydraulic Design Manual, TxDOT 07/2016'. This manual was selected to use rather than computing since limited sufficient data in Phnom Penh for computing C.

Table 9 Runoff Coefficients for Urban Watersheds

Type of drainage area		Runoff coefficient
Business	Downtown areas	0.70-0.95
	Neighborhood areas	0.30-0.70
Residential	Single-family areas	0.30-0.50
	Multi-units, detached	0.40-0.60
	Multi units, attached	0.60-0.75
	Suburban	0.35-0.40
	Apartment dwelling areas	0.30-0.70
Industrial	Light areas	0.30-0.80
	Heavy areas	0.60-0.90
	Parks, cemeteries	0.10-0.25
	Playgrounds	0.30-0.40
	Railroad yards	0.30-0.40
Unimproved areas	Sand or sandy loam soil, 0-3%	0.15-0.20
	Sand or sandy loam soil, 3-5%	0.20-0.25
	Black or loessal soil, 0-3%	0.18-0.25
	Black or loessal soil, 3-5%	0.25-0.30
	Black or loessal soil, > 5%	0.70-0.80
	Deep sand area	0.05-0.15
	Steep grassed slopes	0.70
Lawns	Sandy soil, flat 2%	0.05-0.10
	Sandy soil, average 2-7%	0.10-0.15
	Sandy soil, steep 7%	0.15-0.20

Table 9 (Cont.)

Type of drainage area		Runoff coefficient
	Heavy soil, flat 2%	0.13-0.17
	Heavy soil, average 2-7%	0.18-0.22
	Heavy soil, steep 7%	0.25-0.35
Streets	Asphaltic	0.85-0.95
	Concrete	0.90-0.95
	Brick	0.70-0.85
	Drives and walks	0.75-0.95
	Roofs	0.75-0.95

Source: Hydraulic Design Manual, TxDOT 07/2016: Chapter 4 — Hydrology, Section 12 — Rational Method, page 4-53 & 4-54.

2.4.4. Rainfall intensity (i)

Rainfall intensity (i) is the intensity of a constant intensity design storm with a return period. The IDF curves can be determined by the analysis of storms for a particular site (Garcia, 2016). It is commonly derived from the intensity-duration-frequency (IDF) curves which relate to 2, 5, 10, 25, 50, 100 years return period.

Estimates of the average rainfall intensity for a design storm of duration equal to the calculated ‘time of concentration’ (t_c) of a catchment. The values are determined from the IFD (intensity, frequency, duration) information for the catchment.

2.4.5. Drainage area (A)

Drainage areas are the areas where the precipitation falls off. They are the land features that can be identified by tracing on a map. The area of drainage is limited to not more than 200 acres or 80 ha.

2.5. Summary and limitation of sufficient data

Key issues were reviewed throughout the available sources from official reports, websites, and previous studies. However, some data are not available for the quantification of the Rational Method as follows:

- Rainfall intensity: rainfall intensity of this study is based on the data of rain-gauge derived from Pochentong station. This weather station provides the rainfall statistics for PP. Therefore, rainfall intensity from 1981 to 1997 is employed for further computing runoff rates.;
- Runoff coefficient (C): a lack of data sources for the designed runoff coefficient in land-use of Phnom Penh leads to the use of a design manual form another region. Rather than computing the values of C, the ‘Hydraulic Design Manual, TxDOT 07/2016’ is useful for this study because it covers all land use types required in this study.

CHAPTER III

RESEARCH METHODOLOGY

This chapter describes the methodological framework of this study. Several procedures were carried out and can be divided into four main parts: literature review, selection of study areas, scenario design, and the analysis of GI effectiveness.

3.1. Methodological frameworks

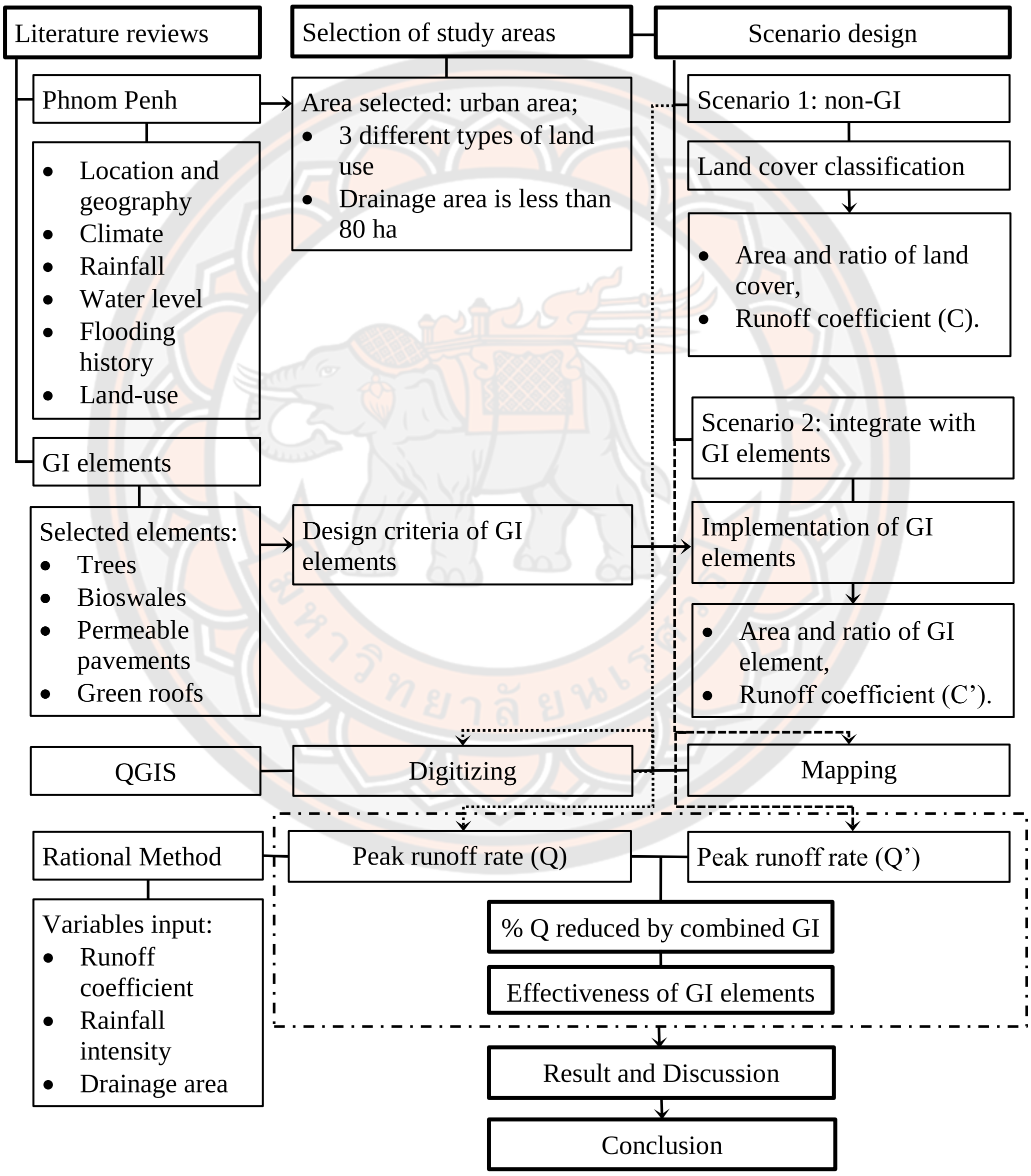


Figure 17 Overall methodological framework of the study.

Figure 17 is an overall methodological framework of the study. It is divided into a literature review, study area selection, scenario designs, peak runoff reduction, and effectiveness of GI elements. A literature review focused on Phnom Penh, GI elements, QGIS, and Rational Method. These reviews were already carried out in

Chapter II. Afterward, the selection of study areas and the design criteria of GI elements are obtained from a literature review. Scenario design is created to compare the differences in the runoff rate between before and after the GI implementation. QGIS is used for the digitizing and the Rational Method is used for computing peak rate runoff. The outcomes are the maps and peak rate of the two scenarios in the three selected study areas (**Chapter IV**). Finally, the outcomes are compared and analyzed for the potential of the effectiveness of GI elements (both single and combined elements) and the reduction of runoff in different land-use types (**Chapter V**).

3.2. Study area selection

Based on the flood-prone communities presented in Chapter 2. Later, three areas were selected to examine the potential of GI to reduce runoff. The selection criteria are:

- Three areas have different land uses in terms of residential, commercial, and mixed land uses,
- The drainage area is less than 80 ha because it is not suitable to use the Rational Method to estimate the areas that are larger than 80 ha.

3.3. Scenario design

The quantification of peak runoff rate was conducted to compare runoff volume of three areas with and without GI implementation or between scenarios 1 and 2.

3.3.1. Scenario 1 (S1)

Scenario 1 (S1) referred to non-GI, the current situation without any GI implementation. In this scenario, land covers were based on the existing condition. It was needed to know about type, area, and the ratio of actual land cover in three designed areas.

1) Land cover classification

The land cover was classified by using an overlay of Google satellite image in QGIS. In the process of analyzing land cover planning in these areas, two steps were implemented. Firstly, an overlay of Google satellite image. Google satellite image was used to identify land covers such as roofs of buildings/houses, streets, parking lots, tree canopies, and any other types of site's properties. All surface cover types (asphalt, concrete, etc.) were validated through Google Earth Pro (top view 2019, the street view 2013-2014) and site visits (2019). The latter was also used to identify the level of permeability. Secondly, manually tracing those land covers by creating shapefile layers in UTM zone 48N (EPSG:3148-Indian 1960) with lines, and polygon features of geometry types.

2) Peak runoff

a) Runoff coefficient (C) of actual land covers

The selection of runoff coefficient (C) values for each part of land covers was based on the Hydraulic Design Manual of Texas Department of Transport (Garcia, 2016). Some of the C values of the land covers that appear in scenario 1 are identical to the ones mentioned in the design manual. Therefore, C of similar land covers was selected and determined by their mean values, as shown in **Table 10**.

Table 10 Runoff coefficient (C) of actual land covers.

Land use/cover		**Runoff coefficient (C)**	
		From the mentioned hydraulic design manual	**This study**
Tree: tree canopies	Over impervious concrete	C unimproved area (steep grassed slopes) = 0.70 C streets (concrete) = 0.90 - 0.95	0.8125
	Over impermeable pavers	C unimproved area (steep grassed slopes) = 0.70 C streets (drives and walks) = 0.75 - 0.95	0.775
	Over impervious asphalt	C unimproved area (steep grassed slopes) = 0.70 C streets (asphalt) = 0.85 - 0.95	0.80
Parks	Grass and tree canopies	C lawn (sandy soil, flat 2%) = 0.05 - 0.10	0.075
Houses/buildings	Sloped roofs	C roofs = 0.75 - 0.95	0.95
	Flat roofs		0.75
Sidewalks	Impermeable pavers	C streets (drives and walks) = 0.75 - 0.95	0.85
Streets	Impervious asphalt	C streets (asphalt) = 0.85 - 0.95	0.90
Parking lots and others (Paths, driveways, campuses, and bare lands)	Impervious concrete	C streets (concrete) = 0.90 - 0.95	0.925

Source: Garcia, 2016: chapter 4: Hydrology, section 12— Rational Method, p. 4-53 & 4-54.

b) Area and ratio of land covers

The areas of land use/covers were acquired from the calculation of the Attribute Table (as defined in **Footnote 5**) tool in QGIS. The following formula was used for computing in those Attribute Table as described below:

- Area = $area => Total area = sum($area)
- Length = $length => Total length = sum($length)

An operator "$" was used as the prefix of any types of geometries (land covers). In the Attribute Table, it is used to calculate the area, length, and any types of geometric calculations in each row. An operator ‘sum’ is used to calculate the total values that were mattered.

After getting land cover areas, the ratio of each land covers area obtained by computing equation **Eq 4**.

$$\% R_i = \frac{A_i}{\sum_{i=1}^{n} A_i} \qquad \textbf{(Eq 4)}$$

Where,

% R_i	=	Ratio of land cover (i=1, 2,…, n)
A_i	=	Area of land cover (i=1, 2,…, n)

3.3.2. Scenario 2 (S2)

Scenario 2 (S2) referred to the integration of GI elements implementation on three land-use types.

1) Implementation of GI elements

As the urban areas in the central of Phnom Penh are highly dense, four elements are applicable s: Tree, Bioswale, Permeable pavements, and Green roofs. These GI elements require minimal spaces. The application of GI elements on the existing impervious land covers depends on their criteria design in the three selected areas. The processing of replacing was manually clicked on QGIS, supported by an overlay of Google satellite image. Several shapefiles were created as points, lines, and polygons for Tree, Bioswale, and Permeable pavements and Green roofs, respectively.

2) Criteria of GI elements

The criteria of GI elements present in this study are designed based on the relationship between appropriate types and sizes of land covers and applicable GI elements in three urban land-uses. For these reasons, the suitable GI elements for replacing existing impervious covers in different land-use types are investigated.

a) Trees

Trees (Tr) were selected to plant by using the following criteria:

- Places: on sidewalks where the widths are wider than 1.5 m
- Tree pits: are divided into three sizes: a. 0.6 m x 0.6 m, b. 1 m x 1m and c. 1.5 m x 1.5 m corresponding to < 2 m, 2 - 4 m, > 4 m wise of sidewalks.
- Type of Tree: Deciduous tree species because they are common and have a high transpiration rate to maximize photosynthesis during the wet season. They also have a large canopy to intercept rainfall.
- The radius of canopy: The average radius of street tree canopies ranged from 1.8 - 5.2 m (at stem diameter of 25 cm) (Pretzsch et al., 2015), so that, a. 1.8 m, b. 2.5 m, and c. 3.5 m of tree canopies radius were employed. In these values, the tree canopies cover not only sidewalks but also streets. It was assumed that tree canopies cover over streets (roads and boulevards) with one-third and two-thirds for sidewalks of total tree canopies, respectively.

Figure 18 shows the example of Tree that will be planted on the sidewalk where the width is more than 4 m (type c). The other types also follow as the designed criteria, shown in **Table 12**.

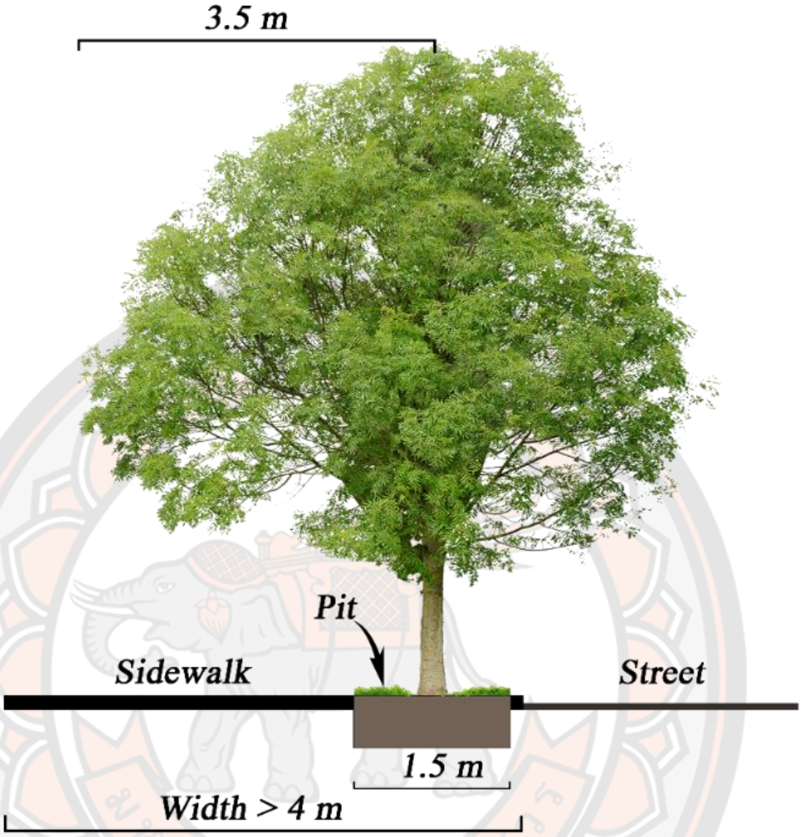


Figure 18 The example of Tree implements on sidewalks where the width is more than 4 m (type c).

b) Bioswales

Bioswales (Bios) was implemented along streets and parking lots. Streets have two types: boulevards and roads. Bios can be applied only on boulevards because roads are too narrow for the implementation of Bios. Hence, the criteria for Bios are designed below:

Along streets: replaced an existing concrete median barrier (some places) on the boulevards:

- Slope: less than 5% and side slope of 3:1
- Vegetation: grasses, shrubs, and small plants
- Substrate: 0.3 m
- Soil depth: 0.9 m (engineered soil or sandy loam)
- Width: 2.4 m
- Length: more than 2.4 m, otherwise it becomes a tree pit.

<u>Parking lots:</u>

- Slope: less than 2 % and side slope of 4:1
- Vegetation: grasses and shrubs
- Substrate: 0.15 m
- Soil depth: 0.5 m (engineered soil or sandy loam)
- Width: 0.6 m
- Length: more than 0.6 m, otherwise it becomes a tree pit.

Figure 20 illustrates the example of Bioswale that will be planted on boulevards.

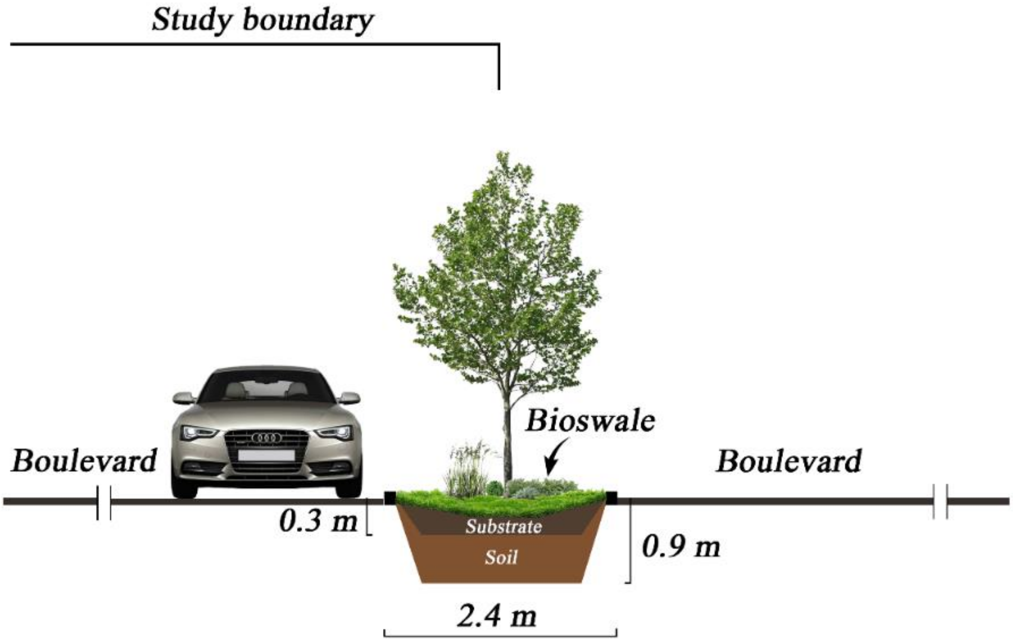


Figure 19 The example of bioswale's criteria implements in the median of the boulevard.

c) Permeable pavements

Permeable pavements (PP) were installed in paths, sidewalks, parking lots, and streets. The replacement of permeable pavements was designed to differ with the consideration of the existing materials as illustrated in **Table 11.**

Table 11 Replacement of impermeable pavements in scenario 1 (S1) by permeable pavements in scenario (S2).

Scenario 1	**Scenario 2**
Impervious pavers	Pervious pavers
Impervious concrete	Pervious concrete
Impervious asphalt	Porous asphalt

d) Green roofs

Green roofs (GR) were applied on only flat roofs due to difficulty in identifying the degree of sloped roofs (typically not exceed 45^0 for the GR implementation) (Mentens et al., 2006).

The intensive green roofs were used to apply on flat roofs due to their higher performance on retaining rainwater.

- Vegetations: sedums, herbs, small plants
- Depth of substrate: 0.15 – 1.6 m

Table 12 summarizes the criteria for implementing four GI elements in a variety of land covers described above.

Table 12 Summary of GI elements criteria for implementing

GI elements	**Criteria**		**Formula**	**Land covers**
Tr				Sidewalks and streets
Pits	Width	Length	Width x Length	
	a. 0.6	0.6	0.6 x 0.6	< 2 Sidewalks
	b. 1	1	1 x 1	2- 4 Sidewalks
	c. 1.5	1.5	1.5 x 1.5	> 4 Sidewalks
Canopies	Radius		ΠR^2	
	a. 1.8		$(\Pi \times 1.8^2) \times 2/3$	< 2 Sidewalks
			$(\Pi \times 1.8^2) \times 1/3$	Streets
	b. 2.5		$(\Pi \times 2.5^2) \times 2/3$	2- 4 Sidewalks
			$(\Pi \times 2.5^2) \times 1/3$	Streets
	c. 3.5		$(\Pi \times 3.5^2) \times 2/3$	> 4 Sidewalks
			$(\Pi \times 3.5^2) \times 1/3$	Streets
Bios				In streets and parking lots
	Width	Length	Width x Length	
	1.2	L	1.2L	In streets
	0.6	L	0.6L	Parking lots

Table 12 (Cont.)

PP			Sidewalks, parking lots, streets, and others
	Subtraction of pits area	$A_{\text{sidewalks}} - A_{\text{pits}}$	Sidewalks
	Subtraction of Bios area	$A_{\text{parking lots}} - A_{\text{Bios}}$	Parking areas
	Subtraction of tree canopies area (and) Bios area	$A_{\text{streets}} - A_{\text{tree canopies}}$	Roads
		$A_{\text{streets}} - (A_{\text{Bios}} + A_{\text{tree canopies}})$	Boulevards
	Subtraction of existing tree canopies	$A_{\text{others}} - A_{\text{existing tree canopies}}$	Others: campuses, driveways, paths, and bare lands.
GR			Flat roofs
	Fully covered	$A_{\text{flat roofs}}$	

Note: Tr = Tree, Bios = Bioswales, PP = Permeable pavements, and GR= Green roofs

3) Peak runoff (Q')

a) Runoff coefficient (C') of GI elements in scenario 2 (S2)

Runoff coefficient (C') of GI elements are derived from the other studies. The values of C' are used by calculating the mean values due to the favor of a value bias in different climate zone.

- Trees performed differently from the other three elements. Trees were planted on sidewalks but the measurement of their runoff coefficient (C') depended on the integration between tree canopies and the ground covers. The reason was the tree canopies, immediately, intercept rainfall before it falls on the ground covers. They were divided into 4 types: tree canopies-pits, tree canopies-pervious pavers, tree canopies-pervious concrete, and tree canopies-pervious asphalt. Armson et al. (2013) found the runoff coefficient of tree canopies to tree pits were between 0.2-0.26 of total rainfall in winter (high rainfall) and summer condition (small crown). Thus, the mean value of tree canopies-pits should be 0.23. Besides, the mean value of the runoff coefficient of tree canopies-pervious asphalt was 0.45. It was determined by the mean value of tree canopies (0.70) as shown in section '3.3.1, 2), a' and pervious concrete's (0.20) (Dietz, 2007). This method was used the same as in tree canopies-pervious pavers and tree canopies-porous asphalt, **Table 13**.
- The mean value of C' of bioswales is 0.13. It is derived from Xiao & McPherson (2011), 0 – 0.06, and Sun et al. (2014), 0.227;
- Permeable pavements: C'= 0.3 to 0.5 for permeable CBP (permeable concrete block pavement), found by Borgwardt (2006), while C'= 0.20 to 0.50 for block pavers found by Hunt et al. (2002). For porous asphalt and

pervious concrete, they are 0.23 and 0.20 found by NYC (2012) and Dietz (2007);

- M. Uhl (2008) found a runoff coefficient of green roofs 0.19 - 0.39, while the C of green roofs ranged from 0 - 0.44 as found by Pimentel-Rodrigues et al. (2017). Thus, the C value of the green roofs could be assumed to be 0.255. This value is for intensive green roofs with a substrate depth of 0.15m.

Table 13 summarizes the mean values of the runoff coefficient (C’) of GI elements acquired from other studies.

Table 13 Runoff coefficient (C’) of GI elements.

S2	**Runoff coefficient (C’)**	
GI elements	**From other studies**	**This study**
Trees: tree canopies		
Over pits	$C_{\text{tree-pits}} = 0.20 – 0.26$ (Armson et al., 2013)	0.23
Over permeable pavers	$C_{\text{tree canopies}} = 0.70$ (Garcia, 2016) $C_{\text{block pavers}} = 0.20 - 0.50$ (Hunt, B. et al., 2002) $C_{\text{plastic grid pavers}} = 0 – 0.26$ (Dreelin et al., 2006)	0.47
Over porous asphalt	$C_{\text{tree canopies}} = 0.70$ (Garcia, 2016) $C_{\text{porous asphalt}} = 0.23$ (NYC, 2012)	0.465
Over pervious concrete	$C_{\text{tree canopies}} = 0.70$ (Garcia, 2016) $C_{\text{pervious concrete}} = 0.20$ (Dietz, 2007)	0.45
Bioswales:		
	$C_{\text{bioswales}} = 0 – 0.06$ (Xiao & McPherson, 2011)	0.13
	$C_{\text{bioswales}} = 0.227$ (Sun et al., 2014)	
Permeable pavements:		
Porous asphalt	$C_{\text{porous asphalt}} = 0.23$ (NYC, 2012)	0.23
Pervious concrete	$C_{\text{pervious concrete}} = 0.20$ (Dietz, 2007)	0.20
Permeable pavers	$C_{\text{block pavers}} = 0.20 - 0.50$ (Hunt, B. et al., 2002)	0.24
	$C_{\text{plastic grid pavers}} = 0 – 0.26$ (Dreelin et al., 2006)	
Green roofs:		
	$C_{\text{green roofs}} = 0 - 0.44$ (Pimentel-Rodrigues & Silva-Afonso, 2017)	0.255
	$C_{\text{green roofs}} = 0.19 - 0.39$ (Uhl & Schiedt, 2008)	

b) Area and ratio of GI elements

The areas of GI elements were obtained from computing in the Attribute Table tool in QGIS. The formula for computing was in the same method described in 3.3.2, 2, b.

After getting land cover areas, the ratio of each land covers area obtained by computing equation **Eq 5**.

$$\% R_j = \frac{A_j}{\sum_{i=1}^{n} A_j} \qquad \textbf{(Eq 5)}$$

Where,

$\% R_j$ = The ratio of land cover (j=1, 2,…, n)

A_j = Area of land cover (j=1, 2,…, n)

3.3.3. Rainfall intensity (i)

In both scenarios (S1 and S2), the desired value of average rainfall intensity (i) for inputting in the Rational Method is a 2-years storm return period which is widely used in several studies for estimating runoff volume. According to data derived from Pochentong meteorological station in Phnom Penh, a 2-years storm return period of the city is 44.8 mm/h. This data of rainfall intensity was used since Pochentong meteorological station is located at a short distance from three study areas.

3.4. Peak runoff reduction

The estimated peak runoff rate reduction in three areas was determined by comparing the peak runoff rate between two scenarios; S1 and S2.

After getting all input variables, peak runoff rates in the three study areas associated with the three scenarios were computed. After that, the percentages of runoff reduction were calculated by **Eq 6**.

$$\%\ \text{Runoff redcution} = \frac{Q_{S1} - Q_{S2}}{Q_{S1}} \qquad \textbf{(Eq 6)}$$

Where,

Q_{S1} = Peak runoff rate in scenario 1

Q_{S2} = Peak runoff rate in scenario 2

3.5. Effectiveness of GI elements

The effectiveness of GI elements was evaluated by analyzing the performance of single and combined GI elements in reducing runoff. The effectiveness of each GI element was computed to determine the most effective elements for alleviating runoff in each area; Area A, Area B, and Area C. Besides, the effectiveness of combined Gi elements was determined into three levels: the highest, medium, and low performance.

3.5.1. Single GI elements

The effectiveness of single GI elements obtained from the comparison of the ratio of peak runoff reduction (**Eq 7**) to the ratio of single GI elements (**Eq 8**) performed by single GI elements. The results of computing in **Eq 9** give the weight to further evaluation of their effectiveness.

$$\%\, Q\ reduced\ by\ single\ GI\ elements = \frac{Q\ of\ single\ GI\ elements}{Q\ reduced\ by\ combined\ GI\ elements} \qquad \textbf{(Eq 7)}$$

Where,

- Q of single GI elements was attained from Rational Method calculation;
- Q reduced by combined GI elements = Σ Q reduced by single GI elements

$$Ratio\ of\ single\ GI\ elements = \frac{Area\ of\ single\ GI\ elements}{Area\ of\ combined\ GI\ elements} \qquad \textbf{(Eq 8)}$$

Where,

- Area of single GI elements obtained from contributing table in QGIS after the implementation of GI in S2;
- Area of combined GI elements = Σ Area of single GI elements.

$$\text{Weight of single GI elements} = \frac{\%\, Q\ reducted\ by\ single\ \ GI\ elements}{\%\, single\ GI\ elements} \qquad \textbf{(Eq 9)}$$

3.5.2. Combined GI elements

The effectiveness of combined GI elements was evaluated by computing the weight of combined GI elements. By comparing the ratio of peak runoff reduction of combined GI elements to the ratio of combined GI elements (**Eq 10**) in A, B, and C, the weights obtained.

$$\text{Weight of combined GI elements} = \frac{\%\, Q\ reducted\ by\ combined\ \ GI\ elements}{\%\, combined\ GI\ elements} \qquad \textbf{(Eq 10)}$$

The outcomes were evaluated to the best, medium, low, and poor by raking their weight.

- The best: Weight ≥ 1,
- High performance: 0.75 ≤ Weight < 1,
- Medium performance: 0.50 ≤ Weight < 0.75
- Low performance: Weight < 0.50

3.6. Summary

The main procedures detailed in this chapter were summarized as the following:

- The selection of the three different land-use types in urban Phnom Penh;
- The two scenarios are used to compare runoff performance of three study areas with and without GI implementation with the support of QGIS for land use classification
- The peak runoff rates will be computed in both scenarios for three different land-use types;
- The comparison of runoff performance will be further analyzed to determine the effectiveness of GI elements by using their weights.

CHAPTER IV

RESULTS

The results were divided into four sections as follows: 1) Study areas; 2) Scenario 1: Non-GI; 3) Scenario 2: Integrate with GI elements; 4) Scenario 1 and 2 that comprised the peak runoff reduction and effectiveness of GI elements.

4.1. Study areas

Three areas, Area A, Area B, and Area C were selected to study as shown in **Figure 20**. They are in Tuol Svay Prei Pir, Wat Phnom, and Teuk L’ak ti Muoy commune, respectively.

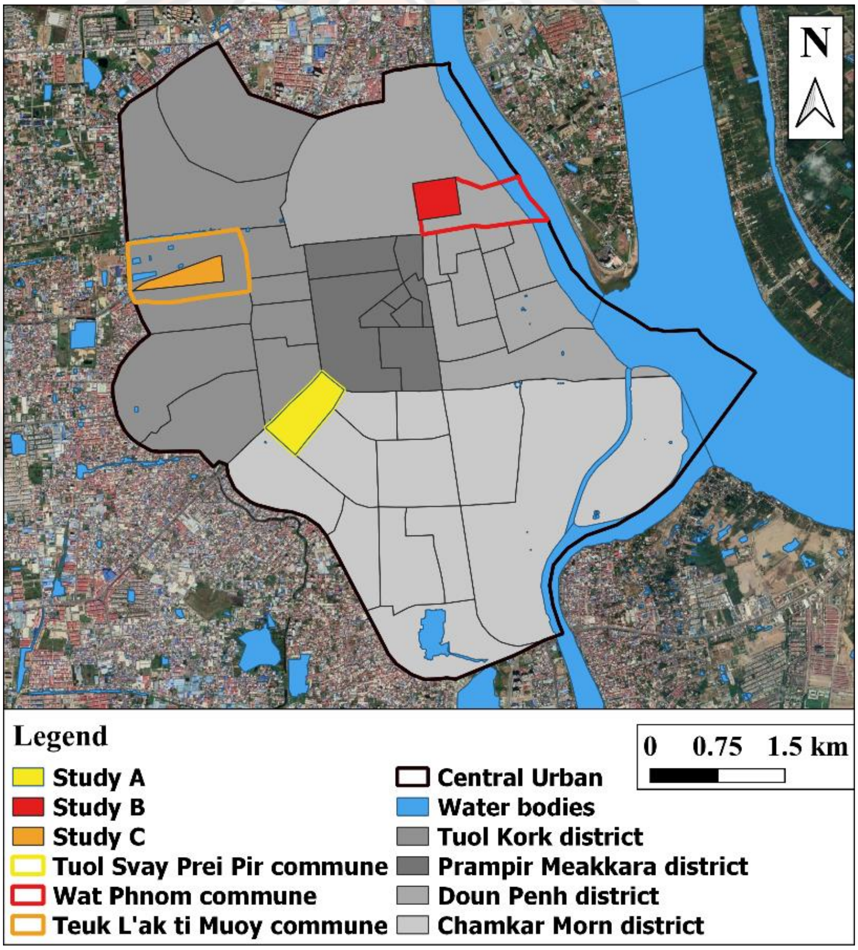


Figure 20 Map of three areas in central urban in Phnom Penh.

Source: Adapted from Open Development Cambodia (ODC)

4.1.1. Area A

Area A, 11°33'11.84"N, 104°54'21.21"E, locates in Tuol Svay Prey Pir, Chamkar Morn district (**Figure 21**). The characteristic of this area is described below:

- Area: 35.80 ha;
- Density: 30,591/km²;
- Land-use type: high-density residential area;
- Characteristic: residential housing, attached roofs with 2-4 stories and composed of a high percentage of impervious cover (approximately 90 - 95 % of impervious cover);
- Flooding problem: the flood depth commonly ranges from 0 – 1 m (Hong et al., 2016) and lasts between 1.5 – 3.0 hours (Heng et al., 2017).

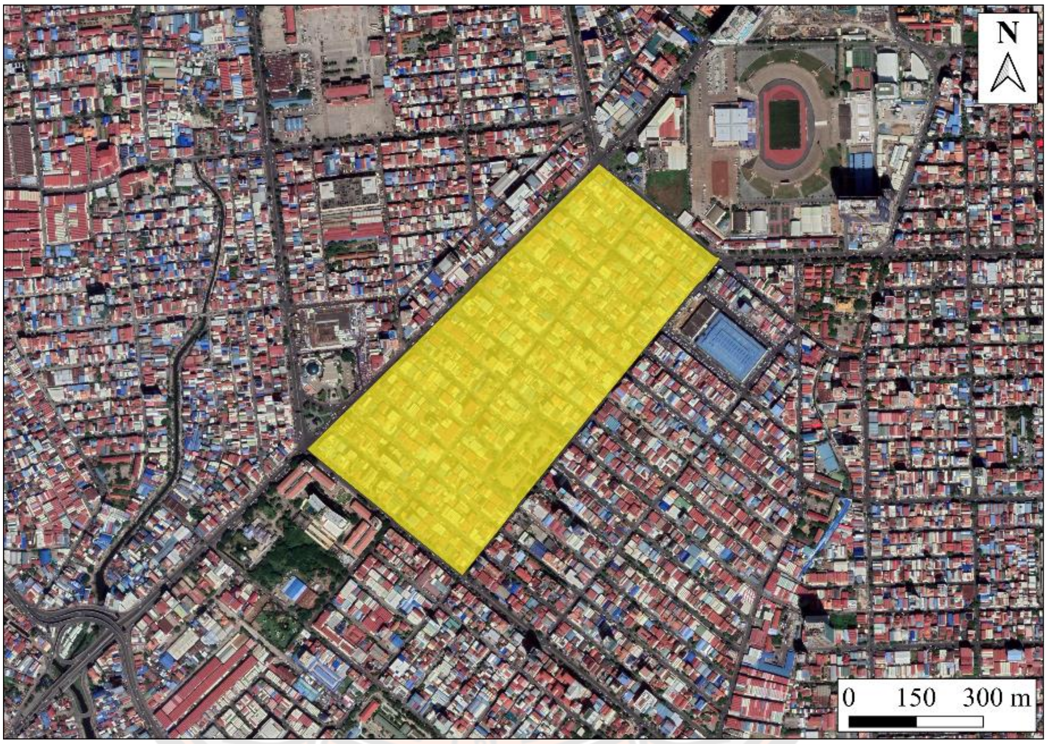


Figure 21 Map of Area A.

4.1.2. Area B

Area B, 11°34'20.39"N, 104°55'13.79"E, situates in Wat Phnom commune, Doun Penh district (near Tonle Sap), as shown in **Figure 22**. The characteristic of this area is explained below:

- Area: 20.83 ha
- Density: 14,378/km²
- Land-use type: medium-density urban area
- Characteristic: commercial and institutional building blocks, campuses, parking lots, with 70 – 75 % impervious covers, and public green spaces.
- Flooding problem: The depth of inundation from rainfall reached mostly up to knees and lasts for 2-3 hours (JICA, 2016; Yim et al., 2016).

Figure 22 Map of Area B.

4.1.3. Area C

Area C, 11° 34' 2.18"N, 104° 53' 40.26" E, is in Teuk L'ak Muoy commune Tuol Kouk district (**Figure 23)**. The characteristics of this area are described below:

- Area: 19.50 ha
- Density: 14,858/km²
- Land-use type: medium-density urban area
- Characteristic: represents a combination of commercial and residential blocks, consists 75 - 80 % of impervious covers.
- Flooding problem: flood depth commonly ranges from 0 – 1 m (Hong et al., 2016) and lasts for 2-3 hours (JICA, 2016)

Figure 23 Map of Area C.

4.2. Scenario 1: non-GI

4.2.1. Land cover classification

1) Area A

Area A, a residential neighborhood with blocks of attached houses. It contained a high percentage of impervious surfaces, as classified in (**Figure 24**).

Figure 24 Land cover classification in Area A.

This area consists of three main land covers, including public green spaces, houses/buildings, and transportations. The remaining areas are paths and campuses, parking lots, and bare land. Additional land covers were grass, flat and sloped roofs, tree canopies, and impervious pavers/concrete/asphalt, as shown in **Table 14**. The previous and impervious covers accounted for 4.03 % and 95.97 % of the total area, respectively.

Table 14 Land cover classification in Area A.

Land covers				Area	Percentage
Unit				(ha)	(%)
Public green spaces	Parks		Grass	0.01	0.04
Houses /buildings	Roofs		Flat	2.01	5.61
			Sloped	18.55	51.82
Transportations	Sidewalks		Tree canopies	0.63	1.76
			Impervious pavers	6.35	17.75
	Streets	Boulevards	Tree canopies	0.07	0.19
			Impervious asphalt	1.47	4.11
		Roads	Tree canopies	0.27	0.75
			Impervious asphalt	4.28	11.97

Table 14 (Cont.)

Land covers			**Area**	**Percentage**
Unit			(ha)	(%)
Others:	Parking lots	Impervious concrete	0.3	0.83
	Paths and campuses	Tree canopies	0.46	1.29
		Impervious concrete	1.10	3.07
	Bare land	Impervious concrete	0.29	0.80

2) Area B

Area B is characterized by the blocks of commercial and institutional buildings, comprising three main land covers. All of these blocks are bordered by roads and boulevards. The three main land covers are public green spaces, commercial and institutional blocks, and transportations. They are covered by grasses, tree canopies, flat and sloped roofs, impervious concrete/pavers/asphalt. **Table 15** and **Figure 25** illustrates the land use/covers after classifying in Area B.

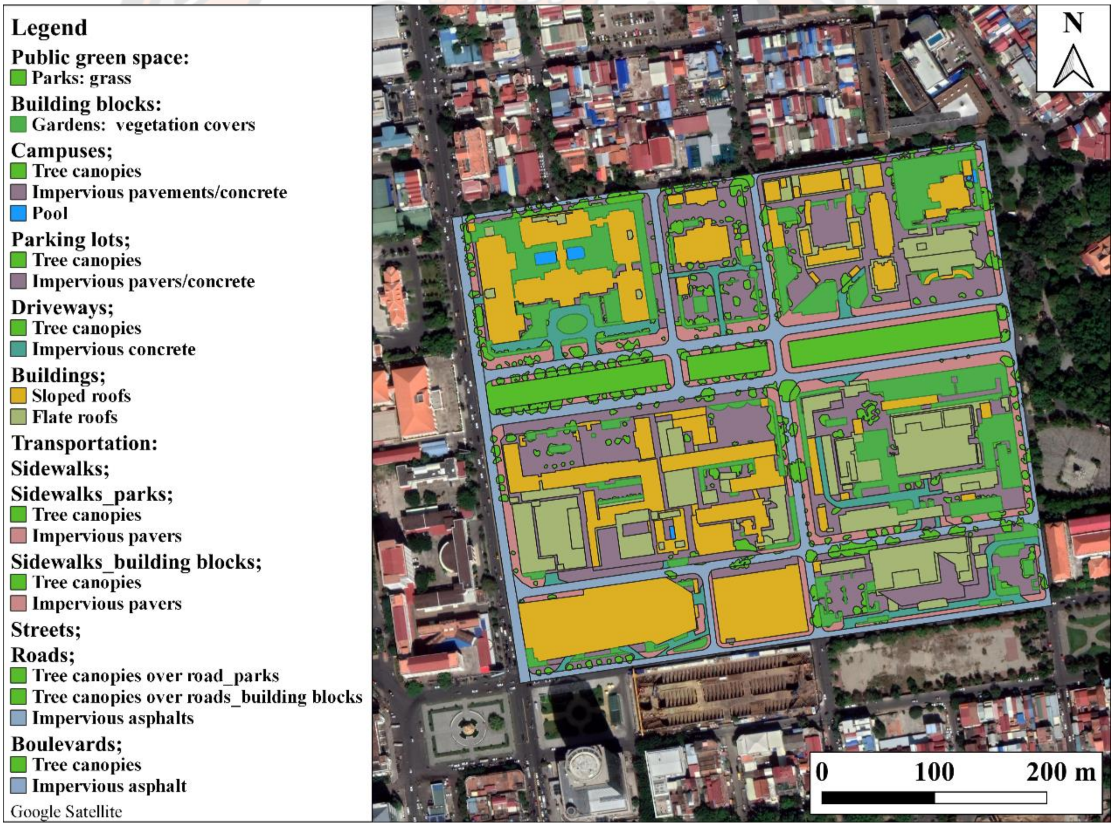


Figure 25 Land cover classification in Area B.

Table 15 Land cover classification in Area B.

Land covers				Area	Percentage
Unit				(ha)	(%)
Public green spaces	Parks		Grasses	0.95	4.54
Commercial and institutional building blocks	Gardens		Vegetation covers	3.26	15.64
	Campuses,		Tree canopies	0.33	1.58
			Impervious concrete	2.53	12.14
			Pool: water	0.05	0.23
	Parking lots		Tree canopies	0.30	1.44
			Impervious pavers/concrete	1.59	7.63
	Driveways		Tree canopies	0.03	0.15
			Impervious concrete	0.65	3.12
	Buildings		Flat	2.51	12.02
			Sloped	4.14	19.87
Transportations	Sidewalks		Tree canopies	0.46	2.21
			Impervious pavers	1.48	7.1
	Streets	Boulevards:	Tree canopies	0.02	0.10
			Impervious asphalt	0.34	1.63
		Roads:	Tree canopies	0.31	1.50
			Impervious asphalt	1.89	9.09

3) Area C

Area C is a mix of commercial, institutional, and residential areas (**Figure 26**). These land-uses were covered by grasses, tree canopies, flat and sloped roofs, and impervious concrete/pavers/asphalt. **Table 16** displays the area and percentage of each land covers in Area C.

Table 16 Land cover classification in Area C.

Land covers			Area	Percentage
Unit			(ha)	(%)
Public green spaces	Parks	Grasses	0.20	1.02
Commercial and institutional building blocks	Gardens	Grasses and tree canopies	3.26	16.73
		Impervious paver	0.27	1.40
	Campuses	Tree canopies	0.46	2.37
		Impervious concrete	1.00	5.11

Table 16 (Cont.)

Land covers				Area	Percentage
	Parking lots		Tree canopies	0.02	0.09
			Impervious concrete	0.99	5.08
	Buildings		Flat roofs	1.55	2.75
			Sloped roofs	2.25	11.04
Residential housing blocks	Campuses, paths, and bar lands		Tree canopies	0.14	0.72
			Impervious concrete/pavers	0.77	3.95
	Roofs		Flat	1.46	4.39
			Sloped	4.09	20.98
Transportations	Sidewalk		Tree canopies	0.6	3.04
			Impervious pavers	1.45	7.43
	Streets	Boulevards	Tree canopies	0.12	0.68
			Impervious asphalt	1.34	6.85
		Roads	Tree canopies	0.13	0.65
			Impervious asphalt	1.11	5.71

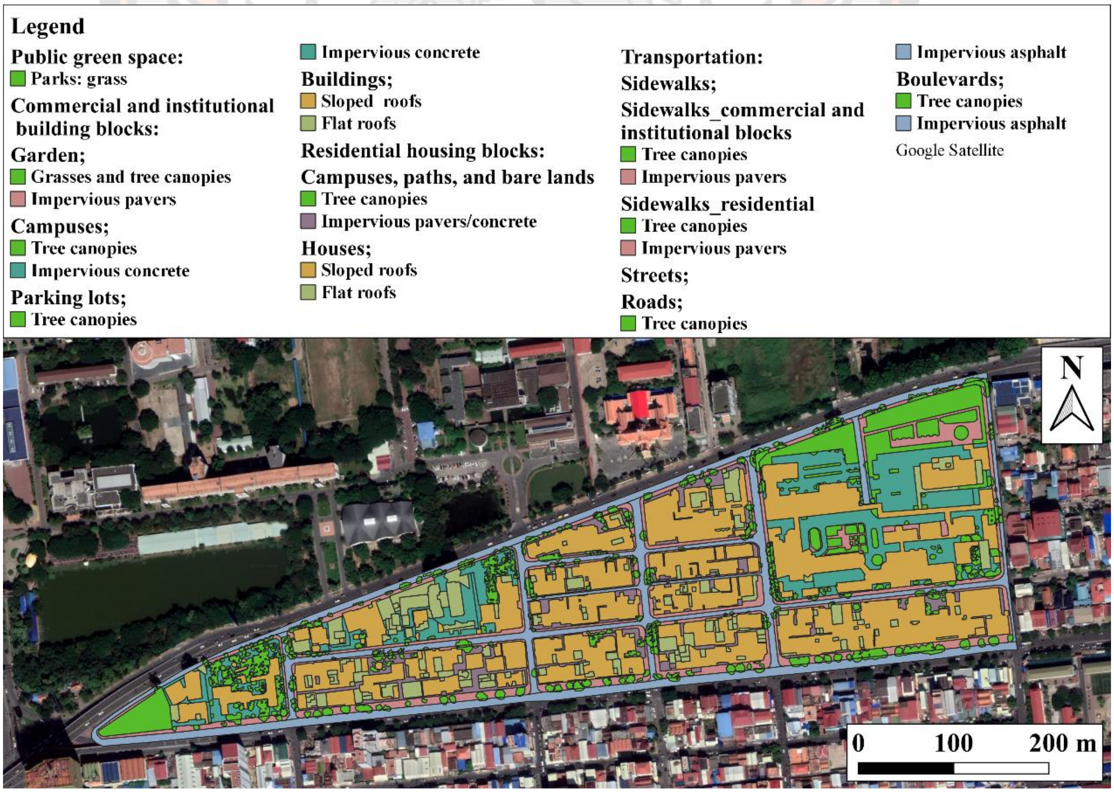


Figure 26 Land cover classification in Area C.

4.2.2. Characteristics of land covers in A, B, and C

Overall, the three areas of A, B, and C had six main land covers including:

- Public green spaces (parks and gardens)
- Roofs (flat and sloped roofs),
- Sidewalks,
- Streets,
- Parking lots, and
- Others: campuses, driveways, paths, and bare lands.

Figure 27, Figure 28, and **Figure 29** show the proportion of land covers in areas A, B, and C, respectively.

In Area A, the sloped roofs had the highest percentage (51.82%) which was more than half of the total area. This area was considered as a high-density residential area with the highest percentage of impervious surface. The second and third largest land cover was taken by sidewalks (19.51%) and streets (17.02%), followed by flat roofs and others (4 – 6%) of the total area. The minor ratio was parking lots and pubic green spaces, less than 1% of the total area (**Figure 27, a)**. This area composed the ratio of impervious to pervious cover by 9.5:0.5 **(Figure 27, b)**.

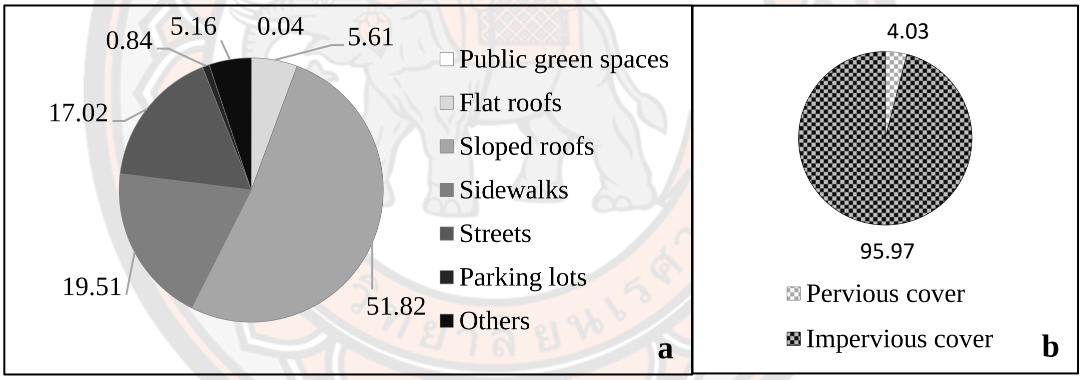


Figure 27 The proportion of land covers in Area A. The percentage of land covers classification (a), the ratio of permeability (b).

Area B, the ratio of pervious cover, and impervious cover account for 27.4 % and 72.6%, respectively **(Figure 28, b**). The largest share was public green spaces, about 1:5 of total area, followed by sloped roofs (19.87%), others (17.22%), streets (12.21%), and flat roofs (12.02%). The sidewalks and parking lots had a comparable percentage, about10%of the total area as shown in **Figure 28 (a)**.

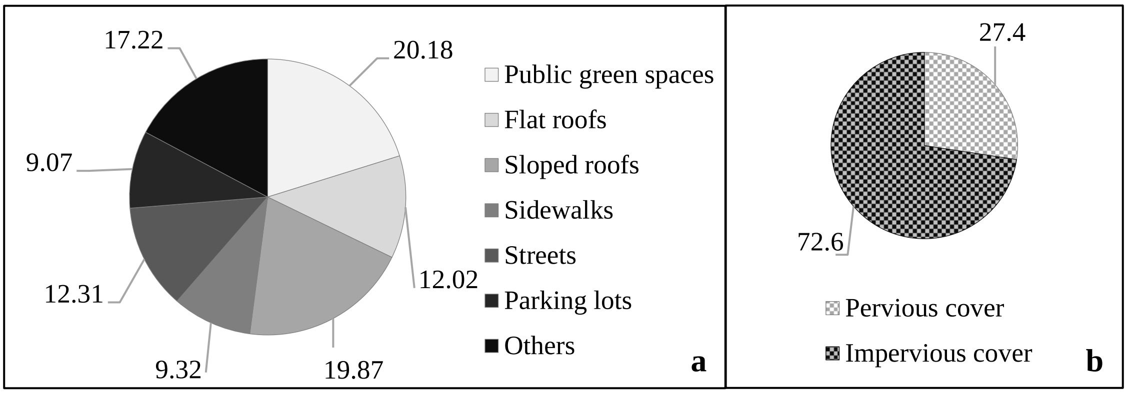


Figure 28 The proportion of land covers in Area B. The percentage of land covers classification (a), the ratio of permeability (b).

In Area C, the sloped roofs had the highest proportion, about 1/3 to the total area. The second-largest share was public green spaces covering almost 1/5 of the total area (**Figure 29, a**). The streets accounted for 14%. For flat roofs and sidewalks, the coverage was 7 – 11% of the total area. Parking lots had the smallest percentage. Overall, the pervious surfaces covered 25.3% and the impervious surfaces covered 74.7% of the total area (**Figure 29, b**).

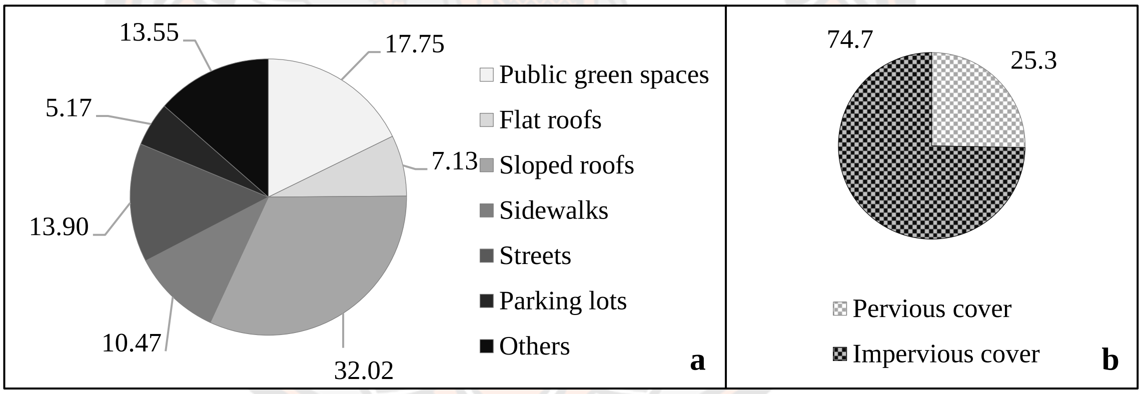


Figure 29 The proportion of land covers in Area C. The percentage of land covers classification (a), the ratio of permeability (b).

To conclude, three study areas had different characteristics, featuring different land covers as described below:

- For a residential land-use, Area A was dominated by sloped roofs, sidewalks, and streets, comparing to B, and C.
- For a commercial land-use, Area B had a larger share of public green spaces, flat roofs, and parking lots.
- For a mixed land-use, Area C had no distinctive land covers. All land covers resembled each other, compared to Area A and Area B.

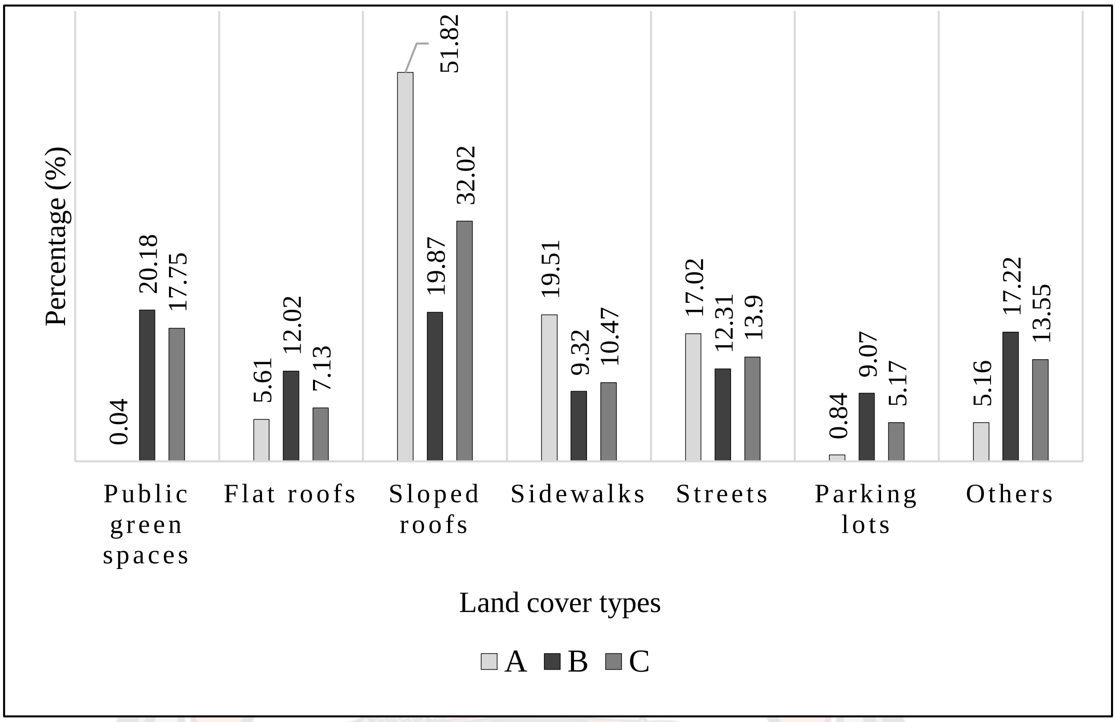


Figure 30 The percentage of land covers classification compared to the total area of Area A, B, and C.

4.2.3. Peak runoff rate (Q)

Through the Rational Method, the distributed runoff volumes of Area A, B, and C were calculated (**Table 17**).

Area A produced the highest runoff (4.03 m^3/s) while areas B and C created less runoff (1.87 m^3/s in Area B, and 1.82 m^3/s in Area C).

Table 17 Peak runoff rate (Q) in Area A, Area B, and Area C for a 2-years storm return period.

Land covers	**A**		**B**		**C**	
Unit	m³/s	%	m³/s	%	m³/s	%
Public green spaces	0.0001	0.00	0.04	2.14	0.03	1.65
Flat roofs	0.19	4.71	0.23	12.30	0.13	7.14
Sloped roofs	2.19	54.34	0.49	26.20	0.74	40.66
Sidewalks	0.73	18.11	0.20	10.70	0.21	11.54
Streets	0.68	16.87	0.28	14.97	0.30	16.48
Parking lots	0.03	0.74	0.21	11.23	0.12	6.59
Others: Campuses, driveways, paths, and bare lands	0.21	5.21	0.41	21.93	0.29	15.93
Total	**4.0301**		**1.87**		**1.82**	

Peak runoff rates taken by land covers in A, B, and C were explained below:

- Area A: the sloped roof had the highest peak runoff rate (2.19 m³/s, 54.34 %) which was more than half of the total peak runoff rate, followed by sidewalks, streets, flat roofs, others, and parking lots. Pubic green spaces produced minimal runoff, only 0.0001 m³/s.
- Area B: the sloped roof had the highest peak runoff rate (0.49 m³/s, 26.30) which accounted for almost 25% of the total peak runoff rate, followed by streets, flat roofs, parking lots, and sidewalks. Pubic green spaces caused the least amount of runoff, only 0.04 m³/s.
- Area C: the sloped roof produced the highest peak runoff rate (0.74 m³/s, 40.66%), followed by streets, others, sidewalks, flat roofs, parking lots. Like Area A and Area B, pubic green spaces created the lowest runoff volume, only 0.03 m³/s.

Figure 31 summarizes the percentage of peak runoff rate distributed by land covers between Area A, B, and C. The characteristics between these areas were described below:

- Sloped roofs produced the highest runoff rate while public green spaces provided the lowest runoff rate;
- Sidewalks and streets were the second-largest sources of runoff. They produced a similar amount of runoff, ranging from 18.11-10.70%. Therefore, runoff caused by sidewalks and streets was highest in Area A, followed by Area C and Area B. Therefore, the runoff volume created by flat roofs, parking lots, and Others of Area B was more than Area C and Area A.

Figure 31 The percentage of peak runoff rate distributed by various land covers in Area A, Area B, and Area C.

4.3. Scenario 2: the integration of GI elements

4.3.1. Implementation of GI elements

In scenario 2 (S2), the impervious covers in scenario 1 were replaced by the GI elements. Four GI elements; including trees (Tr), bioswales (Bios), Permeable pavements (PP), and green roofs (GR), were implemented in the designated areas. However, the exiting pervious covers such as the public green spaces, garden and vegetation covers (grass and tree canopies cover on parks) remained the same in S2. The percentage of Tr, Bios, PP, and GR in S2 was obtained by comparing the surface area of single GI elements with the total area of each Area.

1) Area A

Figure 32 illustrates the map of Area A after the four GI elements were applied to various land covers in scenario 2.

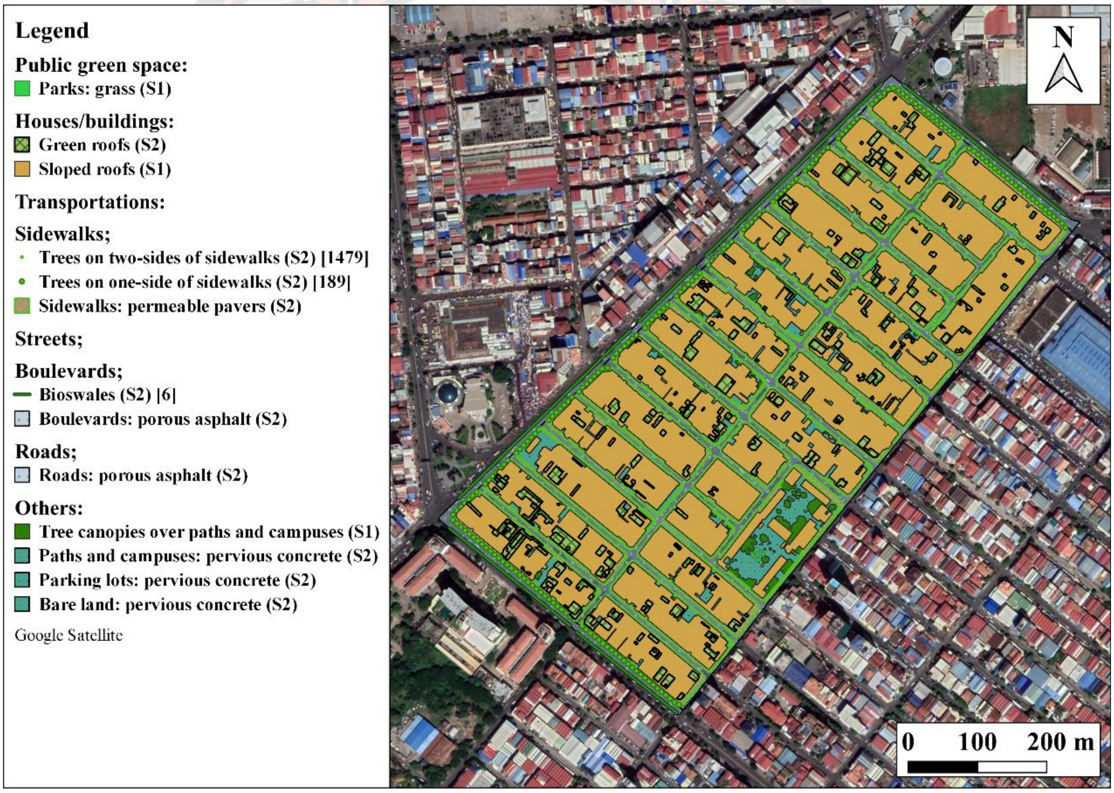


Figure 32 Map of land cover after the implementation of GI elements in scenario 2, Area A.

- The number of 1668 Tr was planted on sidewalks. There were two types of trees; Type b (radius of the canopy was 2.5 m, pit's size was 1 m²), and Type c (radius of the canopy was 3.5 m and pit's size was 2.25 m²). 1479 Tr of Type b were planted on 2- 4 m wide sidewalks; and 180 Tr of Type c were grown on wider sidewalks. Both types shared the 2/3 of total tree canopies over sidewalks and 1/3 of total tree canopies over the streets. In total, tree canopies and pits covered sidewalks by 6.76% of total area, and tree canopies spread over streets accounted for 3.38% of total area.

- About 0.49 % of the total area was replaced by Bios on streets (boulevards).
- Porous asphalt, pervious pavers, and pervious concrete were applied on streets, sidewalks, and parking lots, others (campuses, driveways, paths, and bare lands), accounting for 13.13%, 12.75%, 0.84%, and 3.87% of the total area, respectively.
- GR applied only on flat roofs with a ratio of 5.61 % of the total area.

Table 18 shows the area and percentage of single GI elements.

Table 18 Area and the percentage of GI elements in Area A.

Land covers			GI elements	Criteria	Area	Percentage
Unit					(ha)	(%)
Public green spaces:						
Parks		Grass	-	-	-	-
Houses /buildings:						
Roofs		Flat	Green roofs	Fully covered	2.01	5.61
		Sloped	-	-	-	-
Transportations:						
Sidewalks		Tree canopies	Tree canopies	Two-thirds of tree canopies	2.23	6.23
		Impervious pavers	Tree pits	Type b and c were placed 8 m each	0.19	0.53
			Pervious pavers	Subtraction of tree canopies and tree pits	4.57	12.75
Streets	Boulevards	Tree canopies	Tree canopies	One-third of total tree canopies	0.24	0.68
		Impervious asphalt	Porous asphalt	Subtraction of tree canopies and Bioswale area	1.12	3.12
			Bioswale	Total length (m) x 1.2 m	0.18	0.51
	Roads	Tree canopies	Tree canopies	One-third of tree canopies	0.97	2.70
		Impervious asphalt	Porous asphalt	Subtraction of tree canopies	3.58	10.01

Table 18 (Cont.)

Land covers		**GI elements**	**Criteria**	**Area**	**Percentage**
Others:					
Parking lots	Impervious concrete	Pervious concrete	Fully Covered	0.30	0.84
Paths and campuses	Tree canopies	-	-	-	-
	Impervious concrete	Pervious concrete	Fully covered	1.10	3.07
Bare land	Impervious concrete	Pervious concrete	Fully covered	0.29	0.80
Total				**16.77**	**46.86**

Note: (-) no GI elements implemented in scenario 2.

2) Area B

Figure 33 presents the map of changes in land covers with GI implementation in Area B. The single GI elements replaced the exiting impervious covers according to the criteria design as described below:

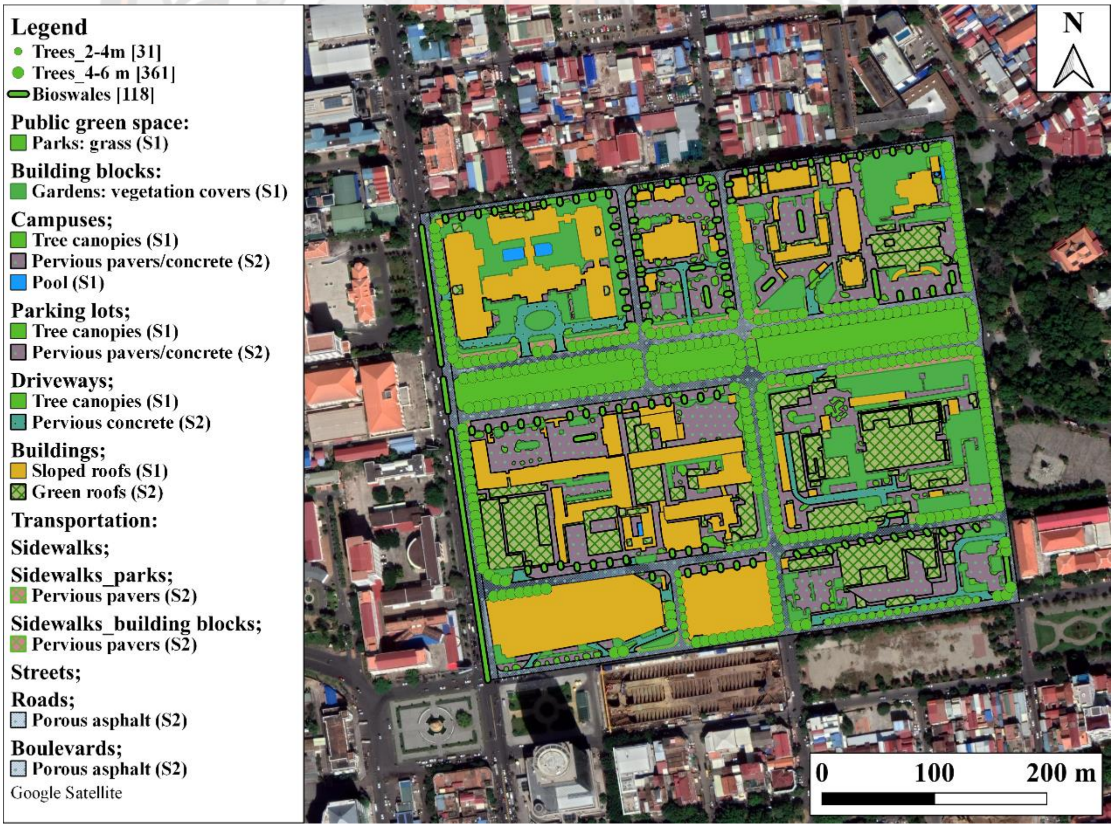


Figure 33 Map of land cover after the implementation of GI elements in scenario 2, Area B.

The area and percentage of single GI elements were derived. Due to the different sidewalk's widths, two tree types, Type b, and Type c were planted. About 31 Tr of Type b were planted on 2-4 m width of sidewalks and 361 Tr of type c were planted on those where the width is more than 4m wise. The tree canopies covered both sidewalks and the streets. They shared two-third and one-third of total tree canopies over sidewalks and streets, respectively. In total, sidewalks were covered by tree canopies and pits by 4.64% of the total area and approximately 2.32% of the total area covered tree canopies over the streets.

- Bios were applied on boulevards and parking lots. In parking lots, Bios with the sizes of 0.6 m x 3 m were placed, accounting for 0.21% and 0.14% of the total area for boulevards and parking lots, respectively.
- PP was applied 4.68% on sidewalks, 9.78% on streets, 7.49% on parking lots, and 15.26% on the other areas.
- Green roofs were applied on flat roofs, accounting for 12.02% of the total area in A.

Table 19 provides the area and the percentage of different land covers in Area B.

Table 19 Area and percentage of GI elements in Area B.

Land covers		**GI elements**	**Criteria**	**Area**	**Percentage**
Unit				(ha)	(%)
Public green spaces:					
Parks	Grasses	-	-	-	
Commercial and institutional building blocks:					
Gardens	Grasses and tree canopies	-	-	-	
Campuses	Tree canopies	-	-	-	
	Impervious concrete	Pervious concrete	Fully cover	2.53	12.14
	Pool: water	-	-	-	
Parking lots	Tree canopies	-	-	-	
	Impervious concrete	Pervious concrete	Subtraction of Bios area	1.56	7.49
		Bioswale	Total length (m) x 0.6 m	0.03	0.14
Buildings	Flat roofs	Green roofs	Fully cover	2.51	12.02
	Sloped roofs	-	-	-	-

Table 19 (Cont.)

Land covers			**GI elements**	**Criteria**	**Area**	**Percentage**
Unit					(ha)	(%)
Transportations:						
Sidewalk		Tree canopies	Tree canopies	Two-thirds of tree canopies	0.88	4.23
		Impervious pavers	Tree pits	Type b and c were placed 8 m each	0.09	0.41
			Pervious pavers	Subtraction of tree canopies and tree pits	0.98	4.67
Streets	Boulevards	Tree canopies	Tree canopies	One-third of total tree canopies	0.04	0.20
		Impervious asphalt	Porous asphalt	Subtraction of tree canopies and Bioswale area	0.27	1.31
			Bioswale	Total length (m) x 1.2 m	0.04	0.21
	Roads	Tree canopies	Tree canopies	One-third of tree canopies	0.44	2.12
		Impervious asphalt	Porous asphalt	Subtraction of tree canopies	1.76	8.47
Total					**10.22**	**56.53**

Note: (-) no GI elements implemented in scenario 2.

3) Area C

Figure 34 shows the map of land covers after the implementation of GI elements in Area C. The percentage of each GI element given in **Table 20**.

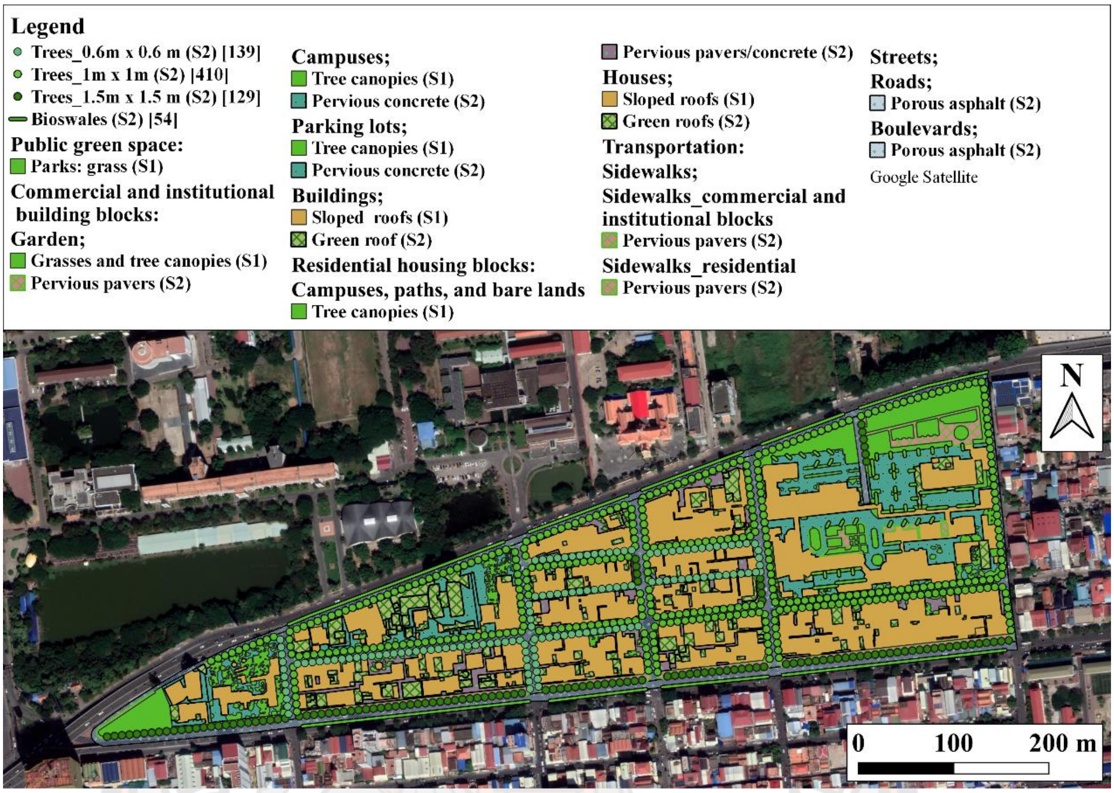


Figure 34 Map of land covers after the implementation of GI elements in scenario 2, Area C.

- Three types of Tr were applied on sidewalks: Type a, Type b, and Type c. About 139 Tr of Type a were planted with a pit size of 0.36 m² and a canopy of 1.8 m radius each. There were 410 Tr grown as Type b. About 129 Tr of Type c were planted. Type a was selected for sidewalks which were less than 2 m wide while Type b and Type c were selected for sidewalks with a width of 2-4 m and more than 4 m, respectively. Since two-third of tree canopies was covered over sidewalks, the ratio of integrated canopies with pits was 7.77 % of the total area. One-third of tree canopies over the streets (boulevards and roads) accounted for 2.46 % of the total area.
- Bios was applied to parking lots and streets. A size of 0.6 m x 5 m x 15 m Bios was placed along parking lots. Bios were also placed along streets by replacing the existing median concrete barriers. They covered about 0.85% of the total concrete barriers.
- PP was applied on various land covers such as sidewalks by 2.69%, streets by 10.58%, parking lots by 4.95%, and others by 9.06% of the total areas;
- GR was applied on flat roofs with 7.14 % of the total area.

Table 20 Area and percentage of GI elements in Area C.

Land covers		GI elements	Criteria	Area	Percentage
Unit				(ha)	(%)
Public green spaces:					
Parks	Grasses	-	-	-	-
Commercial and institutional building blocks:					
Gardens	Grasses and tree canopies	-	-	-	-
	Impervious pavers	Pervious pavers	Fully covered	0.27	1.40
Campuses	Tree canopies	-	-	-	-
	Impervious concrete	Pervious concrete	Fully covered	1.00	5.11
Parking lots	Tree canopies	-	-	-	-
	Impervious concrete	Pervious concrete	Subtraction of Bios area	0.96	4.95
		Bioswale	Total length (m) x 0.6 m	0.03	0.14
Buildings	Flat roofs	Green roofs	Fully covered	0.53	2.75
	Sloped roofs	-	-	-	-
Residential housing blocks:					
Campuses, paths, and bar lands	Tree canopies	-	-	-	-
	Impervious concrete/pavers	Pervious concrete/pavers	Fully covered	0.77	3.95
Roofs	Flat	Green roofs	Fully covered	0.86	4.39
	Sloped	-	-	-	-
Transportations:					
Sidewalks	Tree canopies	Tree canopies	Two-thirds of tree canopies	1.44	7.39
	Impervious pavers	Tree pits	4 m², placed 8 m each	0.08	0.38
		Pervious pavers	Subtraction of tree canopies and tree pits	0.52	2.69
Streets:					
Boulevards	Tree canopies	Tree canopies	One-third of total tree canopies	0.22	1.14

Table 20 (Cont.)

Land covers		GI elements	Criteria	Area	Percentage
Unit				(ha)	(%)
	Impervious asphalt	Porous asphalt	Subtraction of tree canopies and Bioswale area	1.08	5.54
		Bioswale	Total length (m) x 1.2 m	0.17	0.85
Roads	Tree canopies	Tree canopies	One-third of tree canopies	0.25	1.32
	Impervious asphalt	Porous asphalt	Subtraction of tree canopies	0.98	5.04
Total				**9.17**	**43.10**

Note: (-) no GI elements implemented in scenario 2.

4.3.2. Characteristics of GI elements implemented in Area A, Area B, and Area C

Figure 35, **Figure 36**, and **Figure 37** display the characteristics of GI elements applied in a variety of land cover in Area A, Area B, and Area C, respectively. The ratios of GI elements replaced the impervious cover in the existing land covers such as flat roofs, sidewalks, streets, parking lots, and others are shown in **a**. The percentages of single GI elements compared to those of combined GI are presented in **b**. The share of the surface's permeability is presented in **c**.

1) Area A

In Area A (**Figure 35, a** and **b**), the share of individual GI elements is described below:

- 6.76% of the total area was planted by Tr on sidewalks and 3.38% of the total area was covered by tree canopies over streets. Tr shared 21.64% of combined GI elements;
- Bios was applied to 0.51% of streets, accounting for 1.08 % of the combined GI elements;
- Streets (13.13%), sidewalks (12.75%), others (3.87%), and parking lots (0.84%) of the total area were installed by PP. They accounted for 65.30 % of combined GI elements;
- GR was applied to flat roofs account for 5.61% of the total area, equal to 21.65 % of combined GI elements.

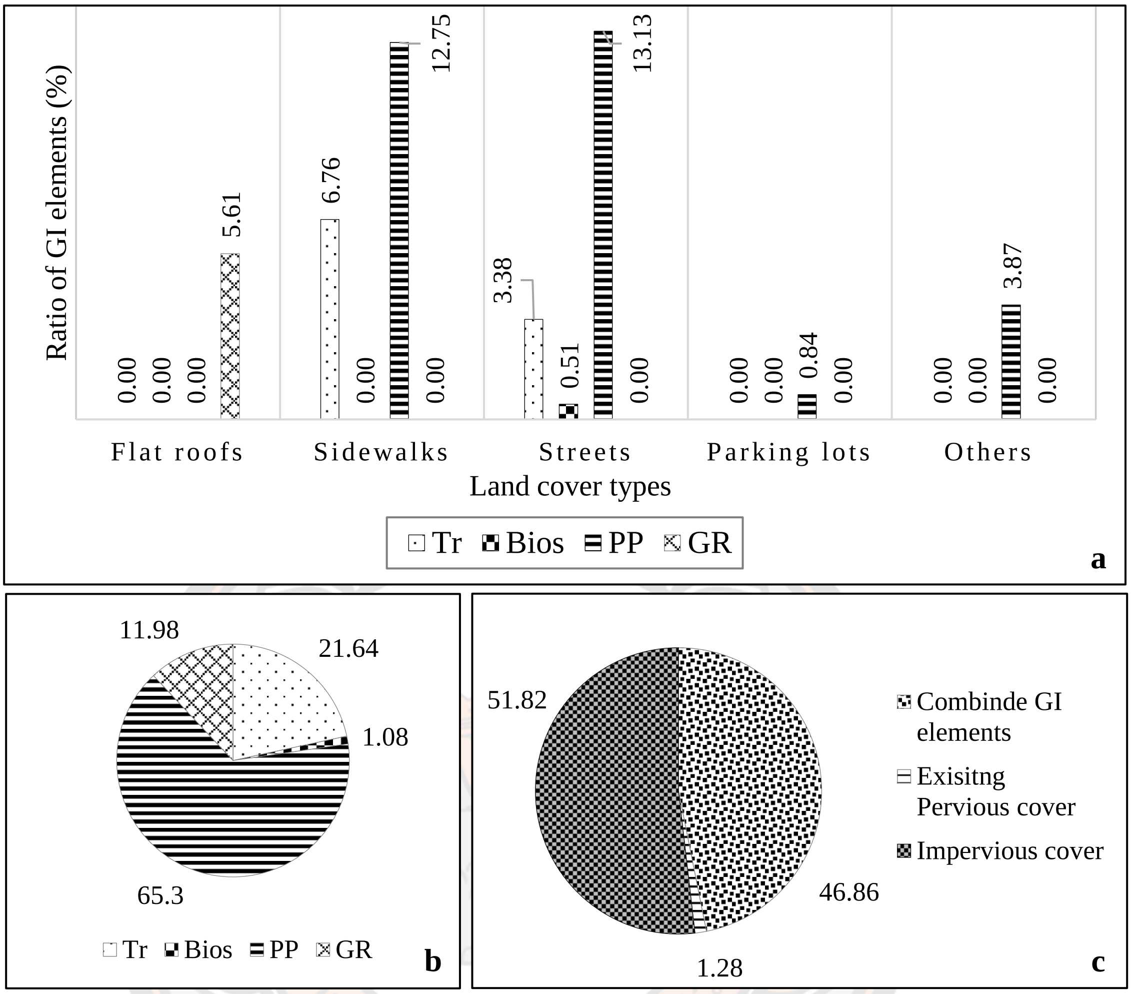


Figure 35 The characteristic of GI elements applied in a variety of land cover in Area A. The ratio of GI elements replaced the impervious covers in exiting land covers (a), The percentages of single GI elements compared to those of combined GI elements (b), the percentages of pervious and impervious surfaces (c).

Note: Tr = Trees, Bios = Bioswales, PP = Permeable pavements, GR= Green roofs.

The implementation of GI changed the percentage of surface's permeability in Area A. The pervious surface increased to 48.14% by the integration of combined GI (46.86%) and the exiting pervious surface (1.28%), and 51.82% of impervious cover (sloped roofs) as shown in **Figure 36, c**.

2) Area B

Figure 36 a and **b** illustrates the implementation of a single GI element as below:

- Tr was planted on sidewalks. They covered 4.64% of the sidewalk area and 2.32% of the total street area. Tr shared 14.19% of combined GI elements;

- Bios were installed by 0.21% and 0.14% of street area t and parking lots. Bios equaled to 0.72% of combined GI elements;
- PP was constructed on various land covers, including others (15.26%), streets (9.78%,), parking lots (7.49%), and sidewalks (4.68%). They accounted for 60.68 % of combined GI elements;
- GR was constructed to flat roofs. It accounted for 12.02% of the total area or equaled to 24.51 % of combined GI elements.

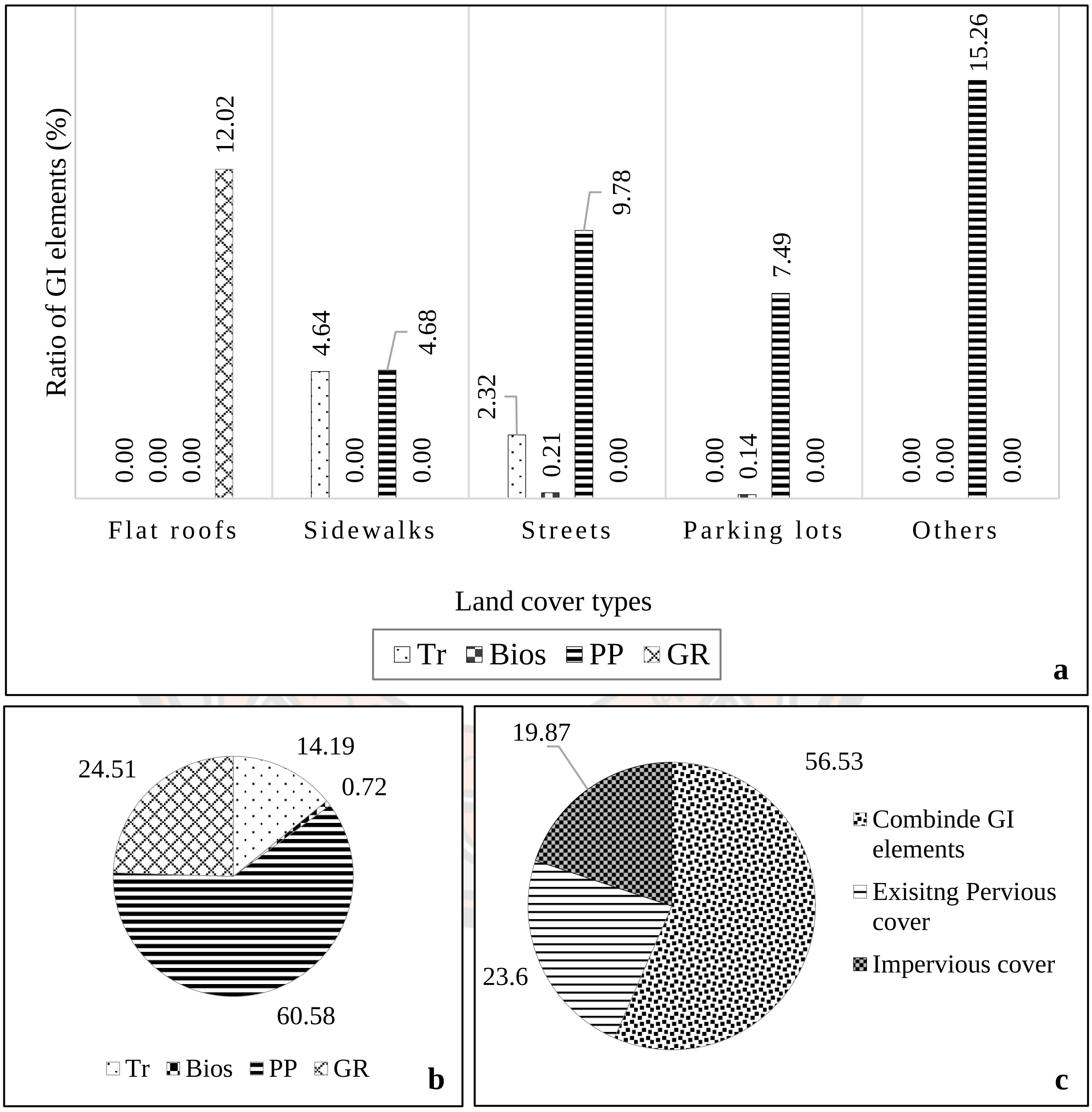


Figure 36 The characteristic of GI elements applied in a variety of land cover in Area B. The ratio of GI elements replaced the impervious covers in exiting land covers (a), The percentages of single GI elements compared to those of combined GI elements (b), the percentages of pervious and impervious surfaces (c).

Note: Tr = Trees, Bios = Bioswales, PP = Permeable pavements, GR= Green roofs

The percentage of pervious surfaces applied in Area B ÷ were 56.53% of combined GI elements, 23.60% of exiting pervious cover (tree canopies and grass), and 19.87% of impervious cover (sloped roofs) as shown in **Figure 37, c**.

3) Area C

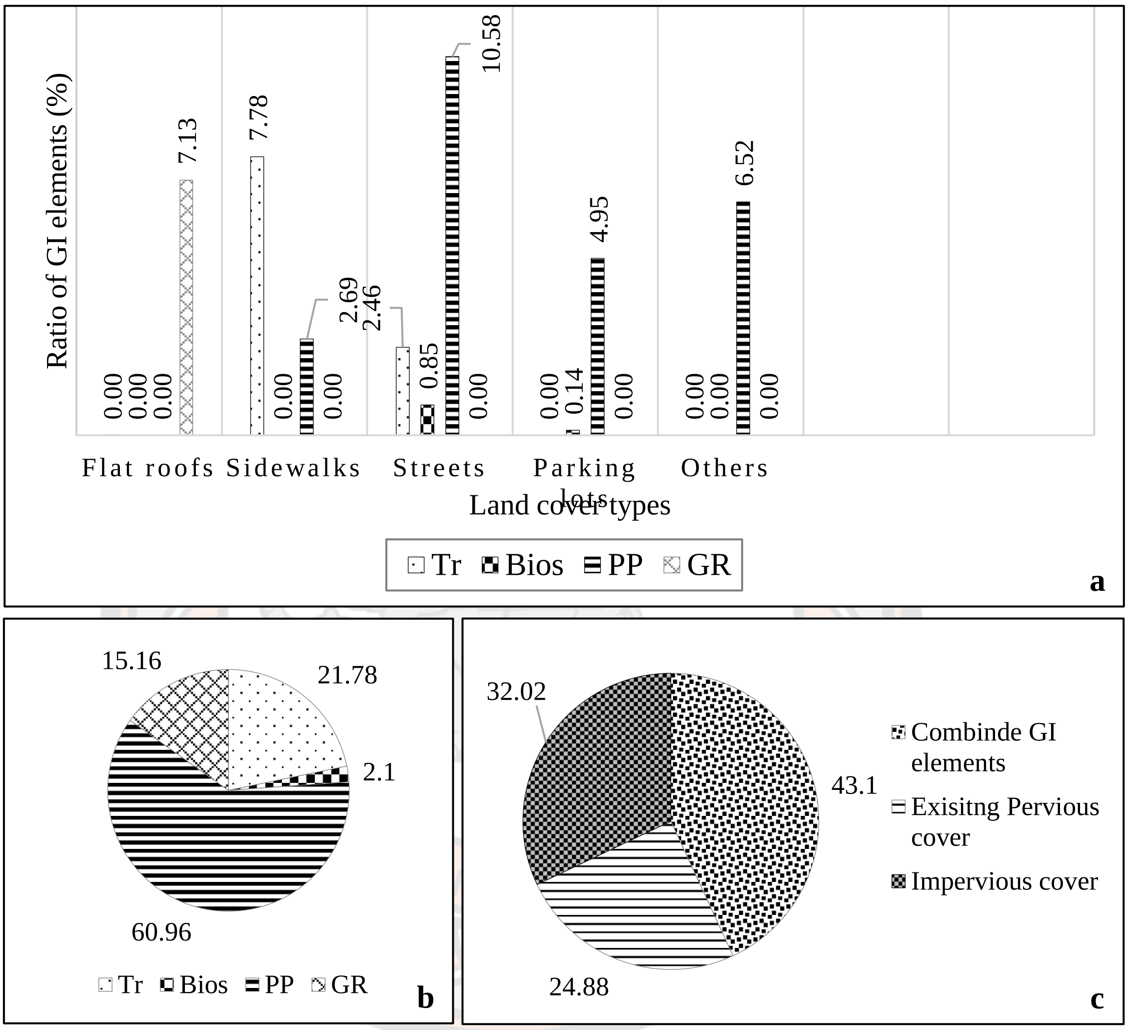


Figure 37 The characteristic of GI elements applied in a variety of land cover in Area C. The ratio of GI elements replaced the impervious covers in exiting land covers (a), The percentages of single GI elements compared to those of combined GI elements (b), the percentage of pervious and impervious surfaces (c).

Note: Tr = Trees, Bios = Bioswales, PP = Permeable pavements, GR= Green roofs.

Figure 37a and **b** identify the implementation of single GI elements in Area C described below:

- Sidewalks took 7.13% of the total area. They were applied with Tr. The canopies were covered over the streets by 2.46% of the total area. Tr shared 21.64% of combined GI elements;

- Bios was applied to the streets by 0.85% and parking lots by 0.14% of the total area. Bios equal to 2.1% of combined GI elements;
- 10.58%, 6.52%, 4.95%, and 2.69% of the total area were replaced by PP to the streets, others, parking lots, and sidewalks, respectively. They accounted for 60.96 % of combined GI elements;
- GR was applied to flat roofs account for 7.13% of the total area, accounted for 15.16 % of combined GI elements.

In Area C, the percentage of the pervious surface increased due to the application of GI element by 67.89%; 43.10% of combined GI elements or24.88% of exiting pervious cover as shown in **Figure 37, c.**

The proportion of GI elements to combined GI elements (**Figure 38**) was compared between Area A, B, and C, as briefed below:

- PP played the main role among the four elements (60 – 65% of the combined GI, while Bios had the least application in the three areas;
- PP was the most applicable element for Area A, comparing to Area B and C;
- Tr and Bios were the most applicable elements for Area C but they are the least applicable elements for Area B;
- GR had the most coverage in Area B, but the least in Area A.

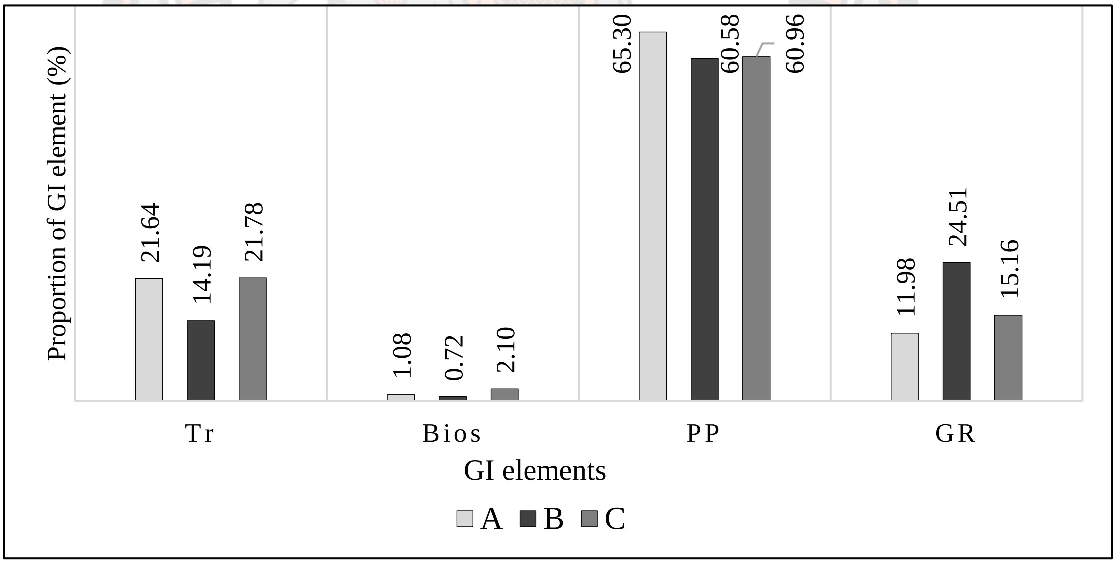


Figure 38 Ratio of GI elements to combined GI elements between Area A, Area B, and Area C

4.3.3. Peak runoff rate (Q’)

Peak runoff rate (Q’) was attained in scenario 2 (S2). **Table 21** shows peak runoff rate (Q’) of GI elements in Area A, Area B, and Area C. Q’ in S2 of public green spaces and sloped roofs had the same value as in S1.

- Area A: The total peak runoff rate in A was 2.80 m^3/s. Sloped roofs created the highest runoff volume, followed by sidewalks and streets. Flat roofs and parking lots created only a small volume of runoff while the pubic green spaces almost had no runoff, only 0.0001 m³/s.

- Area B: Streets had the third-largest share of runoff volume. The other land covers, such as flat roofs and sidewalks had similar runoff volume, followed by parking lots, and public green spaces. The total peak runoff rate was 0.95 m³/s in B.
- Area C: The total peak runoff rate in C was 1.11 m³/s. Runoff volume of sidewalks was in the second rank after sloped roofs, followed by streets, others, and flat roofs. Like Area A and Area B, public green spaces and parking lots produced a very small amount of runoff.

Table 21 Peak runoff rate (Q') in Area A, Area B, and Area C for a 2-years storm return period.

Land covers	**A**	**B**	**C**
Unit	m³/*s*	m³/*s*	m³/*s*
Public green spaces	0.0001	0.04	0.03
Flat roofs	0.06	0.08	0.05
Sloped roofs	2.19	0.49	0.74
Sidewalks	0.28	0.08	0.11
Streets	0.20	0.09	0.083
Parking lots	0.01	0.0604	0.021
Others: Campuses, driveways, paths, and bare lands	0.07	0.11	0.08
Total	**2.80**	**0.95**	**1.11**

Differences in runoff characteristics of three different land-uses (**Figure 39**) were described below:

- For a residential land-use, Area A, a vast of runoff produced from the sloped roof and sidewalks.
- For a commercial land-use, Area B had a larger runoff from public green spaces, flat roofs, streets, parking lots, and the Others.
- For a mixed land-use, Area C, the runoff rate created from each land cover is similar.

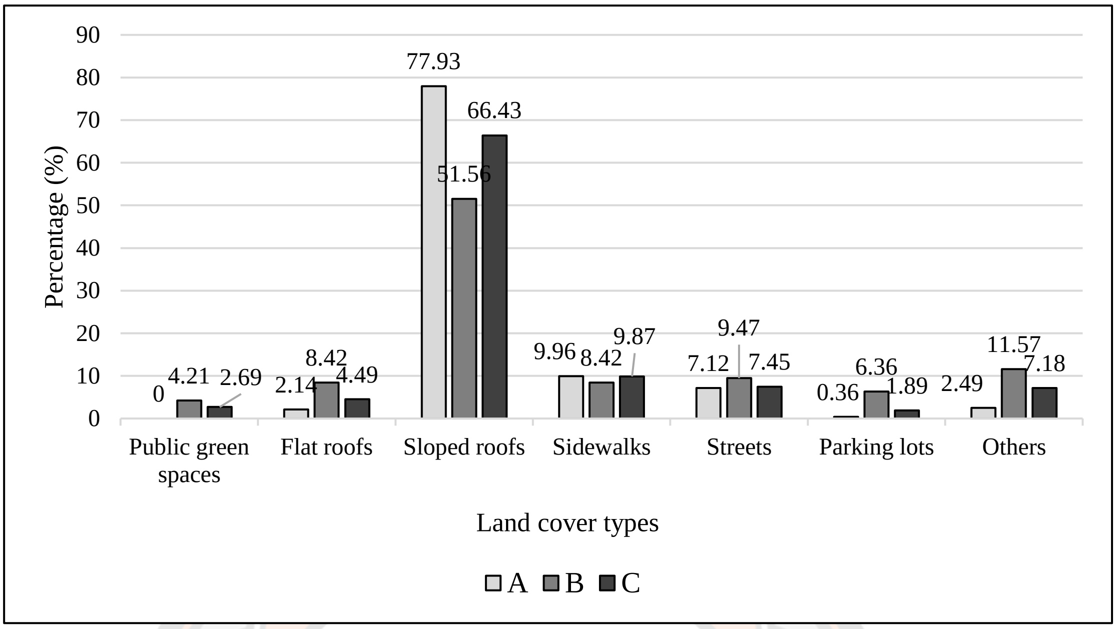


Figure 39 Percentage of runoff rate (Q') relevant to various land covers between Area A, Area B, and Area C.

4.4. Scenario 1 and 2

4.4.1. Peak runoff reduction

Runoff reduction is derived from comparing the peak runoff rate between scenarios 1 and 2. The replacement of existing impervious covers by combined GI element integrates with exiting pervious covers give the total reduction in A, B, and C.

1) Area A

The peak runoff rate and the ratio of single GI elements implemented in Area A are shown in **Table 22**.

Table 22 Peak runoff rate (m^3/s) and the runoff reduction (%) performed by GI elements replaced on relevant land covers in Area A.

Scenario	**S1**	**S2**			**S1-S2**	
Item (unit)	Q (m^3/s)	GI elements	(%)	Q (m^3/s)	Q (m^3/s)	(%)
Public green spaces	0.0001			0.0001	0	0.00
Flat roofs	0.19	GR	5.61	0.06	0.13	10.66
Sloped roofs	2.19			2.19	0	0.00
Sidewalks	0.73			0.27	0.45	36.89
		Tr	6.76	0.13		17.76
		PP	12.75	0.14		19.12

Table 22 (Cont.)

Scenario	**S1**	**S2**			**S1-S2**	
Item (unit)	Q (m³/s)	GI elements	(%)	Q (m³/s)	Q (m³/s)	(%)
Streets	0.68			0.20	0.48	39.34
		Tr	3.38	0.07		13.77
		Bios	0.51	0.002		0.40
		PP	13.13	0.13		25.57
Parking lots	0.03	PP	0.84	0.01	0.02	1.64
Others	0.21	PP	3.87	0.07	0.14	11.48
Total	4.0301		46.86	2.80	1.23	100
Reduction						**30.52**

The results of runoff reduction from various impervious covers were described below:

- Tr accounted for 10.14% of the total area or 21.64% of combined GI, applied on sidewalks by 6.76%, and on streets by 3.38%. They reduced runoff 17.76% and 13.77% of the total runoff reduction from sidewalks and streets, respectively;
- Bios were applied on streets, accounting for 0.51% of the total area, and equivalent to 1.08 % of combined GI elements. Bios reduced runoff by 0.40% of the total runoff reduction.
- About 30 % of PP was applied on sidewalks (12.75%), streets (13.13%), parking lots (0.84%), and others (3.87%). PP accounted for 65.30 % of combined GI elements and they reduced runoff from sidewalks, streets, parking lots, and others by 19.12%, 25.57%, 1.64%, and 11.48% of total runoff reduction, respectively.
- Green roofs were applied on 5.61% of flat roofs, equivalent to 11.98 % of combined GI elements and reduced runoff by 10.66% of the total runoff reduction.

The percentage of impervious surfaces decreased due to the presence of GI elements. In S1, 95.97% of the impervious cover was reduced to 51.82% in S2 by the implementation of 46.86% of combined GI elements in Area A. A 44.15% decrease in impervious surfaces, stormwater was reduced by 30.52%, contributing to 1.23 m³/s reduction for a 2-years storm return period.

2) Area B

Table 23 illustrates the peak runoff rate and ratio reduction performed by GI elements replaced relevant impervious covers.

Table 23 Peak runoff rate (m^3/s) and the runoff reduction (%) performed by GI elements replaced on relevant land covers in Area B.

Scenario	**S1**	**S2**			**S1-S2**	
Item (unit)	Q (m^3/s)	GI elements	(%)	Q (m^3/s)	Q (m^3/s)	(%)
Public green spaces	0.04			0.04	0	0.00
Flat roofs	0.23	GR	12.02	0.11	0.12	16.50
Sloped roofs	0.49			0.49	0	0.00
Sidewalks	0.20			0.08	0.12	13.20
		Tr	4.64	0.05		8.25
		PP	4.68	0.03		4.95
Streets	0.28			0.0907	0.19	20.83
		Tr	2.32	0.03		6.89
		Bios	0.21	0.0007		0.16
		PP	9.78	0.06		13.78
Parking lots	0.21			0.0604	0.15	16.46
		Bios	0.14	0.0004		0.11
		PP	7.49	0.06		16.35
Others	0.41	PP	15.26	0.11	0.3	33.01
Total	1.87		56.53	0.95	0.91	100
Reduction						**48.87**

Here is how single GI elements performed in B:

- Tr was planted, accounting for 6.96% of the total area, or equaled to 14.19% of combined GI. Tr was applied on sidewalks 4.64% and streets 2.32%. They reduced runoff by 8.25 % and 6.89% of the total runoff reduction from sidewalks and streets, respectively;
- Bios was applied on streets (0.21%) and parking lots (0.0004%) of the total area, accounting for 0.72% of combined GI elements. They reduced runoff 0.16 % from streets and 0.11% from parking lots.
- 37.21% of the total area was implemented with PP, equivalent to 60.58 % of the combined GI elements. PP was applied on sidewalks (4.68%), streets (9.78%), parking lots (7.49%), and other land covers (15.26%). They accordingly reduced runoff by 4.95%, 13.78%, 16.35%, and 33.01% respectively.
- Green roofs were applied on flat roofs (12.02%), equivalent to 24.51 % of the combined GI elements. They reduced runoff by 16.50% of total runoff reduction.

Impervious surfaces decreased from 72.6% to 19.87% after 56.53% of GI elements were implemented. The amount of 0.91 m^3/s of peak runoff was reduced when 52.73% of impervious covers were replaced. Finally, 48.87% of peak runoff rate was reduced by combined GI elements for a 2-years storm return period.

3) Area C

The peak runoff rate and the share of individual GI elements implemented in C are shown in **Table 24**.

Table 24 Peak runoff rate (m³/s) and the runoff reduction (%) performed by GI elements replaced on relevant land covers in Area C.

Land cover	**S1**	**S2**			**S1-S2**	
Item (unit)	Q (m³/s)	GI elements	(%)	Q (m³/s)	Q (m³/s)	(%)
Public green spaces	0.03			0.03	0	0.00
Flat roofs	0.13	GR	7.13	0.05	0.08	11.32
Sloped roofs	0.74			0.74	0	0.00
Sidewalks	0.21			0.11	0.1	14.15
		Tr	7.78	0.09		11.58
		PP	2.69	0.02		2.57
Streets	0.30			0.083	0.217	30.71
		Tr	2.46	0.02		7.40
		Bios	0.85	0.003		1.11
		PP	10.58	0.06		22.20
Parking lots	0.12			0.0204	0.099	14.10
		Bios	0.14	0.0004		0.28
		PP	4.95	0.02		13.82
Others	0.29	PP	6.52	0.08	0.21	29.72
Total	1.82		43.10	1.11	0.71	100
Reduction						**38.82**

The results of runoff reduction from various impervious covers were described below:

- Tr was applied on sidewalks by 7.78% and on the streets by 2.46% of the total area. Its application equals to 21.78% of combined GI and helps to reduce runoff by 11.58% and 7.40% of total runoff reduction from sidewalks and streets.
- Bios were applied on streets by 0.85% and parking lots by 0.14% of the total area which equivalent to 2.1% of combined GI elements. Bios reduced runoff by 1.11% from streets and 0.28% from parking lots of total runoff reduction.
- 24.74% of PP was applied in different areas, equivalent to 60.96% of combined GI elements. PP on sidewalks, streets, parking lots, and other land cover reduced runoff 2.57%, 22.20%, 13.82%, and 29.72% of the total runoff reduction, respectively.

- Green roofs were applied on flat roofs for 7.13%, equivalent to 15.16% of the combined GI elements. Green roofs reduced runoff by 11.32% of the total runoff reduction.

The implementation of 43.10% of combined GI elements in S2 reduced impervious covers by 42.68% (from 74.7% to 32.02%). GI minimized the peak runoff rate from 1.82 m³/s to 1.11 m³/s. As a result, the overall reduction was 38.82%, accounting for 0.71 m³/s in C.

The largest runoff reduction of runoff is found for Area B, followed by Area C and Area A, representing 48.87%, 38.82%, and 30.52%, respectively.

4.4.2. The effectiveness of GI elements

1) Single GI elements

The effectiveness of single GI elements obtained from the comparison of the ratio of single GI elements to the ratio of peak runoff reduction performed by single GI elements. The results of the weight of each element indicate their effectiveness in Area A, B, and C.

Table 25 shows the weight of GI elements and the percentage of peak runoff reduction in Area A. The effectiveness of the GI elements was in order: Tr>PP=GR>Bios. Tr performed the best (weight ≥ 1) for Area A. PP and GR showed high performance (0.75 ≤ weight < 1), while Bios had poor performance (weight < 0.50).

Table 25 Weight of single GI elements in Area A

Single GI elements (%)		Reduction (%)	Weight
Tr	21.64	31.67	1.46
Bios	1.08	0.39	0.35
PP	65.3	57.77	0.88
GR	11.98	10.57	0.88

Table 26 illustrates the weight of GI elements and the percentage of peak runoff reduction in Area B. The effectiveness of the GI elements was in order: PP>Tr>GR>Bios. Tr and PP were the two best elements (weight ≥ 1) in Area B for minimizing runoff. GR moderately performed (0.50 ≤ weight < 0.75) while Bios had the lowest performance (weight < 0.50).

Table 26 Weight of single GI elements in Area B.

Single GI elements (%)		Reduction (%)	Weight
Tr	14.19	15.14	1.07
Bios	0.72	0.72	0.37
PP	60.58	60.58	1.12
GR	24.51	24.51	0.67

Table 27 shows the weight of GI elements and the percentage of peak runoff reduction in Area C. The effectiveness of the GI elements was in order: PP>Tr>GR>Bios. The best element (weight ≥ 1) in Area C was PP. Other elements that had high performance (0.75 ≤ weight < 1) were Tr and GR. Bios had the moderate performance (0.50 ≤ weight < 0.75) for runoff mitigation.

Table 27 Weight of single GI elements in Area C.

Single GI elements (%)		Reduction (%)	Weight
Tr	21.78	18.98	0.87
Bios	2.1	1.39	0.66
PP	60.96	68.31	1.12
GR	15.16	11.32	0.75

As a result, the effectiveness of single GI elements valued by the weight between the three areas (**Figure 40**) was acquired as briefed below:

- The best elements among these four elements were Tr and PP.
- Tr performed best in Area A and B and had a high performance in Area C.
- PP reduced runoff the best in Area B and C, and also had a high performance in Area A;
- GR had a high performance in Area A and C, but it moderately reduced for Area B;
- Bios had low performance in Area A and B, but it was at a moderate level in Area C for decreasing runoff.

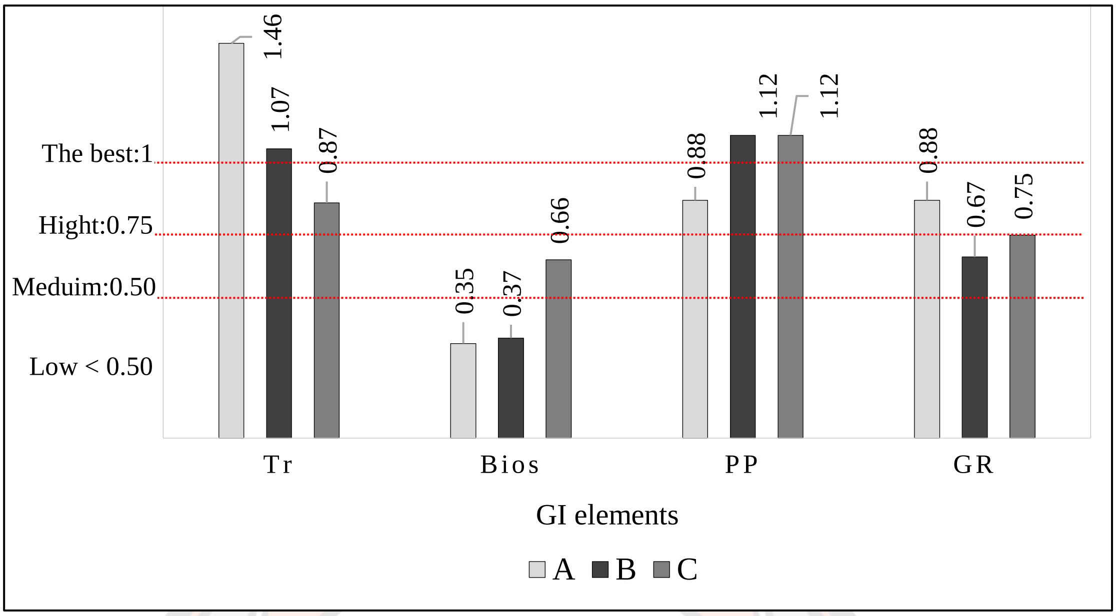


Figure 40 The weight of single GI elements in Area A, Area B, and Area C.

2) Combined GI elements

The effectiveness of combined GI elements was evaluated by computing the weight of combined GI elements. The ratio of combined GI elements and the ratio of peak runoff reduction of combined GI elements were compared. **Table 28** shows the weight of combined GI elements the weights in A, B, and C.

Table 28 Weight of combined GI elements in Area A, Area B, and Area C.

Items	**A**	**B**	**C**
Combined GI elements (%)	46.86	56.53	43.10
Runoff reduction performed by combined GI (%)	30.52	48.87	38.82
Weight	**0.65**	**0.86**	**0.90**

In overall, the total peak runoff was reduced by 30.52% (1.23 m^3/s), 48.87% (0.91 m^3/s), and 38.82% (0.71 m^3/s) due to the application of 46.86 %, 56.53%, and 43.10% of combined GI elements in Area A, Area B, and Area C, respectively. The largest weight of combined GI elements was in Area C (0.90), followed by Area B (0.86), and Area A (0.65).

Therefore, the effectiveness of combined GI elements between the three areas was obtained. Area B and Area C have a good performance to reduce stormwater runoff ($0.75 \leq$ Weight < 1), while Area A had moderate performance ($0.50 \leq$ Weight < 0.75).

CHAPTER V

DISCUSSION AND CONCLUSIONS

The chapter summarizes the key findings and highlights the performance of GI elements for urban peak runoff mitigation in the tropical climate. It also suggests key issues for the future researches and limitations of this dissertation.

5.1. The performance of GI elements in different land uses in Phnom Penh

5.1.1. GI application for residential land-use

Area A, a typical residential land use, is characterized by 2-4 stories attached houses and a high percentage of diverse impervious covers. The diverse impervious covers mainly include roofs (sloped and flat), sidewalks, and streets with the small share of paths, driveways, parking lots, and bare land. These impervious covers have a different amount of surface coverage. The sloped roofs appear in the largest part of impervious covers is more than half (51.82%) of the total area. The second and third largest land covers are sidewalks (105) and streets (10%). The public green spaces have the smallest share, less than 1%. Overall, Area A composed of impervious covers to pervious cover with a ratio of 9.5:0.5.

In scenario 2, GI elements are implemented to decrease runoff and their application is varied according to the existing land covers in Area A. Permeable pavements are most applicable in Area A because it can be employed in sidewalks, streets, parking lots, and several land covers, such as paths, campuses, and bare lands. Permeable pavements account for 65% of the combined GI elements. The second most applicable is trees, accounting for 25% since they are suitable only in some parts of streets and sidewalks. Trees are planted on one-third of sidewalks and one-fifth of streets. The third most applicable element is green roofs, with a share of 10% because they are applied only on flat roofs. The least applicable element is bioswales which take a share of only 1% of the combined GI due to a lack of the boulevards in a residential area.

In total, almost half (46.86%) of the total area was applied by GI elements and 30.52% of the total runoff was reduced from scenario 1. The most and least effective elements are measured by their weight levels (**Figure 41**). The results show that trees are the most important element among the four GI elements due to their highest weight, which is more than one. Permeable pavements and green roofs have high scores. Permeable pavements have the largest share, accounting for 65% of the combined GI elements, but they reduced runoff only 5.5%. In contrast, bioswales show the lowest level of performance because they are least applicable. They, therefore, reduced the smallest amount of runoff.

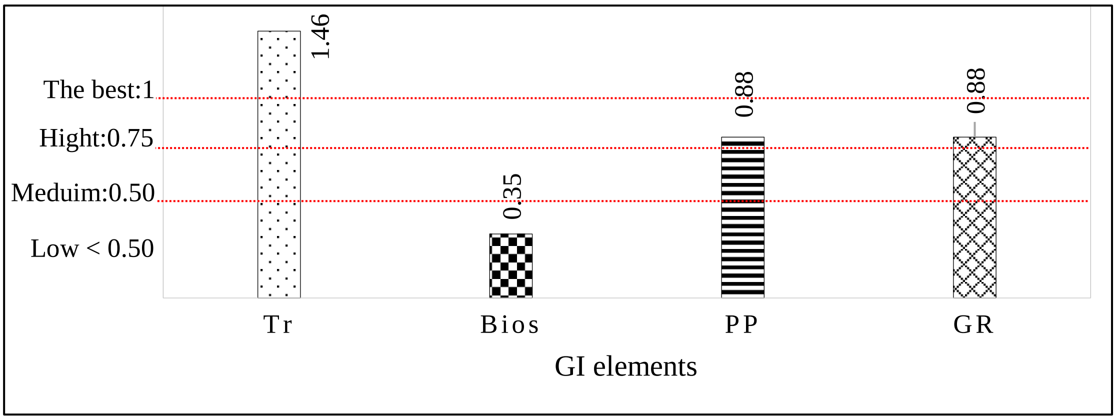


Figure 41 The weights of single GI elements in Area A.

5.1.2. GI application for commercial land-use

Area B represents a typical commercial and institutional land uses. It consists of commercial buildings, campuses, and parking lots, covering about 70 – 75 % of the impervious surface. Area B is extensively dominated by public green spaces, flat roofs, and parking lots. Each land cover accounts for 30% of the They take a ratio of the total area.

All four GI elements are applied in this land-use. Permeable pavements are the most applicable element with a 60% share of the combined GI. The high percentage of coverage is attributed to the large proportion of sidewalks and streets (boulevards and roads) in this area, enabling the application of permeable pavements on both land covers. Green roofs are the second most applicable element. They account for 25% of the combined GI due to the large share of flat roofs in this land-use. The third one is trees, with a ratio of 1:10 to the combined GI. The least applicable element is bioswales due to the narrow space available along streets, the same as in Area A. In total, more than half (56.54%) of the total area was covered by GI elements in scenario 2 and almost half (48.86%) of the total runoff was reduced from scenario 1.

The results show that trees and permeable pavements are the most effective elements since their weights (**Figure 42**) are more than one. The underlying cause is that their wide application on sidewalks and the other land covers, accounting for 20% of the total area. Importantly, they are able to reduce runoff up to one-third (33.01%) of the total reduction. Green roofs are considered as having moderate performance. Despite the large share of green roofs, which account for 65% of the combined GI, they only reduced runoff by 5.5%. Bioswales also had poor performance because their coverage was the lowest. Their capacity in runoff reduction is therefore low.

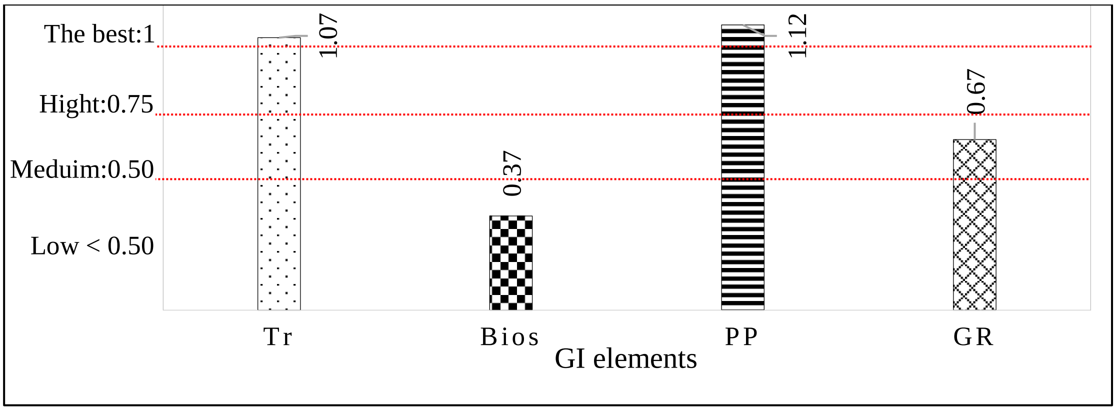


Figure 42 The weights of single GI elements in Area B.

5.1.3. GI application for mixed land-use

A typical mixed land-use (Area C) is characterized by a combination of residential and commercial land-uses. The area consists of roofs (40%), followed by and public green spaces (20%). Streets, sidewalks, and the other land covers account for 10% each. Land cover that has the least coverage is parking lots, only 5% to the total area. Overall, impervious covers account for 66.7% of Area C.

Permeable pavements are the most applicable GI element due to a large area of sidewalks, street, and parking lots for replacing with permeable materials. Consequently, permeable pavements took a share of 60% to the combined GI elements. The second most applicable element is trees, accounting for 20%. Like permeable pavements, trees are largely planted on streets and sidewalks, resulting in their high proportion. The third most applicable element is green roofs, with a share of 15% due to the presence of some housing large buildings with flat roofs in this area. The least applicable element is bioswales (2%) due to the limited space of boulevards.

In total, the combined GI elements are implemented by 43.10% of Area C and the runoff is mitigated by 38.82%. Considering each element that reduces runoff compares to their application, the weight of each element is derived (**Figure 43**). The best GI element in Area C is Permeable pavements due to their large coverage and efficiency in runoff reduction. Tree and green roofs are considered as a high performance. They approximately reduce runoff by 2:10 (trees) and by 1:10 (green roofs) of total reduction and their application up to 3.5:10 of combined GI elements. The last element, bioswales, had the poorest performance because of its small area of application.

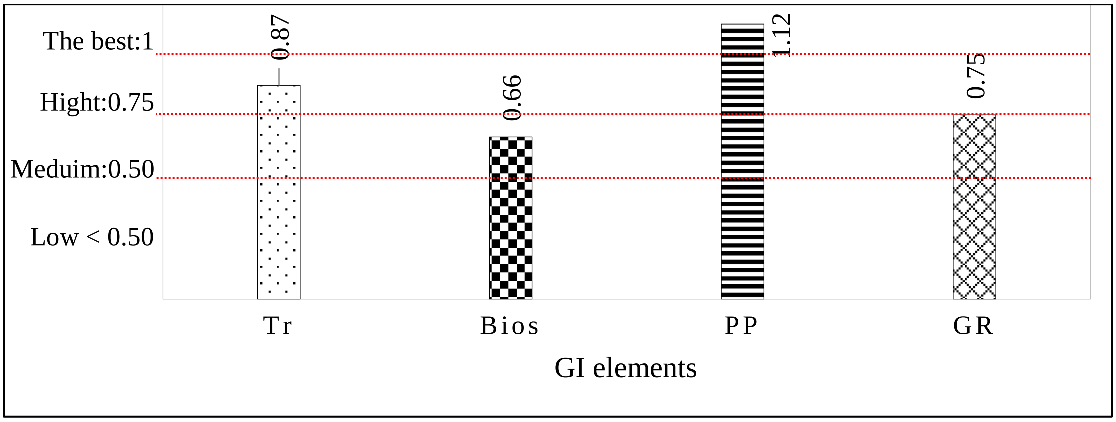


Figure 43 The weight of single GI elements in Area C.

5.2. The performance of GI elements between the three land-uses

The performance of GI elements in different land-uses was investigated by estimating the runoff reduction corresponding to the capacity of relevant existing land covers. For a residential land-use, Area A is extensively covered by sloped roofs, sidewalks, and streets. Accordingly, permeable pavements were the most applicable GI element in Area A. On the other hand, green roofs were the most inapplicable element. For commercial land-use, Area B has a larger share of public green spaces, flat roofs, and parking lots, comparing to Area A and C. Therefore, green roofs can be largely applied in Area B while trees and bioswales are less applicable. For a mixed land-use, comparing to Area A and B, Area C has no distinctive land covers. However, it is recorded that trees and bioswales are applicable in the majority of Area C. Briefly, permeable pavements play the main role among the four elements (60 – 65% of the combined GI, while bioswale had the least application in the three areas (less than 3%) since most of the existing streets are not wide enough for the natural drainage system.

The best elements among these four elements are trees and permeable pavements. However, trees can be most effective only in residential and commercial land-use due to the runoff from the large coverage dominated by sidewalks, and streets are greatly reduced. On the other hand, permeable pavements are prominent in commercial and mixed land-use. A similar reason to trees, permeable pavements is an important element that reduces high runoff from various land covers that aggregately shares a huge proportion in these two land-uses. Green roofs have a moderate performance in commercial land use but at a high level in residential and mixed land-use. Despite the high usage of coverage replaced on flat roofs, it reduced less comparing to the other land uses because of the higher runoff coefficient (0.26) from Green roofs. The last GI element, bioswales, has low performance in residential and commercial land-use and average performance in a mixed land-use. The minor available spaces accord with smaller runoff reduction from the parking lots and the streets are found in residential and commercial but resemble in mixed land-use. It is concluded that permeable pavements and trees are comparable and the best performance while bioswale is the least in the three land-uses.

The combined GI elements in mixed land use are the most effective to reduce runoff, compared to residential and commercial land-use because there are no distinctive land covers in mixed land-use which provide the approximate spaces for the implementation of single GI elements implementation. While the percentage of permeable pavements, green roofs, and bioswales in mixed land-use are higher than the other two land-use, their runoff coefficient is lower than trees. Thus, it is fair that the larger coverage of these three elements reduces more runoff than in residential and commercial land-use.

5.3. The performance of GI elements for Phnom Penh city

The performance of GI elements for Phnom Penh city can be derived from the measurement of the three land-uses. Phnom Penh city is made up of central urban and core urban (**Chapter II, 2.1.4, 2**). The capital city consists of residential land-use by 42.24% (1224.68 ha), commercial land-use by 34.98% (1014.2 ha), and mixed land-use by 22.79% (660.71 ha). If 30.52% of runoff was reduced by implementing 46.86% of the total area of residential land-use (35.8 ha), it also can be assumed 30.52% of runoff was reduce when 46.86% of GI implemented in entire residential land-use in central Phnom Penh. So does the same in the two other land-uses. Therefore, the runoff reduction in entire central Phnom Penh can be potentially up to 39.40% when 49.39% of GI was applied in the entire central Phnom Penh (**Table 29**). The integration of GI elements into the central of Phnom Penh shows high performance in this study (Weight 0.90).

Table 29 Runoff rate reduction in central urban in Phnom Penh.

The three typical areas					
Land-use type	Area	Ratio	GI/each land-use	Q reduction	Weight
Unit	ha	%	%	%	
Area A	35.8	-	46.86	30.52	0.65
Area B	20.83	-	56.53	48.86	0.86
Area C	19.5	-	43.10	38.82	0.90
Central Urban					
Land-use type	Area	Ratio	GI/each land-use	Q reduction	Weight
Unit	ha	%	ha	%	
Residential	1224.68	42.24	573.885	30.52	-
Commercial	1014.2	34.98	573.327	48.86	-
Mixed	660.71	22.79	284.766	38.82	-
Total	**2899.59**	**100**	**1431.98 (49.39%)**	**39.40**	**0.90**

Note: GI/each land-use = % GI of a typical land-use x area of a typical land-use For example: GI/residential land-use = 1224.68 x 46.86% =573.885 ha

5.4. The performance of GI in tropical cities

The reduction of peak runoff rate is 39.40% when the combined GI elements were replaced the impervious covers by 49.39% in three areas of a central Phnom Penh. Similarly, Martínez et al. (2018) conducted a study in the highly urbanized catchment in tropical climate (Cali, Colombia). They found that the replacement of GI by optimally 32% of the study area reduced peak runoff by 28% for a two-year event (Martínez et al., 2018). Their finding is comparable to our study since their weight (0.875) as high as ours. Apart from that, Mei et al. (2018) investigated the integrated assessment of various GI for flood mitigation in a highly urbanized watershed in residential, administrative, and commercial areas in Beijing, China (Mei et al., 2018). They indicated that the peak flow rate up to 80.62% under the 2-year rainfall after 36.59 % coverage was applied by GI. This huge value can be noted due to the temperate monsoon climate with an average annual rainfall that is smaller than our study by one-third (522.4 mm). It is worth noting that the main climatic factors affecting the runoff volume of the tropics are high-intensity rainfall, greater capacity to generate runoff, larger peak flows (Rivard et al., 2006).

Despite the higher rainfall intensity, evaporation plays an important role in hydrologic cycles to reduce runoff because the evaporative potential is very high throughout rainy seasons in the tropical monsoon climate (Tsujimoto et al., 2008). As the benefit of the high temperature, six to nine months per year (Rivard et al., 2006), the application of GI for runoff reduction is also significant in the tropical climate. This subjects to the diversity of vegetation (species) and substrate/underground soil. For example, the amount of peak runoff reduction in Hong Kong suggests that green roofs with thicker soil layers are advisable in locations with relatively high and long-lasting precipitation (annual average precipitation 2,350 mm and annual average evapotranspiration 1,123 mm) and high evapotranspiration. Both peak and average runoff reduction increase with green roofs soil thickness (Liu, Xin & Chui, 2019).

5.5. Limitation

The investigation of the potential performance of GI elements for reducing runoff in urban land use in this study has two limitations as described below:

- Three different urban land-uses including residential, commercial, and mixed land use are selected to study. Either Area A, Area B, or Area C is a derivation of each land use type as they are major land uses for cities.
- The use of runoff coefficient values (C and C’) and rainfall intensity (i) are derived from other literature.

It is necessary to remind that the accuracy is not high, however, this study is primarily focused on the comparison of the potential of GI elements for reducing runoff.

5.6. Future studies

For more accuracy in the future study, a site survey is recommended to examine:

- The values of the runoff coefficient (C) for the given drainage areas depends primarily on three factors: the soil property, the land use type, and the slope of the catchment for the changes of flows. Therefore, it is needed for the investigation of the entire city.
- The values of the runoff coefficient of GI elements (C’) associates with the layer criteria, soil composition, vegetation, and geographic of catchments. The geography of catchment includes storm characteristics (rainfall intensity and duration) and temperature.

5.7. Conclusion

This research demonstrates the potential of green infrastructure (GI) for stormwater runoff reduction in urban areas of a tropical country. Three typical land-uses in Phnom Penh were investigated, including residential, commercial, and a mixture of residential and commercial land-uses. Two scenarios were compared: scenario 1 (S1) referred to the current situation when no GI was applied (S2) referred to the integration of GI elements in three different land-use types. In sceanrio1, seven land covers were classified such as public green spaces (parks and gardens), roofs (flat and sloped roofs), sidewalks, streets (roads and boulevards), parking lots, and other land covers (campuses, driveways, paths, and bare lands). These land covers have different ratios. Particularly, Area A is dominated by sloped roofs, sidewalks, and streets while a larger share of public green spaces, flat roofs, and parking lots are found in Area B. Area C, as a mixed land-use, has no distinctive land covers.

The characteristic of each land-use influences the performance of each GI elements. In scenario 2, four GI elements include trees, bioswales, permeable pavements, and green roofs are implemented in these three land-uses to investigate their performance for reducing the peak runoff rate. Permeable pavements are the most applicable GI element that shares up to 65% of the combined GI elements as permeable pavements can be applied to four land covers: sidewalks, streets, parking lots, and other land covers. On the other hand, bioswales are marginally applicable because it is applied only on boulevards and parking lots, which has a small share of impervious surfaces. Trees and green roofs are the second and third largest applicable elements, ranging from 15 - 25% of the combined GI elements. In total, the combined GI elements account for 50% of the total area in Area A and Area B. It reduces runoff by 30% for area A, and 40% for Area B. In Area C, a ratio of runoff reduction is 40% when 45% of combined GI element is applied.

The comparison between the capacity that the GI element reduces runoff to their application result in their effectiveness (weight). Accordingly, the effectiveness of both single and combined GI elements between Area A, Area B, and Area C was obtained. By measuring their weights, trees and permeable pavements had the best performances while bioswale had the poorest performance. The runoff reduction in entire central Phnom Penh consisted of three typical land-use, which approximately reduced by 39.40% of the total area when 49.39% of GI is applied in the entire central Phnom Penh.

To conclude, the application of GI is crucial to cope with urban floods by alleviating stormwater runoff in a tropical climate. The integration of GI elements into the central of Phnom Penh shows high performance of GI in this study. The criteria of GI to the properties of land-use should be carefully considered according to the different characteristics of land-use and the share of the existing land cover, and climate to achieve the best GI performance of runoff reduction.

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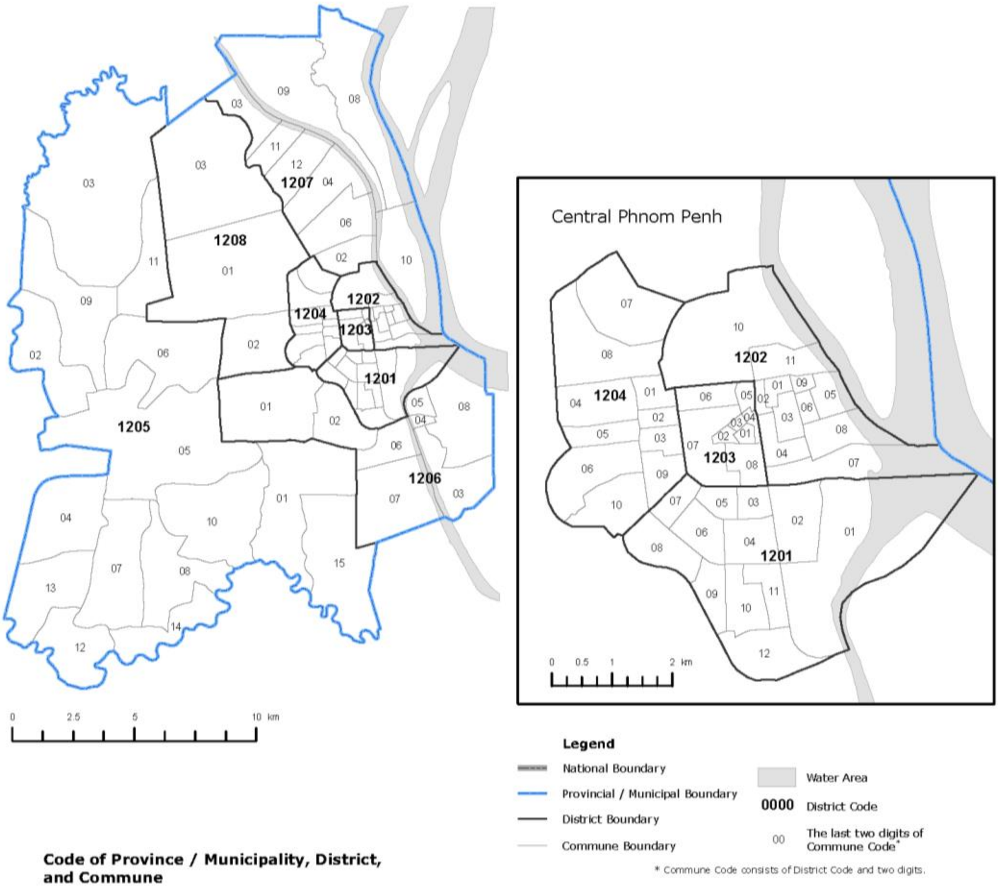
APPENDIXES

APPENDIX 1: MAPS

Administrative areas in Phnom Penh Municipality by district and commune



Code of Province / Municipality, District, and Commune

12 PHNOM PENH

1201 Chamkar Mon

120101	Tonle Basak
120102	Boeng Keng Kang Muoy
120103	Boeng Keng Kang Pir
120104	Boeng Keng Kang Bei
120105	Oulampik
120106	Tuol Svay Prey Ti Muoy
120107	Tuol Svay Prey Ti Pir
120108	Tumnob Tuek
120109	Tuol Tumpung Ti Pir
120110	Tuol Tumpung Ti Muoy
120111	Boeng Trabaek
120112	Phsar Daeum Thkov

1202 Doun Penh

120201	Phsar Thmei Ti Muoy
120202	Phsar Thmei Ti Pir
120203	Phsar Thmei Ti Bei
120204	Boeng Reang
120205	Phsar Kandal Ti Mouy
120206	Phsar Kandal Ti Pir
120207	Chakto Mukh
120208	Chey Chummeah
120209	Phsar Chas
120210	Srah Chak
120211	Voat Phnum

1203 Prampir Meakkakra

120301	Ou Ruessei Ti Muoy
120302	Ou Ruessei Ti Pir
120303	Ou Ruessei Ti Bei
120304	Ou Ruessei Ti Buon
120305	Monourom
120306	Mittakpheap
120307	Veal Vong
120308	Boeng Prolit

1204 Tuol Kouk

120401	Phsar Depou Ti Muoy
120402	Phsar Depou Ti Pir
120403	Phsar Depou Ti Bei
120404	Tuek L'ak Ti Muoy
120405	Tuek L'ak Ti Pir
120406	Tuek L'ak Ti Bei
120407	Boeng Kak Ti Muoy
120408	Boeng Kak Ti Pir
120409	Phsar Daeum Kor
120410	Boeng Salang

1205 Dangkao

120501	Dangkao
120502	Trapeang Krasang
120503	Kouk Roka
120504	Phleung Chheh Roteh
120505	Chaom Chau
120506	Kakab
120507	Pong Tuek
120508	Prey Veaeng
120509	Samraong Kraom
120510	Prey Sa
120511	Krang Thnong
120512	Krang Pongro
120513	Prateah Lang
120514	Sak Sampov
120515	Cheung Aek

1206 Mean Chey

120601	Stueng Mean Chey
120602	Boeng Tumpun
120603	Preaek Pra
120604	Chhbar Ampov Ti Muoy
120605	Chhbar Ampov Ti Pir
120606	Chak Angrae Leu
120607	Chak Angrae Kraom
120608	Nirouth

1207 Ruessei Kaev

120702	Tuol Sangkae
120703	Svay Pak
120704	Kilomaetr Lekh Prammuoy
120706	Ruessei Kaev
120708	Preaek Lieb
120709	Preaek Ta Sek
120710	Chrouy Changvar
120711	Chrang Chamreh Ti Muoy
120712	Chrang Chamreh Ti Pir

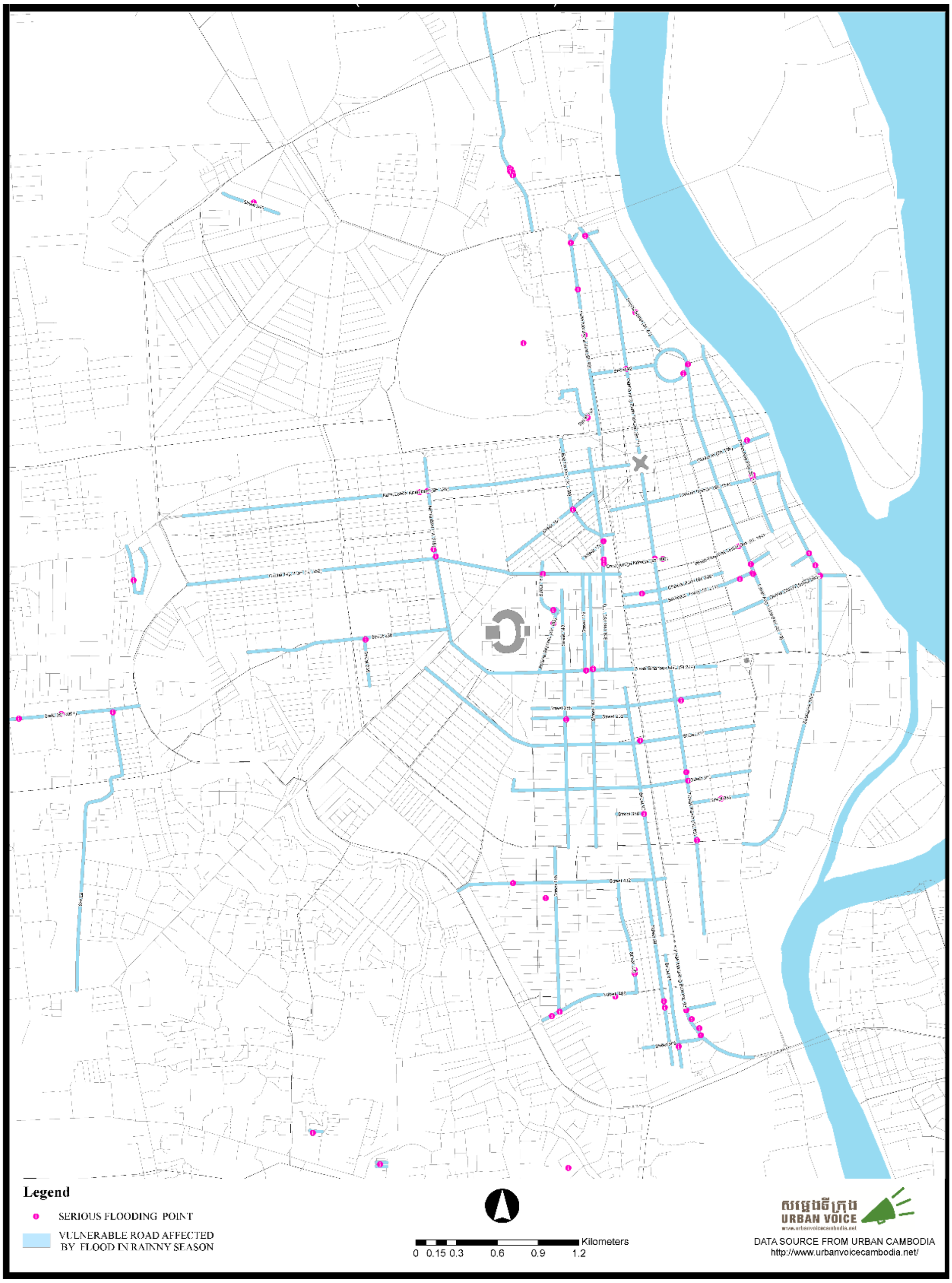
1208 Sen Sok

120801	Phnom Penh Thmei
120802	Tuek Thla
120803	Khmuonh

* Codes and boundaries are as of September 7, 2009.

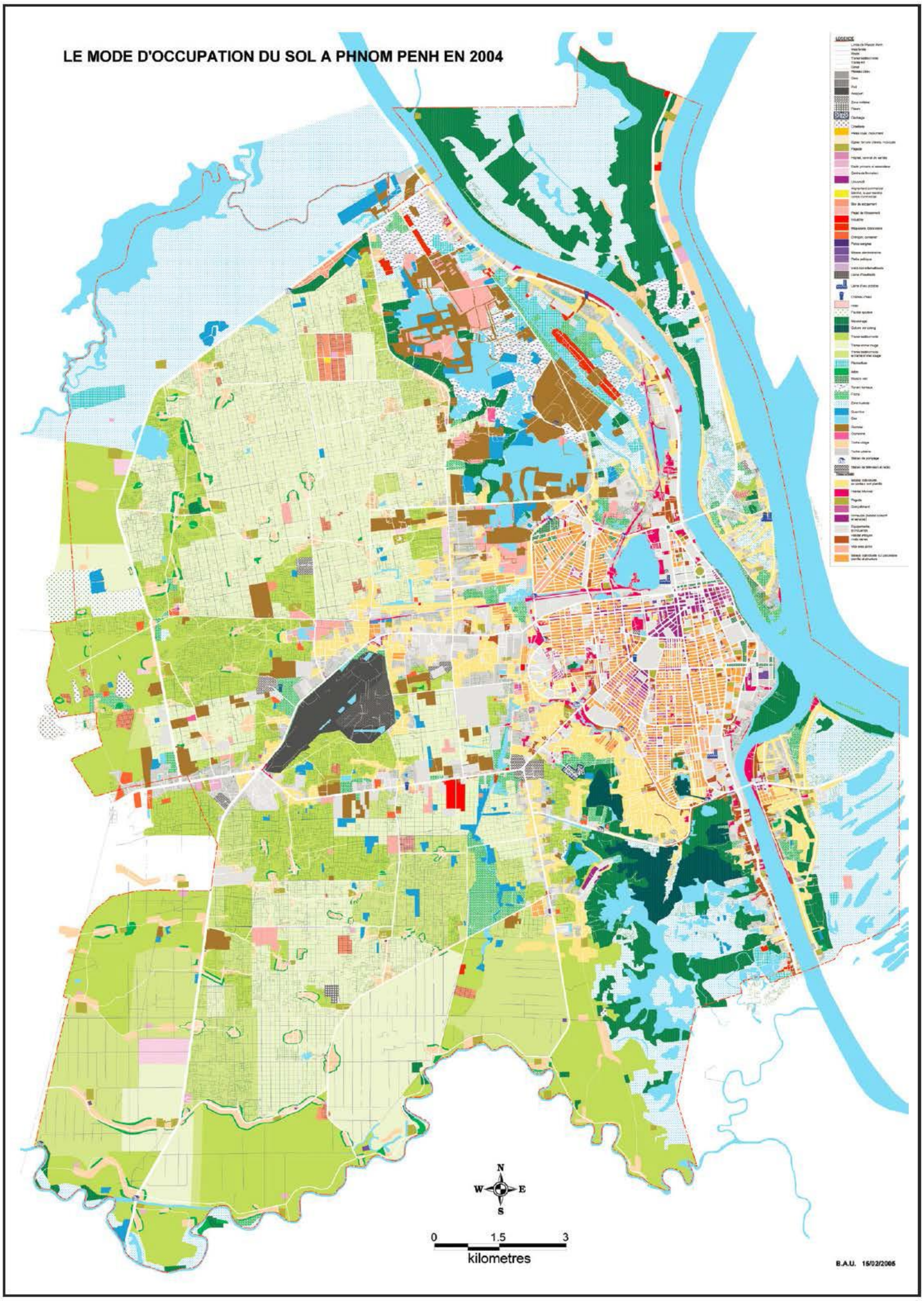
Source: JICA

Map of flooding road of central Phnom Penh in 2013



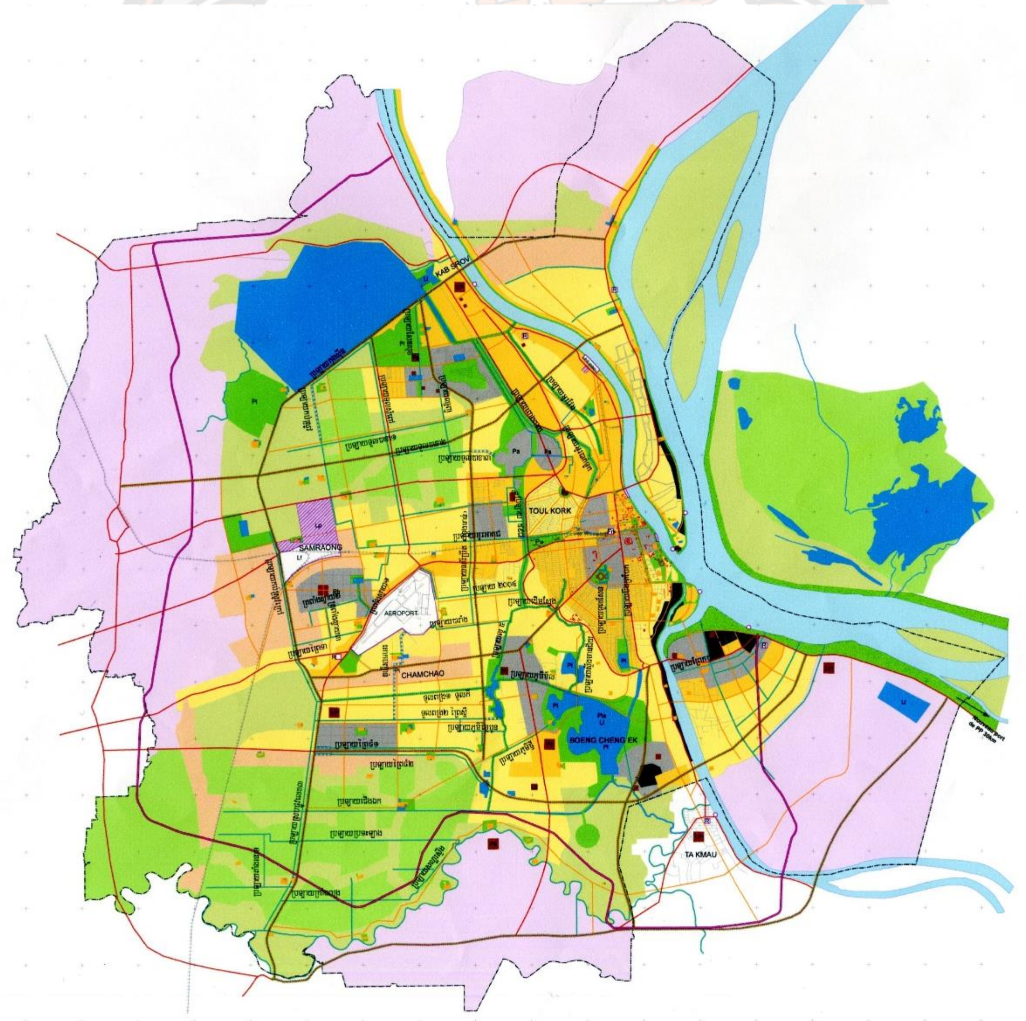
Source: Urban Voice Cambodia (2014).

Land-use of Phnom Penh in 2004



Source: White Book on Development and Planning of Phnom Penh, PPCC (2007) as cited by JICA (2016)

Land-use of Phnom Penh in 2035



Source: White Book on Development and Planning of Phnom Penh, PPCC (2007)

APPENDIX 2: DATA AND CALCULATION

Scenario 1 (S1): land-use classification (area and ratio) and peak runoff rate (Q)

Formula:

$$A\ (\text{ha}) = A\ (\text{m}^2) \times 0.0001$$

$$\text{Ratio}\ (\%) = \frac{\text{Ai}\ (\text{i}_{1,2,\ldots,n}) \times 100}{\sum_{i=1}^{n} \text{Ai}}$$

$$Q = \frac{1}{360}\ \text{CiA}$$, i=44.8 mm for a 2-years storm return period.

Area A

Land use/cover		**Area**	**Area**	**Ratio**	**C**	**I**	**Q**
Unit		m²	ha	%	-	mm/h	m³/s
Houses/buildings	Flat roofs	20094.54	2.01	5.61	0.75	44.8	0.19
	Sloped roofs	199414.78	18.55	51.82	0.95	44.8	2.19
Total			**20.56**	**57.43**			**2.38**
Transportation:							
Sidewalks	Tree canopies	6316.15	0.63	1.76	0.78	44.8	0.06
	Impermeable pavers	69858.67	6.35	17.75	0.85	44.8	0.67
Roads	Tree canopies	2673.11	0.27	0.75	0.80	44.8	0.03
	Impervious asphalt	45507.64	4.28	11.97	0.90	44.8	0.48
Boulevards	Tree canopies	690.33	0.07	0.19	0.80	44.8	0.01
	Impervious asphalt	15417.79	1.47	4.11	0.90	44.8	0.16
Total			**13.08**	**36.53**			**1.41**
Others:							
Parks	Grass	147.53	0.01	0.04	0.08	44.8	0.00014
Paths and campuses	Tree canopies	4600	0.46	1.29	0.81	44.8	0.05
	Impervious concrete	11000	1.10	3.07	0.93	44.8	0.13
Parking lots	Impervious concrete	3009.88	0.30	0.84	0.93	44.8	0.03
Bare lands	Impervious concrete	2856.79	0.29	0.80	0.93	44.8	0.03
Total			**2.16**	**6.04**			**0.24**
Overall			**35.80**	**100**			**4.03**

Area B

land use/cover			**Area**	**Area**	**Ratio**	**C**	**I**	**Q**
Unit			m²	ha	%	-	mm/h	m³/s
Recreational area: Public green space								
Parks:			9462.84	0.95	4.54	0.1	44.8	0.01
Total			**9462.84**	**0.95**	**4.54**			**0.01**
Commercial and Services:								
Green spaces	grass & tree canopies		32584.38	3.26	15.64	0.08	44.8	0.03
Pools	Water		484.24	0.05	0.23	1	44.8	0.01
Campuses	Tree canopies		3296.57	0.33	1.58	0.81	44.8	0.03
	Impervious concrete/ impervious pavers		28590.5	2.53	12.14	0.93	44.8	0.29
Parking lots	Tree canopies		3007.67	0.30	1.44	0.81	44.8	0.03
	Impervious concrete		18893.11	1.59	7.63	0.93	44.8	0.18
Driveways	Tree canopies		312.236	0.03	0.15	0.81	44.8	0.00
	Impervious concrete		6803.88	0.65	3.12	0.93	44.8	0.07
Buildings	Sloped roofs		41396.78	4.14	19.87	0.95	44.8	0.49
	Flat roofs		25043.91	2.50	12.02	0.75	44.8	0.23
Total			**160413.27**	**15.38**	**73.83**			**1.38**
Transportation:								
Sidewalks	Tree canopies	Parks	1566.95	0.16	0.75	0.78	44.8	0.02
		Commercial	3033.77	0.30	1.46	0.78	44.8	0.03
	Impermeable pavers	Parks	5299.28	0.37	1.79	0.85	44.8	0.04
		Commercial	14105.14	1.11	5.31	0.85	44.8	0.12
Roads	Tree canopies	Parks	628.7	0.06	0.30	0.80	44.8	0.01
		Commercial	2496.61	0.25	1.20	0.80	44.8	0.02
	Impervious asphalt		22055.88	1.89	9.09	0.90	44.8	0.21
Boulevards	Tree canopies		203.72	0.02	0.10	0.80	44.8	0.00
	Impervious asphalt		3589.5	0.34	1.63	0.90	44.8	0.04
Total			**52979.55**	**4.50**	**21.63**			**0.48**
Overall			**222855.66**	**20.83**	**100**			**1.87**

Area C

Land use/cover			Area	Area	Ratio	C	I	Q
Unit			m²	ha	%	-	mm/h	m³/s
Recreational area:								
Parks:			1992	0.20	1.02	0.1	44.8	0.00
Total			**1992**	**0.20**	**1.02**			**0.00**
Commercial and Services:								
Green spaces	Grass & tree canopies		32607.57	3.26	16.73	0.08	44.8	0.03
	Paths: impermeable pavers		2735.51	0.27	1.40	0.85	44.8	0.03
Campuses	Tree canopies		4622.67	0.46	2.37	0.81	44.8	0.05
	Impervious concrete and impervious pavers		14591.71	1.00	5.11	0.93	44.8	0.11
Parking lots	Tree canopies		166.12	0.02	0.09	0.81	44.8	0.00
	Impervious concrete		10071.52	0.99	5.08	0.93	44.8	0.11
Buildings	Sloped roofs		21519.78	2.15	11.04	0.95	44.8	0.25
	Flat roofs		5351.03	0.54	2.74	0.75	44.8	0.05
Total			**91665.91**	**8.69**	**44.56**			**0.64**
Residential								
Campuses	Tree canopies		1405.88	0.14	0.72	0.81	44.8	0.01
	Impervious concrete/ impervious pavers		9115.82	0.77	3.95	0.93	44.8	0.09
Buildings	Sloped roofs		40903.78	4.09	20.98	0.95	44.8	0.48
	Flat roofs		8558.50	0.86	4.39	0.75	44.8	0.08
Total			**59983.98**	**5.86**	**30.05**			**0.67**
Transportation:								
Sidewalks	Tree canopies	Commercial	1851.54	0.19	0.95	0.78	44.8	0.02
	Impermeable pavers		6972.01	0.51	2.63	0.85	44.8	0.05
	Tree canopies	Residential	4081.4	0.41	2.09	0.78	44.8	0.04
	Impermeable pavers		13444.12	0.94	4.80	0.85	44.8	0.10
Roads	Tree canopies		1267.72	0.13	0.65	0.80	44.8	0.01
	Impervious asphalt		12400.99	1.11	5.71	0.90	44.8	0.12

Area C (Cont.)

Land use/cover		**Area**	**Area**	**Ratio**	**C**	**I**	**Q**
Unit		m²	ha	%	-	mm/h	m³/s
Boulevards	Tree canopies	1334.34	0.13	0.68	0.80	44.8	0.01
	Impervious asphalt	14695.96	1.34	6.85	0.90	44.8	0.15
Total		**56048.08**	**4.75**	**24.37**			**0.51**
Overall		**209689.97**	**19.50**	**100**			**1.82**

Scenario 2 (S2): GI element replaced to exiting impervious covers (area and ratio) and peak runoff rate (Q’).

Formula:

-Number of Tree = Length of sidewalk (m) / 8

-Area of tree pits (ha) =
- Number of Tree x area of tree pit (2.25 m^2) x 0.0001, for Sidewalk-type c
- Number of Tree x area of tree pit (1 m^2) x 0.0001, for Sidewalk-type b
- Number of Tree x area of tree pit (0.36 m^2) x 0.0001, for Sidewalk-type a

-Area of canopy (ha) =
- Number of Tree x (3.14 x 3.5^2) x 0.0001, for type c
- Number of Tree x (3.14 x 2.5^2) x 0.0001, for type b
- Number of Tree x (3.14 x 1.8^2) x 0.0001, for type a

-Area of the canopy over sidewalks, no pits = Area of the canopy (ha) x 2/3 - Area of tree pits (ha)

-Area of the canopy over transports = Area of the canopy (ha) x 1/3

Area A

Land use/cover		**Area**	**Ratio**	**C**	**I**	**Q**
Unit		ha	%	-	mm/h	m^3/s
Houses/buildings	Green roofs	2.01	5.61	0.26	44.8	0.06
	Sloped roofs	18.55	51.82	0.95	44.8	2.19
Total		**20.56**	**57.43**			**2.26**
Transportation:						
Sidewalks	Tree canopies	2.23	6.23	0.47	44.8	0.13
	Permeable pavers	4.57	12.75	0.24	44.8	0.14
	Pits	0.19	0.53	0.23	44.8	0.01
Roads	Tree canopies	0.97	2.70	0.47	44.8	0.06
	Porous asphalt	3.58	10.01	0.23	44.8	0.10
Boulevards	Tree canopies	0.24	0.68	0.47	44.8	0.01
	Porous asphalt	1.12	3.12	0.23	44.8	0.03
	Bioswale	0.18	0.51	0.13	44.8	0.003
Total		**13.08**	**36.53**			**0.48**

Area A (Cont.)

Land use/cover		Area	Ratio	C	I	Q
Unit		ha	%	-	mm/h	m³/s
Others:						
Parks	Grass	0.01	0.04	0.08	44.8	0.00
Paths and campuses	Tree canopies	0.46	1.28	0.45	44.8	0.03
	Pervious concrete	1.10	3.07	0.20	44.8	0.03
Parking lots	Pervious concrete	0.30	0.84	0.20	44.8	0.01
Bare lands	Pervious concrete	0.29	0.80	0.20	44.8	0.01
Total		**2.16**	**6.04**			**0.07**
Overall		**35.80**	**100**			**2.80**

Area B

Land-use/cover		Area	Ratio	C	I	Q
Unit		ha	%	-	mm/h	m³/s
Recreational area:						
Parks:		0.95	4.54	0.1	44.8	0.01
Total		**0.95**	**4.54**			**0.01**
Commercial						
Green spaces	grass & tree canopies	3.26	15.64	0.08	44.8	0.03
Pools	Water	0.05	0.23	1	44.8	0.01
Campuses	Tree canopies	0.33	1.58	0.45	44.8	0.02
	Impervious concrete	2.53	12.14	0.20	44.8	0.06
Parking lots	Tree canopies	0.30	1.44	0.45	44.8	0.02
	Impervious concrete	1.56	7.49	0.20	44.8	0.04
	Bioswale	0.03	0.14	0.13	44.8	0.0005
Driveways	Tree canopies	0.03	0.15	0.45	44.8	0.00
	Impervious concrete	0.65	3.12	0.20	44.8	0.02
Buildings	Sloped roofs	4.14	19.87	0.95	44.8	0.49
	Green roofs	2.50	12.02	0.26	89.60	0.08
Total		**15.38**	**73.83**			**0.76**

Area B (Cont.)

Land-use/cover			**Area**	**Ratio**	**C**	**I**	**Q**
Unit			ha	%	-	mm/h	m³/s
Transportation:							
Sidewalks	Tree canopies	Parks	0.29	1.41	0.47	44.8	0.02
		Commercial	0.59	2.82	0.47	44.8	0.03
	Impermeable pavers	Parks	0.21	0.99	0.24	44.8	0.01
		Commercial	0.77	3.68	0.24	44.8	0.02
		Pits	0.084325	0.404806	0.23	44.8	0.0024
Roads	Tree canopies	Parks	0.44	2.12	0.47	44.8	0.03
		Commercial					
	Impervious asphalt		1.76	8.47	0.23	44.8	0.05
Boulevards	Tree canopies		0.04	0.20	0.47	44.8	0.002
	Impervious asphalt		0.27	1.31	0.23	44.8	0.008
	Bioswale		0.04	0.21	0.13	44.8	0.0007
Total			**4.50**	**21.63**			**0.17**
Overall			**20.83**	**100**			**0.94**

Area C

Land use/cover		**Area**	**Ratio**	**C**	**I**	**Q**
Unit		ha	%	-	mm/h	m³/s
Recreational area:						
Parks:		0.20	1.02	0.1	44.8	0.00
Total		**0.20**	**1.02**			**0.00**
Commercial						
Green spaces	Grass & tree canopies	3.26	16.73	0.08	44.8	0.03
	Paths: permeable pavers	0.27	1.40	0.24	44.8	0.01

Area C (Cont.)

Land use/cover			**Area**	**Ratio**	**C**	**I**	**Q**
Unit			ha	%	-	mm/h	m³/s
Campuses	Tree canopies		0.46	2.37	0.45	44.8	0.03
	Pervious concrete and pervious pavers		1.00	5.11	0.20	44.8	0.02
Parking lots	Tree canopies		0.02	0.09	0.45	44.8	0.00
	Pervious concrete		0.96	4.95	0.20	44.8	0.02
	Bioswale		0.03	0.135711	0.13	44.80	0.000428
Buildings	Sloped roofs		2.15	11.04	0.95	44.8	0.25
	Green roofs		0.54	2.74	0.26	44.8	0.02
Total			**8.69**	**44.56**			**0.39**
Residential							
Campuses	Tree canopies		0.14	0.72	0.45	44.8	0.01
	Pervious concrete		0.77	3.95	0.20	44.8	0.02
Buildings	Sloped roofs		4.09	20.98	0.95	44.8	0.48
	Green roofs		0.86	4.39	0.75	44.8	0.03
Total			**5.86**	**30.05**			**0.54**
Transportation:							
Sidewalks	Tree canopies	Commercial	0.50	2.56	0.47	44.8	0.03
	Permeable pavers		0.17	0.88	0.24	44.8	0.01
	Pits		0.03	0.133725	0.23	44.80	0.000746
	Tree canopies	Residential	0.94	4.83	0.47	44.8	0.05
	Permeable pavers		0.35	1.81	0.24	44.8	0.01
	Pits		0.05	0.251118	0.23	44.80	0.001401

Area C (Cont.)

Land use/cover		Area	Ratio	C	I	Q
Unit		ha	%	-	mm/h	m³/s
Roads	Tree canopies	0.26	1.32	0.47	44.8	0.01
	Porous asphalt	0.98	5.04	0.23	44.8	0.03
Boulevards	Tree canopies	0.22	1.14	0.47	44.8	0.01
	Porous asphalt	1.08	5.54	0.23	44.8	0.03
	Bioswale	0.17	0.850813	0.13	44.80	0.002683
Total		4.75	24.37			0.19
Overall		**19.50**	**100**			**1.11**

The effectiveness of GI elements

Area A				
GI elements	**%/total area**	**%/combined GI elements**	**% reduction**	**Weight**
Tr	10.14	21.64	31.67	1.46
Bios	0.51	1.08	0.39	0.36
PP	30.59	65.3	57.77	0.88
GR	5.61	11.98	10.57	0.88
Combined GI elements	**46.85**	**100**	**100**	**0.65**
Area B				
GI elements	**%/total area**	**%/combined GI elements**	**% reduction**	**Weight**
Tr	6.96	14.19	15.14	1.07
Bios	0.35	0.72	0.27	0.37
PP	37.21	60.58	68.09	1.12
GR	12.02	24.51	16.50	0.67
Combined GI elements	**56.54**	**100**	**100**	**0.86**
Area C				
GI elements	**%/total area**	**%/combined GI elements**	**% reduction**	**Weight**
Tr	10.24	21.78	18.98	0.87
Bios	0.99	2.1	1.39	0.66
PP	24.74	60.96	68.31	1.12
GR	7.13	15.16	11.32	0.75
Combined GI elements	**43.10**	**100**	**100**	**0.90**

FOOTNOTES

FOOTNOTES

1 http://www.phnom-penh.climatemps.com/precipitation.php

2 https://weather-and-climate.com/average-monthly-precipitation-Rainfall,Phnom-Penh,Cambodja

3 Earth Observation for Sustainable Development (EO4SD) is an ESA (the European Space Agency) initiative, which aims to achieve an increase in the uptake of satellite-based information in the regional and global IFI programs. The European Space Agency (ESA) has been working closely with the International Finance Institutes (IFIs) and their client countries to demonstrate the benefits of Earth Observation (EO) in the IFI development programs.

4 To note that, there is 373 km² of the area is called ‘core city’ in their report, while the overall area of PP is 678.46 km².

5 Attribute Table consists of many Field Calculator. It is allowed to perform calculations based on the existing attribute values or defined functions, for instance, to calculate length or area of geometry features.

GLOSSARIES

GLOSSARIES

Area A = A typical residential housing land-use, attached roofs with 2-4 stories and composed of a high percentage of impervious cover (approximately 90 - 95 % of impervious cover).

Area B = A typical commercial land-use, commercial and institutional building blocks, campuses, parking lots, with 70 – 75 % impervious covers, and public green spaces.

Area C = A typically mixed land-use represents a combination of commercial and residential blocks, consists 75 - 80 % of impervious covers.

Bioswales : A vegetated channel designed with underlying engineered structures, with a diversity of plants, to capture and treat stormwater runoff.

Combined sewer overflows : The sewer overflow or excess stormwater that is over the capacity of the sewer system. The overflows contain not only stormwater but also untreated human and industrial waste, toxic materials, and debris.

Combined stormwater systems : The sewers are designed to collect rainwater runoff, domestic sewage, and industrial wastewater in the same pipe. Most of the time, combined sewer systems transport all of their wastewater to a sewage treatment plant, where it is treated and then discharged to a water body.

Coniferous tree species : Any tree species with typically long needle-shaped leaves and adaptable to the cold weather. Their leaves do not fall off in the winter and they can be found across many areas in North America, Europe, and Asia.

Deciduous tree species : Any tree species with broad flat leaves rounded shape, and spreading branches that catch a lot of light and require a great amount of water. They occur in places with high rainfall, warm summers, and cooler winters and lose their leaves in winter. They are found in temperate and tropical climates all over the world.

Evapotranspiration : The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

Evergreen tree species	:	Any tree species with thicker leaves and more leathery than those of deciduous trees. They are needle-like or scale-like in cone-bearing trees, tall, straight trunks with form a symmetrical shape branch. Many evergreens are coniferous trees or conifers but not all. They have tall,
Green infrastructure elements or GI elements	:	Any technical technique planned and managed primarily for stormwater control, but also exhibit social, economic, and environmental benefits.
Green roofs	:	A vegetated roof; composed of a series of layers that are mostly installed on a rooftop to collect and infiltrate runoff.
High-density urban	:	A particular area (cities) where many people are living in.
Impervious covers/surfaces	:	Any mainly artificial structures including pavements: asphalt, concrete, brick, stone, rooftops, etc. that not allowing fluid to pass through.
Infiltration	:	A process of flow of water from aboveground into the subsurface/soil.
Inundation	:	To cover with extensive water or to denote the process of a dry area being permanently drowned or submerged.
Land-use	:	A function of land as it is used for. It is categorized according to economic, cultural activities, and certain purposes.
Permeable pavements	:	A pervious ground surface, with a variety of forms, installed for stormwater gradually infiltrating into the soils at pedestrians, driveways, etc.
Percentage	:	A fraction of a hundred.
Pervious covers/surfaces	:	Any surface that allows the water to percolate into the underlying soil. Pervious surfaces include grass, mulched groundcover, planted areas, vegetated roofs, and permeable pavements.
Proportion	:	An equation stating that two or more ratios are equivalent.

Quantum GIS (QGIS)	:	A free and open-source, desktop geographic information system application, which used to analyze and edit spatial information, composing and exporting graphical maps.
Rainfall intensity–frequency–duration	:	A graphical representation of the probability that a given average rainfall intensity will occur.
Ratio	:	A comparison between two quantities of the same kind.
Rational Method	:	A formula for estimating peak discharge of runoff from a catchment above a specific point calculated using the peak discharge, rainfall intensity for the selected period, runoff coefficient, and catchment area.
Runoff	:	The flow of water that occurs when excess stormwater is generated during precipitation and snowmelt.
Runoff coefficient	:	The C factor in the rational formula which equals the ratio of the rate of runoff to the rate of rainfall. It indicates the proportion of the rainfall rate that is contributing to the runoff rate and as such is always < 1.
Soil permeability	:	the characteristic of a soil that governs the rate at which water moves through it. This depends largely on soil texture, structure, presence of compacted or impeding layers, and the size and interconnection of pores.
Stemflow	:	Rainwater that runs down at a tree’s stem or bole to the ground surface.
Stormwater runoff	:	A flow of water; rain, storm, and snow, over the ground impervious surfaces.
Time of concentration	:	The shortest time necessary for all points within a catchment to contribute simultaneously to flow past a specified point.
Throughfall	:	Rainwater that passes through a tree’s canopy or drips off tree surfaces onto the ground.
Tree canopy	:	The layer of leaves, branches, and stems of trees that cover the ground when viewed from above.

Urbanization	:	This refers to the development of buildings and/or an increase in the number of people.
Water-sensitive urban designs	:	An approach to reuse stormwater, stopping it from reaching our waterways by mimicking the natural water cycle as closely as possible. For example, Rainwater tanks collect stormwater run-off from impervious surfaces such as roofs, reducing the amount that enters our waterways and can be reused to flush toilets, wash clothes, water gardens and wash cars, significantly reducing demand on drinking water.