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Research on Landscape and Aesthetics of Infrastructure

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Abstract

Dominantly, urbanization process deleteriously impacts on land use change in terms of increasing impervious cover and surface runoff, which has been causing urban flooding in the urbanized area. These issues are even worse in particularly for developing countries.

Cambodia is one of the countries situated in Mekong River Basin. Phnom Penh City (PPC), the capital of Cambodia, is located at the intersection of Mekong River, Tonle Sap River, and Basak River. Since 2003, after a decade of cutting-edge economic development, land reclamations for land use development have been gradually increasing among investors. The laws on land use planning and environmental protection were promulgated in 1994 and 1996, respectively. Regardless of concerns respecting to topography, soil, and imperviousness conditions, the manner of current land use development and design are more focusing on aesthetic aspects with ideal infrastructure being shaped symmetrically and geometrically. Consequently, it's been causing many negative effects to the social and environmental aspects. Particularly, it's been accelerating the urban flooding extents during the rainy season. With great concerns of current land use development trends, this research demonstrates an appropriate land use planning concept for PPC. In this context, watershed-based method, a useful key concept for flooding mitigation planning, is introduced.

The aim of this research is to develop a watershed-based methodology for land use planning in PPC, where is suffering from urban flooding. The objectives of the research are divided into fourth contexts. (1) Clarification the research trends of watershed-based land use analysis, which have been discussed widely not only in the fields of hydrology, environmental management but also in land use and landscape planning. (2) Preparation of GIS-based spatial databases for watershed-based land use analysis under the lack of sufficient public databases in PPC. (3) Conception of watershed-based land use planning for PPC at macro scale reflecting on the interaction between upstream and downstream of one's development area as part of the watershed unit. (4) Introduction of Hydrological Sensitive Areas (HSAs) identified as the source of runoff and design measures of Low Impact

Development-Best Management Practices (LID-BMPs) to discuss at both middle and micro scales of land use planning for PPC.

This dissertation is composed of 8 chapters. **Chapter 1** describes research background and the motivation, research objectives, existing studies in PPC, research methodologies, positions and framework, and structure of this dissertation.

Chapter 2 presents the basic information of PPC including geography, demographic, administration, and economic. The historical perspectives of urban development in PPC from pre-colonial to current periods are demonstrated. The current condition of urban development in PPC is illustrated with the law of urban relative development and limitation of sufficient data, existing land use and master plan, ongoing project development plan, and flooding issues in both national and city scales.

Chapter 3 is to clarify the research trends in watershed-based land use analysis including basic tools, factors, methodologies, study regions, scales and areas, and the relationship of these factors in watershed-based land use analysis. A total of 55 targets academic paper comes from international journals and conference papers with various academic publishers had been reviewed. The findings show that integration of Remote Sensing (RS) and GIS was proven to be an important technology for temporal analysis and qualification of spatial phenomena for land use analysis with less time and low cost. From the viewpoints of watershed scale planning, the nature of using an application to analyze rural watersheds is not static. There is much variation among planners because the threshold values used for stream definition differ. With this respect, threshold values to define the scale of the watershed are illustrated in the next chapter.

Chapter 4 presents the preparation of GIS-based spatial databases for watershed delineation, determination of threshold values for macro, middle and micro scales of watershed, and detection of land use using remote sensing data. Importance steps of land use detection method using remote sensing image and GIS with the combination of the first level of the land use classification system of remote sensor data are demonstrated for land use in 2005 and 2015 of PPC.

Chapter 5 illustrates the concept of watershed-based land use planning for PPC at macro scale. This concept is considered as the primarily screening assessment of critical area for development from the watershed-based land use planning perspective. Analyzes are performed based on two contexts. Firstly, the transformation of land use pattern in 2005, 2015, and master plan in 2020 based on zoning area in each watershed is carried out. Secondly, the relationship between upstream and downstream area is demonstrated based upon the interaction of zoning area and outside of zoning area as part of the watershed. From the macro scale planning, the importance of the relationship between upstream and downstream of a watershed is illustrated and proved as an essential factor to discuss in land use planning for flood prevention as well as mitigation. The critical development area is identified based on the difference of urban land use change ratios between 2005 and 2015 taken place in zoning and outside of zoning areas.

Chapter 6 discusses the concept of watershed-based land use planning for PPC at middle scale. First, Hydrological Sensitive Areas (HSAs), a source of runoff, is introduced to define zoning indicator as part of the watershed unit. This is involved in the creation of soil databases and numerical calculation of Soil Water Storage, identification of Wetness Index, the creation of the pervious and impervious covers, and determination the threshold value of HSAs for PPC. Second, the trend of land use development in PPC is illustrated through defined HSAs, current situation of HSAs based on site survey, and the master plan in 2020. Based on the analysis, by taking account into HSAs, zoning indicators, in the development plan enable the planner to avoid for the development of areas having a high potential of increasing flood risk.

Chapter 7 introduces a concept of watershed-based land use planning for PPC at micro scale. Design measures known as Low Impact Development-Best Management Practices (LID-BMPs) following the existing methods are applied to zoning indicators. 7 types of LID-BMPs: Green roof, Rain barrel, Grass swale, Porous pavement, Bioretention, Retention pond, and Detention pond are used for better design proposing to the zoning indicators in the form of grids. Analytical Hierarchy

Process (AHP) integrated into Grey Rational Analysis (GRA) method with the modification of reference sequence are used for numerical calculations of weights to define the suitability maps for these 7 types of measures by performing GIS-based multi-criteria assessment modeling on zoning indicators. For safety planning and designs, readjustment for both zoning indicators and suitability maps are carried out. Consequently, finalized map of HSAs and suitability maps of the case study are identified and treated as an index for controlling development area.

Finally, **Chapter 8** summarizes the key findings, the conceptual framework of watershed-based methodology for urban flooding mitigation and the technical method of watershed-based methodology for land use planning in PPC, and the future researches and limitations of this dissertation. This dissertation addresses a review on research trends of watershed-based land use analysis, preparation of GIS-based spatial databases, concepts of watershed-based land use planning for PPC at macro, middle, and micro scales based upon the lack of sufficient public databases. This research contributes to the development of land use planning based on watershed in PPC. Besides, this developed methodology can be a reference for cities where urban flooding is the key issues in the urban development.

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CHAPTER 1
Introduction

1.1 Research background

Dominantly, urbanization process deleteriously impacts on land use change in term of increasing impervious cover and surface runoff, which has been causing urban flooding in the urbanized area[1), 2)]. These problems are even worse especially for the developing countries[3)].

Cambodia is one of the countries situated in Mekong River Basin while Phnom Penh City, the capital of Cambodia, is located at the intersection of Mekong River, Tonle Sap River, and Basak River with district boundaries as shown in **Fig.1.1**.

Phnom Penh City (PPC) is known as a city with urban development that is closely related to the water[4)]. Originally, this city was built on the high riverbank which then continually expanded to the lower plain lying behind the riverbank. These low-lying areas have been protected by the creation of successive concentric dikes[4)]. In the 1960s, the city was known as “the Pearl of Asia”, which was built up by many green areas and water features while the blooming architecture. The necessity of careful consideration on sustainable water management for the city planning was defined with prerequisites of two dominant seasons, wet and dry. However, after three decades of civil war, degradation of the city, as well as infrastructure, has been occurred[5)].

After a decade of cutting-edge economic development, since 2003 this development has been leading to the significant increment of land price in the city. As the result, purchasing of public parks and spaces around the city have been rapidly raising among both local and foreign investors for building satellite cities. Replacement of wetlands functioned as natural reservoirs, retention pond and buffer zones for water flow have been filled and utilized for construction purpose. The planning policy has no longer been considered for the sustainable stormwater management but rather focusing on aesthetic aspects with ideal infrastructures being shaped symmetrically and geometrically.

Parallel to these developments, various city infrastructures have rapidly growing in number which led to the economic growth; however, water storages and absorbable soil have been decreasing, which have been causing many negative effects not only to the environmental but also to the social aspects. In particularly, these developments have caused the inundation to become a tremendous problem during the rainy season (May-October) as shown in **Fig.1.2**. As rainfall is a critical issue in rainy season, through the open canals and sewage pipes, the city wastewater and most of the storm water are lead to the surrounding water storages as wetlands, which biologically purify the contaminated water before entering to the rivers; the lack of wetlands and open spaces lead to the acceleration of flooding extents. Whereas repeated negative impacts of life quality including health issue, traffic problem, infrastructure deterioration, losing individual income and governmental budget for the reconstruction of infrastructure happens almost every rainy season.

With great concern of current land use development trends in PPC, where flooding is one of the main issues in urban planning, watershed-based methodology, a useful key concept applied for not only in hydrology, environmental management but also in land use and landscape planning fields[9], is introduced for flooding mitigation planning as well as future sustainable planning.

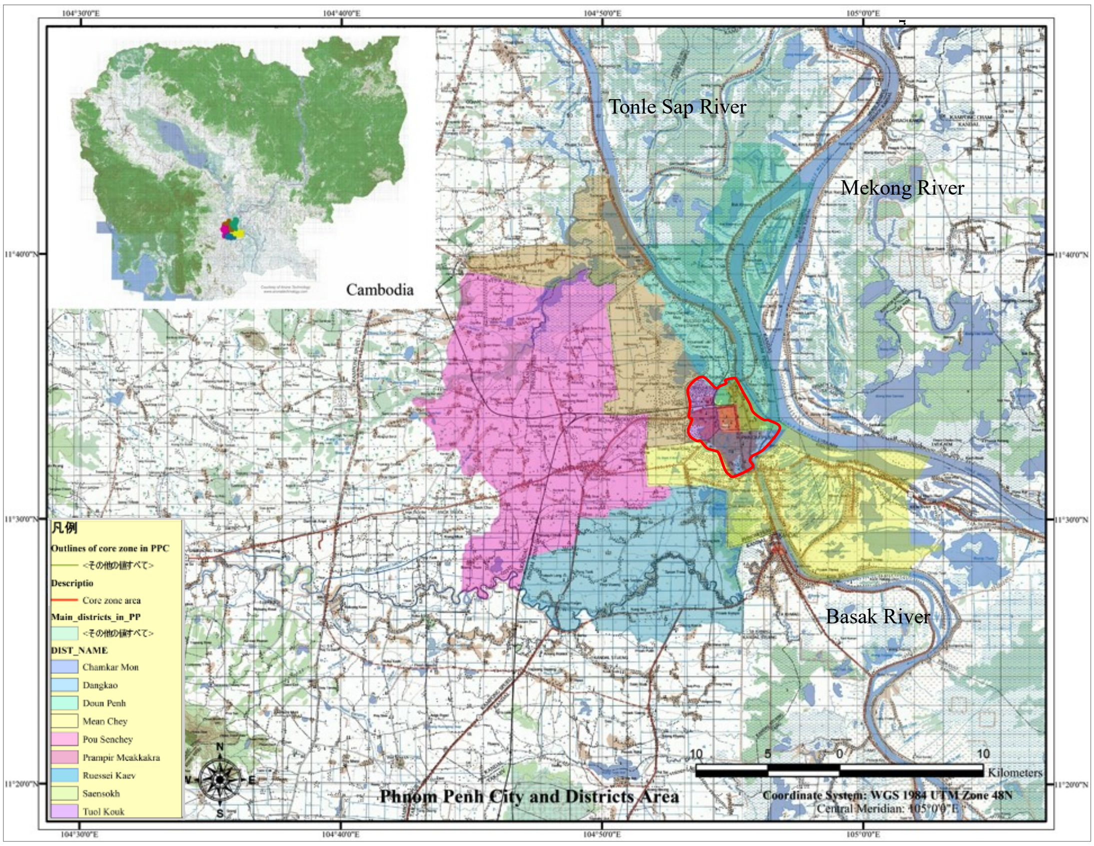


Fig.1.1 Phnom Penh City and its district boundaries[6), 7)].

Fig.1.2 Urban flooding in Phnom Penh City[8].

1.2 Research goal and objectives

The aim of this research is to develop a watershed-based methodology for land use planning in PPC suffering from urban flooding with the following fourth objectives:

1. Clarification the research trends of watershed-based land use analysis, which have been introduced widely not only in the fields of hydrology, environmental management, but also in land use and landscape planning.
2. Preparation of GIS-based spatial databases for watershed-based land use analysis under the lack of sufficient public databases in PPC
3. Conception of watershed-based land use planning for PPC at macro scale reflecting on the interaction between upstream and downstream of one's development area as part of the watershed.
4. Introduction of Hydrological Sensitive Areas (HSAs) and design measures of Low Impact Development-Best Management Practices (LID-BMPs) to discuss at middle and micro scales of

land use planning in PPC.

1.3 Existing studies in PPC, research methodologies, positions and framework

1.3.1 Existing studies in PPC

Few existing studies in PPC are defined and focused in this part. Other existing researches on watershed-based land use analysis are clarified in **Chapter 3**.

a) Watershed related study

Fundamentally, most of the existing studies on the issues of flood simulation and analyze of drainage system are based on the partition of 21 watershed basins divided according to the topography, hydraulic characteristics, and land use[10)].

b) Flood prone area

In the presence of flood prone map, highlighted of areas having a high vulnerability to flooding disaster is demonstrated. One of the typical analyses known as "Two-dimensional Unsteady Flow Method" was applied to the municipality of PPC with 11 case studies including 2, 5, 10 and 30 years return periods and overflow with 10 and 30 years in terms of taking account into with and without the presence of project simulation[10)]. With the available data of Digital Elevation Model (DEM), a simple flood modeling technique was carried out with the simulation of 2-dimensional flood model in the center area of PPC[11)]. A case study of Boeung Kak area drainage assessment with 3 scenarios and an existing case was simulated for extents of flood mapping with the illustration of peak flood impact[12)]. Major flood risk area in PPC was then identified by Mekong River Commission (MRC) [13)].

c) Design measures

With the goal of preserving and enhancing of ecological, cultural and aesthetical value for PPC, the proposal of design measures based on sustainable stormwater management with several techniques including infiltrating surface like grass, filter strips and swales, gravel, soak ways, permeable paving, etc. and adjusted architecture like rooftop vegetation, water harvesting, and floodable housing, is proposed in a case study with the consideration of the analysis of PPC and master plan of PPC in 2020[5)].

1.3.2 Research methodologies

The developed methodology presented in this dissertation is defined based on the necessity of appropriate and applicable concept of land use planning for urban flooding mitigation planning as well as for future sustainable land use planning in cities of developing countries like PPC, where the urban flooding is one of the key issues in urban development.

The main methodologies of this dissertation are firstly involved in the wide review of existing methodologies, selecting the appropriate methodologies and developing it to apply for PPC. Secondly, self-created GIS-based spatial databases for PPC is conducted with the aid of GIS. Thirdly, a site survey is conducted to validate the analyzed results and the development for practical use.

The watershed-based methodology developed in this dissertation is multidisciplinary approaches involved in the interaction between human activities and natural resources in land use issues, in which the research trends of this realm are reviewed with different research fields not only in hydrology, environmental management but also in land use and landscape planning[9)].

From the review of research trends in watershed-based land use analysis, trends of basic tools including land use detection methods, threshold definition methods in watershed delineation process, and one of the factors considered in watershed-based land use analysis as expressed in **Fig.1.3** are used for developing a watershed-based methodology for land use planning in PPC.

With the trialing threshold value method, the methodology developed in this dissertation is discussed based on three scales of the watershed: macro, middle, and micro. With the aid of land use detection using remote sensing data, a new concept of watershed-based land use planning for PPC at macro scale is illustrated. Hydrological Sensitive Areas (HSAs), a method of land suitability and allocation analysis considered as one among five factors in watershed-based land use analysis, land use detection for creating impervious surface area ratios, creation of soil databases using sub-soil data, and site survey are used for demonstrating the concept of watershed-based land use planning for PPC at middle scale. GIS-based multi-criteria assessment modeling for design measures on HSAs with site survey is discussed at micro scale planning. Suitability maps of a case study at micro scale with the flowchart of a watershed-based methodology for land use planning in PPC are finalized and proposed to PPC.

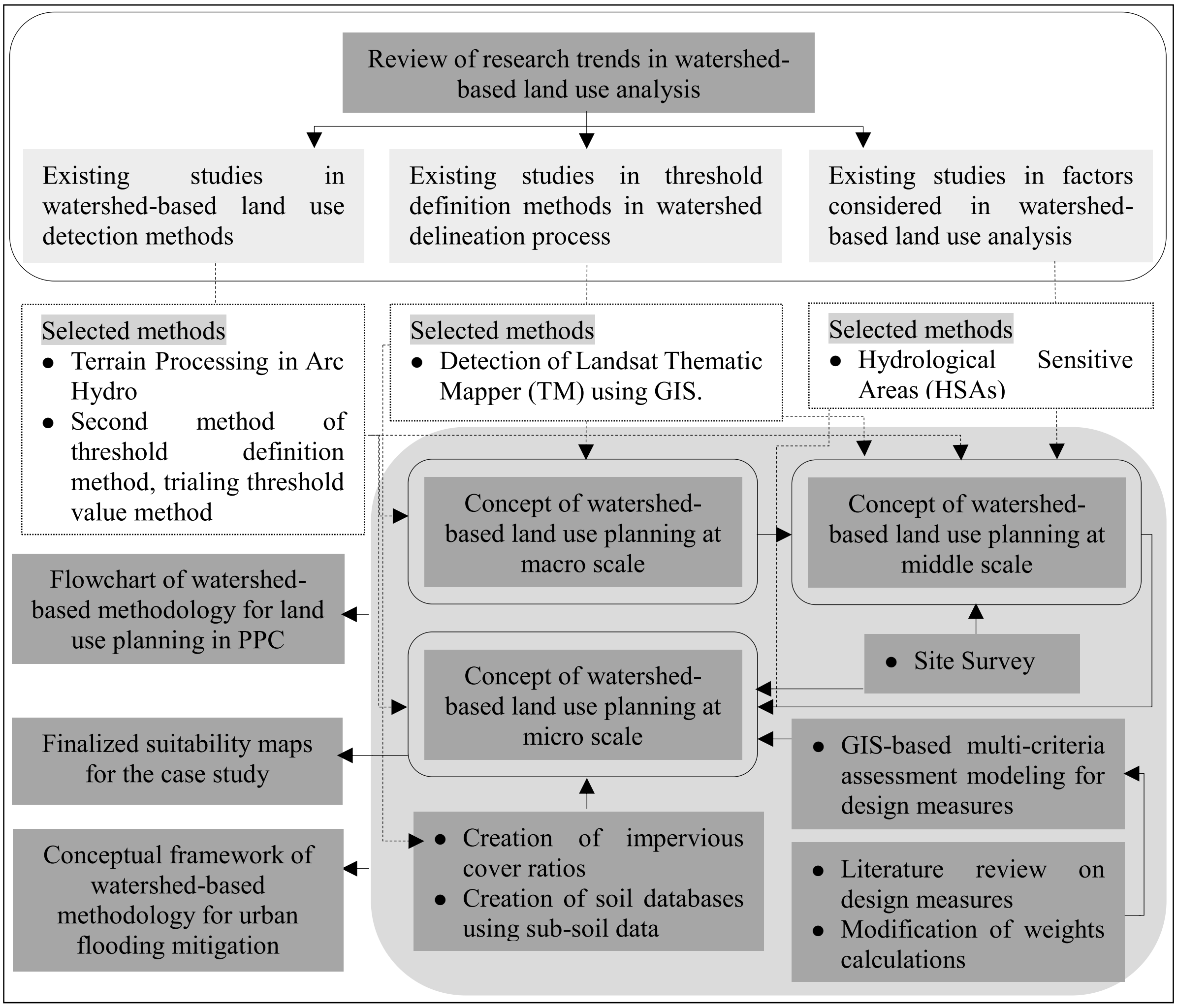


Fig.1.3 Research flow

1.3.3 Research positions

Very limited researches have been conducted on planning in PPC and thus carried out in this research. The unique of this dissertation is composed of three main components as follows:

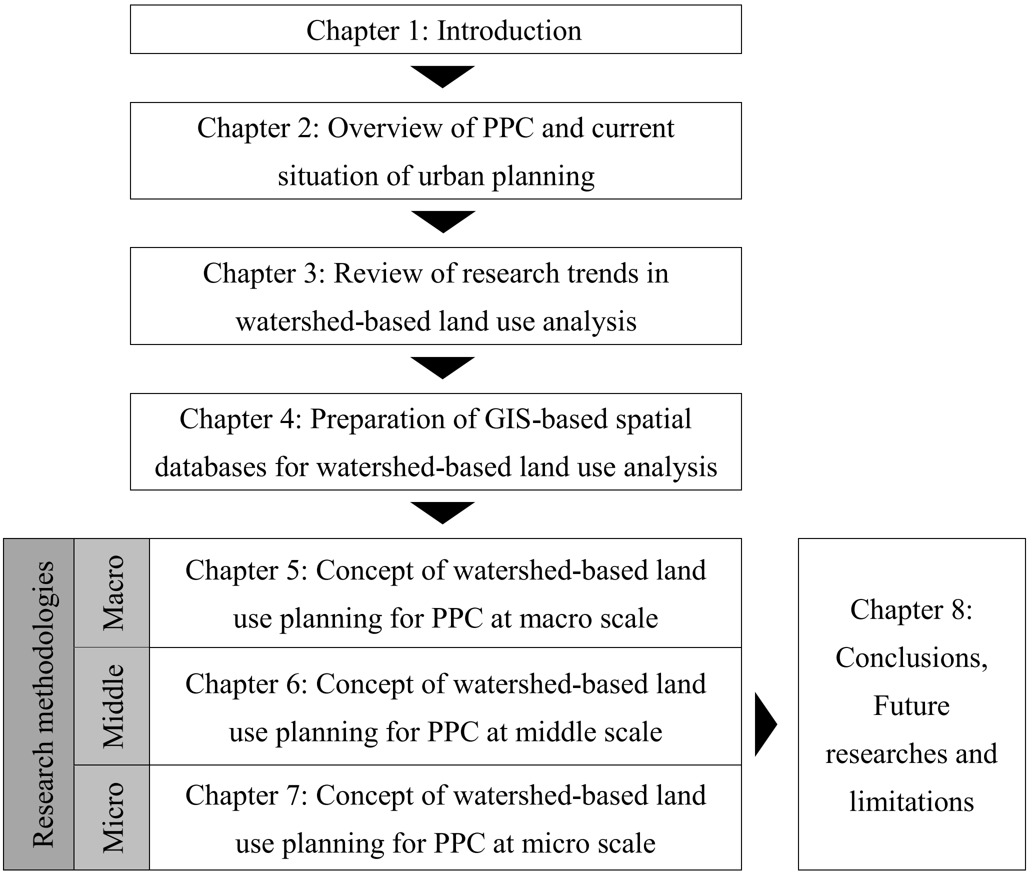
1. The ideas of the watershed-based methodology are combined and introduced to land use planning in PPC.
2. Scales of the watershed: micro, middle, and macro are defined and introduced to PPC's land use planning.
3. Concrete analysis results with the flowchart of a watershed-based methodology for land use in

PPC are proposed to the development of land use planning in PPC.

1.3.4 Research framework

Research framework in this research is shown in **Table 1.1**.

Table 1.1 Research framework.



1.4 Structure of Dissertation

This dissertation is composed of 8 chapters.

Chapter 1: An introduction shows the necessities of this research in current urban development in Phnom Penh City. Research background, research goal, and objectives, research methodology, positions and framework of this research are explained.

Chapter 2: Overview of PPC and current situation of urban planning in PPC are demonstrated. Basic information of PPC is firstly explained. History aspect of urban development in PPC has demonstrated afterwards. Finally, the current situation of urban development in PPC is illustrated.

Chapter 3: A wide literature review of existing studies to clarify the research trends of watershed-based land use analysis is conducted including basic tools, factors, methodologies, study regions, scales and areas, and the relationship of these factors in watershed-based land use analysis.

Chapter 4: Demonstration of GIS-based spatial databases preparation for watershed-based land use planning is presented. Determination of threshold value for three scales: macro, middle and micro from watershed planning perspective are conducted afterwards. Importance steps of land use detection method using remote sensing image with the combination of first level land use classification system are then demonstrated.

Chapter 5: Concept of watershed-based land use planning for PPC at macro scale is presented in terms of two contexts. Firstly, the transformation of land use pattern in 2005, 2015, and master plan in 2020 based on zoning area in each watershed is presented. Secondly, the relationship between upstream and downstream area is discussed based upon the interaction of zoning area and outside of zoning area as part of the watershed.

Chapter 6: Concept of watershed-based land use planning for PPC at middle scale is conducted. It's involved in the creation of soil database and numerical calculation of soil water storage, identification of wetness index, the creation of impervious cover ratios, and determination of threshold value of Hydrological Sensitive Areas (HSAs) for PPC. Based on defined HSAs, the actual condition of HSAs determined from site survey and master plan in 2020, land use development trends in PPC is identified.

Chapter 7: Concepts of watershed-based land use planning for PPC at micro scale is discussed. Low Impact Development-Best Management Practices from existing method are introduced for better design measures applied to HSAs. Suitability matrix of LID-BMPs is defined based on HSAs and site survey at a micro-scale case study. Finalized maps of HSAs and suitability for design measures of LID-BMPs are conducted.

Chapter 8: Summary of key findings, future researches and limitations are presented in the last chapter of this dissertation.

References:

1. DeFries, R. and Eshleman, K. N.: Land-use change and hydrologic process: A major focus for the future, *Hydro. Process,* Vol. 18, pp. 2183-2186, 2004.
2. Bhaduri, B., Harbor, J. O. N., Engel, B. and Grove, M.: Assessing watershed-scale, long-term hydrologic impacts of land-use change using a GIS-NPS model, *Environmental Management*, Vol. 26, No. 6, pp. 643-658, 2000.
3. Miguez, M. G., Rezende, O. M. and Veról, A. P.: City growth and urban drainage alternatives: sustainability challenge, *J. Urban Planning and Development*, Vol. 141, Issue 3, 2015.
4. Molyvan, V.: Modern Khmer Cities. *1st Edition, Reyum Publishing*, 2004. (Khmer Language).
5. Englund, G. and Ryttar, S.: The blue pearl of Asia: Flooding as an urban asset-a beautiful and resilient future Phnom Penh, *Final thesis in landscape planning 30+30 hp*, *Swedish University of Agricultural Science*, 2008.
6. Aruna Technology Ltd, *1: 100,000 Scale Topographic Map WGS84/UTM Coordinates*, viewed 10 October 2014, from http://arunatechnology.com/resources/downloads/.
7. Open Development Cambodia, *Base Map*, viewed 01 October 2014, from http://archive.opendevelopmentcambodia.net/maps/downloads/?%20map=base&submit=Search.
8. City of Water, *Phnom Penh Rains on CNN Report*, viewed 02 February 2017, from https://cityof water.files.word press.com/2012/05/img0062jpg-2092994_p9.jpg.
9. Lim, L. and Sasaki, Y.: Review of research trends in watershed-based land use analysis, *J. Infrastructure Planning and Management,* JSCE, Vol.4, 227-242, 2016.
10. JICA Report PDF, 1999, *The Study on Drainage Improvement and Flood Control in the Municipality of Phnom Penh*, viewed 02 October 2015, from http://open_jicareport.jica.go.jp/618/618/618_109_ 11527892.html.
11. Demonstrator of interactive flash flood mapping for Phnom Penh, *flood simulation*, viewed 02 February 2017, from http://flooddemo.jennylestil.com/.
12. Rogencamp, G., Benham, S., Caddis, B., Spralja, D and Dearnley, C, 2008, *Boeung Kak Area*

Drainage and Flooding Assessment, viewed 02 February 2017,

from https://cityofwater.files.wordpress.com/2012/01/final-bk-flooding-assessment-report.pdf.

13. Mekong River Commission, *Flood Information*, viewed 01 May 2017,

from http://ff w.mrcmekong.org/topo.htm#here.

CHAPTER 2
Overview of PPC and current situation of urban planning

2.0 Summary of chapter

This chapter is composed of mainly three main parts. In the first part, overall view of PPC, basic information including geography, demographic, administration, and economic are explained. In the second part, the historical aspect of urban development from pre-colonial to current periods in PPC is summarized afterwards. In the final part, the current situation of urban development in PPC including the law of urban relative development and limitation of the sufficient data, land use map and master plan, ongoing project development plans, and flooding issues in PPC are discussed next.

2.1 Overview of PPC

2.1.1 Geography

Cambodia has an area of 181,035 km^2. It entirely lies within the tropics and dominated by monsoons, tropical wet and dry. Its landscape is characterized by a low-lying central plain as shown in **Fig.2.1**.

Phnom Penh City (PPC), the capital of Cambodia, is located in the south-central region of the country, at the intersection of 4 rivers: Upper and Lower Mekong Rivers, Tonle Sap River and Basak River as shown in **Fig.2.2**. Freshwater and other natural resource are provided to the city through these rivers. PPC is known as the largest and the most populous city of Cambodia. Encompassing an area of 678.46 km^2, about 0.37% of the total country's area, Phnom Penh metropolitan area is the heart of Cambodia, which functions as centers of economic, industrial, politic, cultural heritage and diplomacy.

Under French colonial for 90 years, this city once was known as "the Pearl of Asia", a French-built city in the 1960s. Currently, many French colonial buildings are remained and scattered around and along main boulevards in PPC.

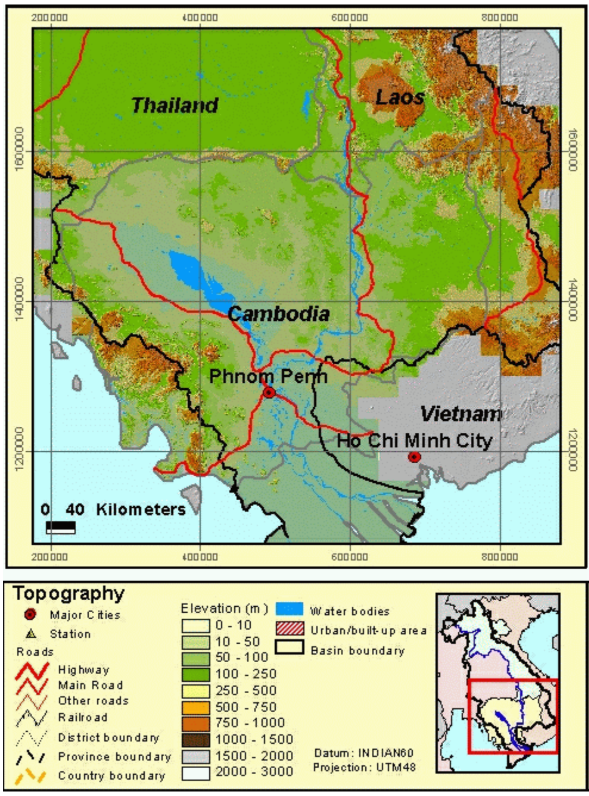


Fig.2.1 Topographic map of Cambodia[1].

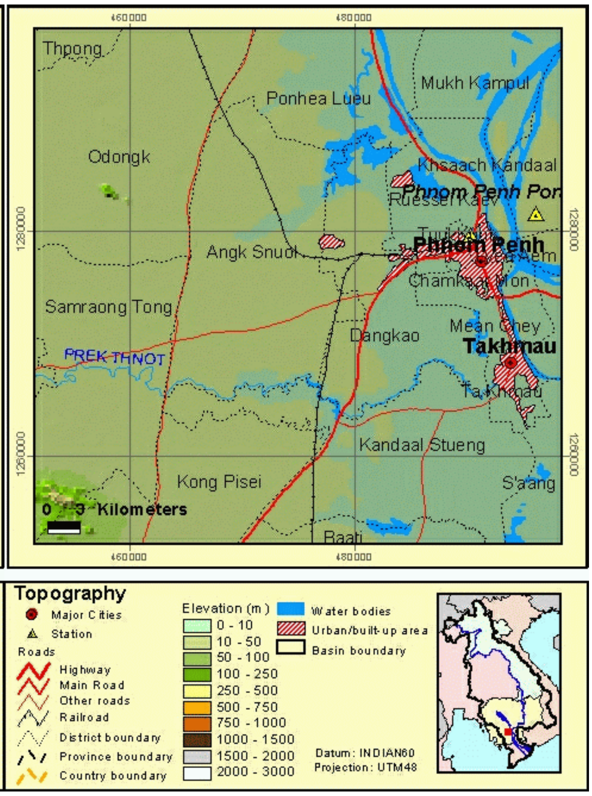


Fig.2.2 Topographic map of Phnom Penh City[1].

a) Climate

Having a tropical wet and dry climate, two seasons are distinct in Phnom Penh City (PPC). The rainy season lasts from May to October with elevated temperature and humidity. Dry season, from November to April, is dominated by dry winds from Continental Shelf[2]. PPC is suffered from the intense and short duration of rain during the rainy season, which causes constraint in evacuating of these waters. The most intense rainfall generally occurs during September and October as expressed in **Fig.2.3** while the driest period is January and February[3]. Temperature normally varies from 18 to 38 °C.

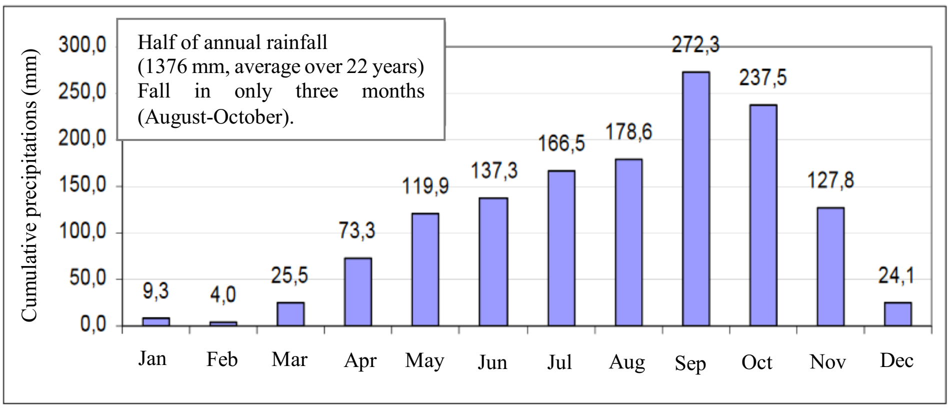


Fig.2.3 Cumulative precipitations in Phnom Penh City from 1981-2003[3].

b) Water levels

On Mekong River system, from Department of Hydrology of General Directorate of Irrigation, Meteorology and Hydrology (GDIMH), Ministry of Agriculture, Forestry, and Fisheries (MAFF), three water level gauging stations are provided: Chaktomuk has been observed since 1960 with the exception between January 1975 and June 1980, Phnom Penh Port, and Changvar water level gauging station records are only available from 1993.

The gauging stations are observed twice a day, at 7:00 and at 19:00[2)]. The water level at 7 am of Mekong River at Phnom Penh Chaktomuk is expressed in **Fig.2.4**.

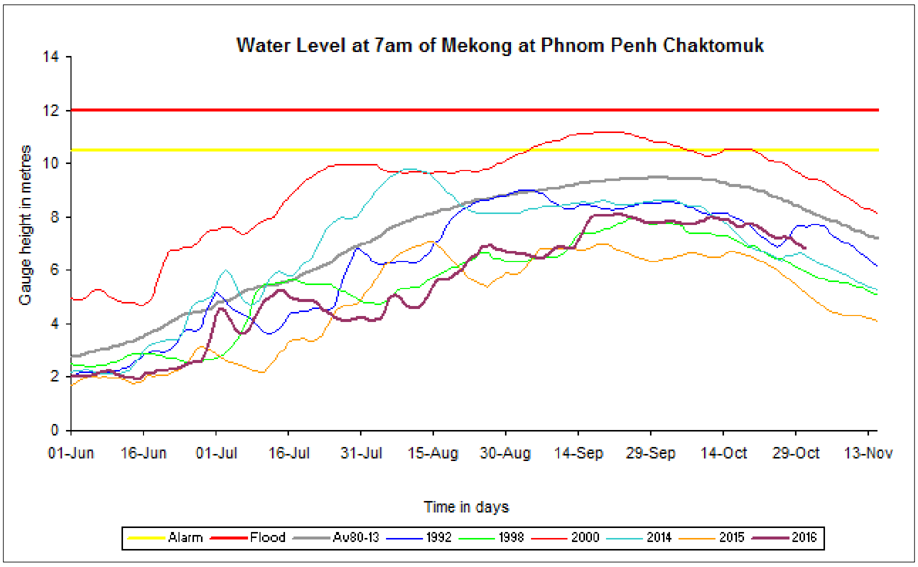


Fig.2.4 Water level at 7 am of Mekong at Phnom Penh Chaktomuk[1)].

2.1.2 Demographic

Cambodia population is over 15 million people with estimation of total population and population of male and female in the certain age group are as shown in **Fig.2.5** and **Fig.2.6** respectively. As of 2011, in Phnom Penh City (PPC), the population is around 1.5 million with the estimation of population in 2030 as shown in **Fig.2.7**.

90% of Phnom Penh's population is Cambodian with religious of Theravada Buddhism. Whereas the rest of 10% are Chinese, Vietnamese and another small group of ethnics.

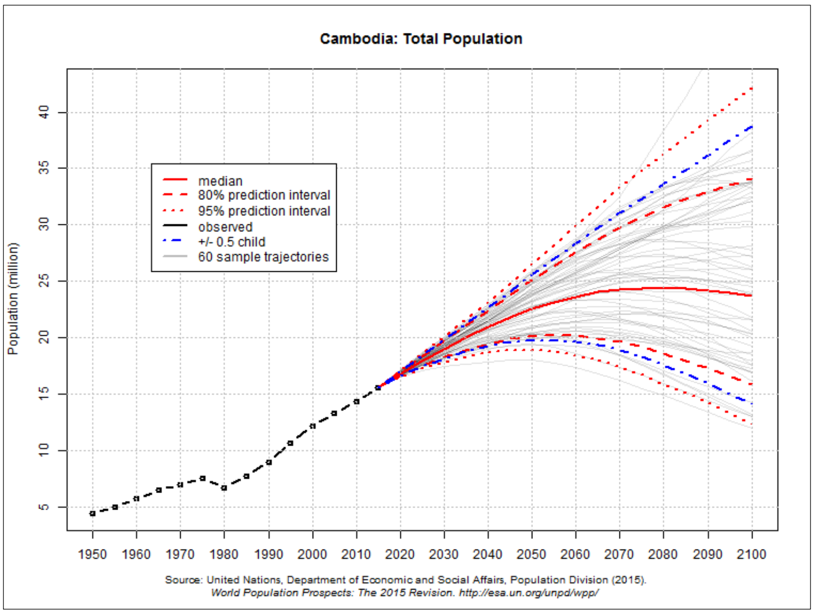


Fig.2.5 Estimation of total population in Cambodia[4].

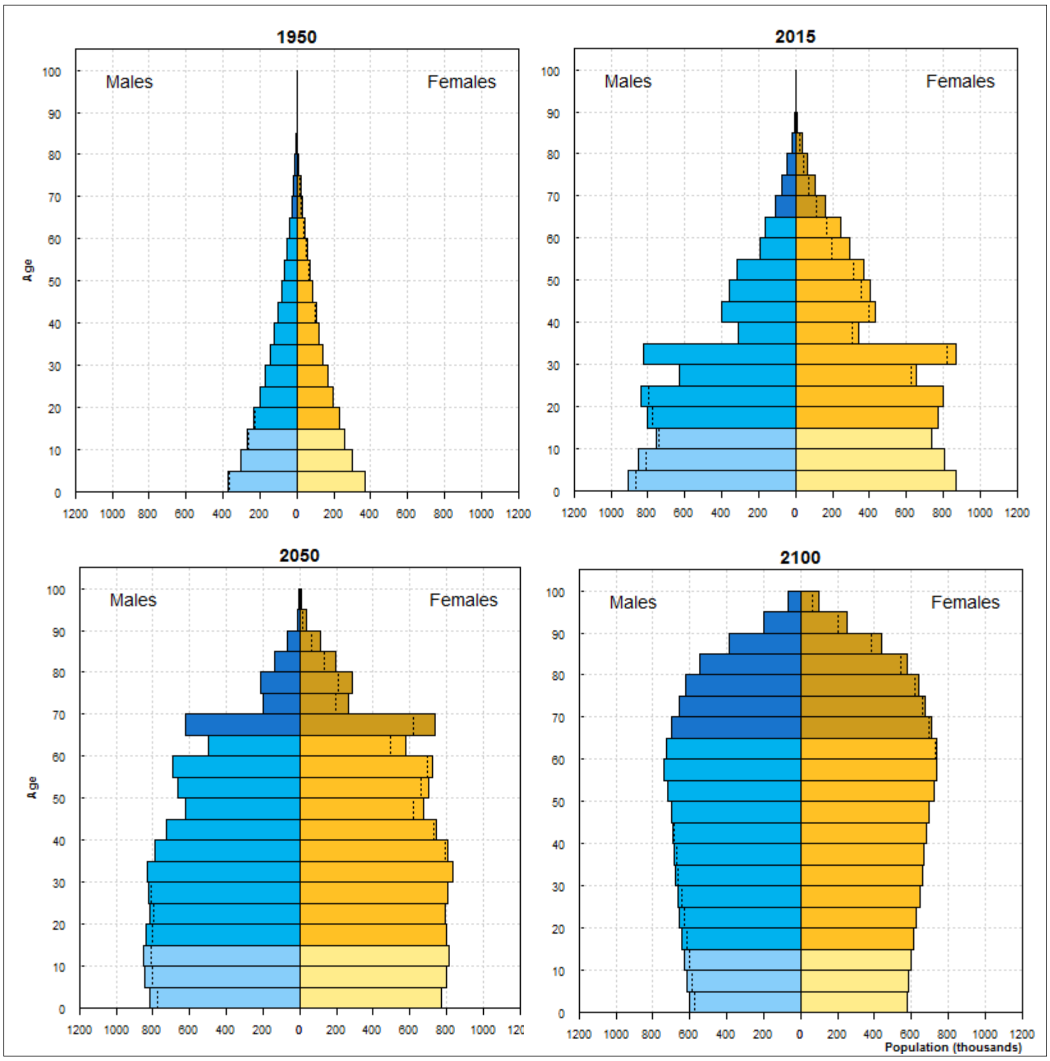


Fig.2.6 Estimation of the population of male and female in a certain age group in Cambodia[4].

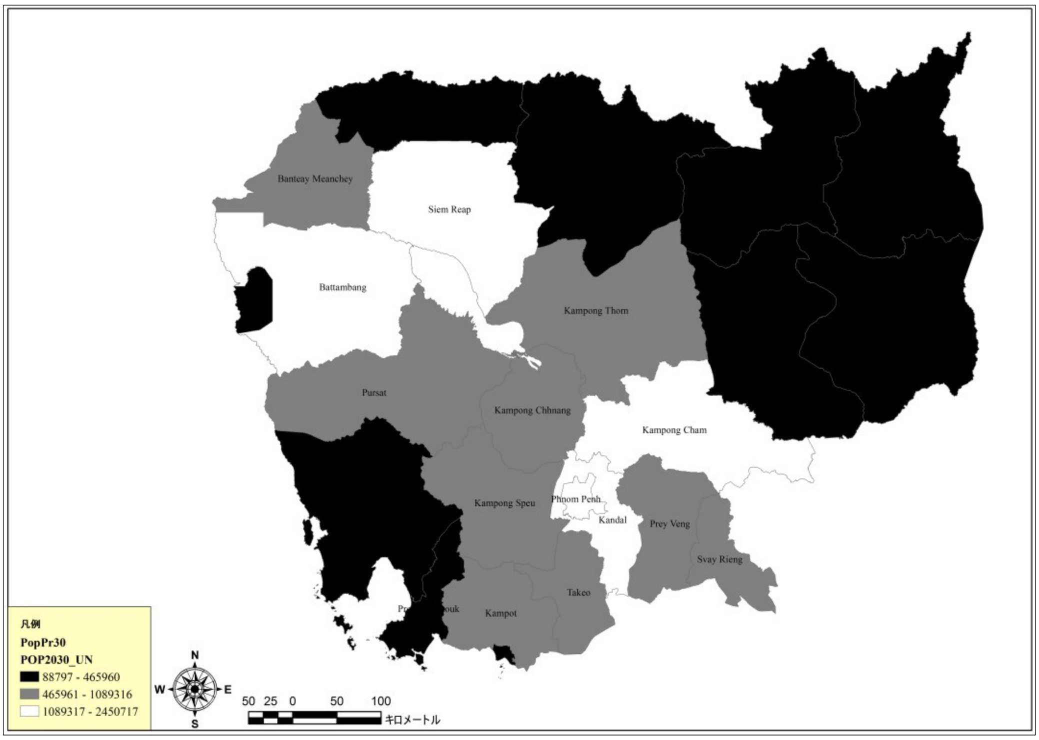


Fig.2.7 Estimation of population in Phnom Penh City[5), 6)].

2.1.3 Administration

Hierarchy territorial division of Phnom Penh City (PPC) are Khan (district), Sangkat (commune) and Kroms (villages) [7)] as shown in **Fig.2.8**. All Khans are governed by Municipality of Phnom Penh City. As of 2011, a total of 9 Khans are subdivided into 96 Sangkats and 897 Kroms[6)]. List of Phnom Penh administrative districts is shown in **Table 2.1**.

Table 2.1 List of Phnom Penh Administrative Districts[6)].

Districts' names	Communes 'numbers	Villages' numbers	Population as of 2011
Chamkar Mon	12	95	182,004
Doun Penh	11	134	126,550
Prampir Meakkakra	8	66	91,895
Tuol Kouk	10	143	171,200
Dangkao	13	87	73,287
Mean Chey	12	83	327,801
Ruessei Kaev	11	43	196,684
Sen Sok	6	49	147,867
Pou Senchey	13	197	184,437

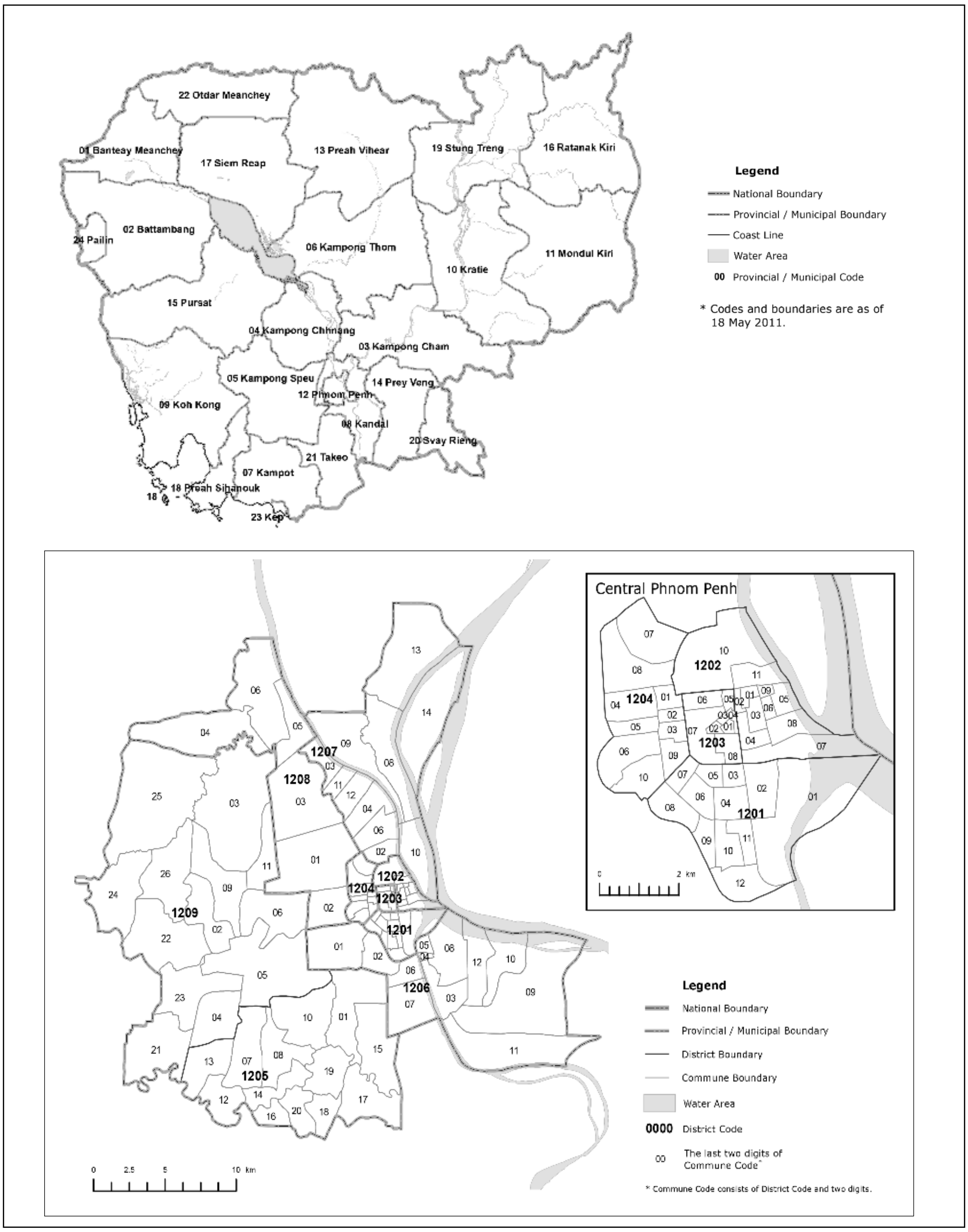


Fig.2.8 Hierarchy territorial division of Phnom Penh City[7].

2.1.4 Economic

Phnom Penh's main economy is based on commercial interests including garments, small enterprises, and medium size enterprises.

Since the 1990s, the economy of Cambodia has steadily increased, Western-style malls and new shops have been opening[8] as shown in **Fig.2.9**. More and more franchises from foreign countries have been obtaining and introducing to Phnom Penh' markets. Skyscrapers, high-rise buildings, and modern satellite cities projects have been gradually increasing as expressed in **Fig.2.10**, which have brought about the increase of life quality with the cityscape as shown in **Fig.2.11**.

Fig.2.9 Shopping mall[8].

Name of projects	
	
Phnom Penh Tower[9] (Completed).	Gold Tower 42[10] (On hold).
	
Vattanac Capital (left) and OCIC Tower (right). (24 January 2017)	Diamond Island City. (25 January 2017)

Fig.2.10 Example of Skyscrapers, high-rise buildings, and modern satellite cities

Fig.2.11 Cityscape of PPC and its development[8].

2.2 Historical perspectives of urban development in PPC

2.2.1 Urban development in PPC (1432-1995)

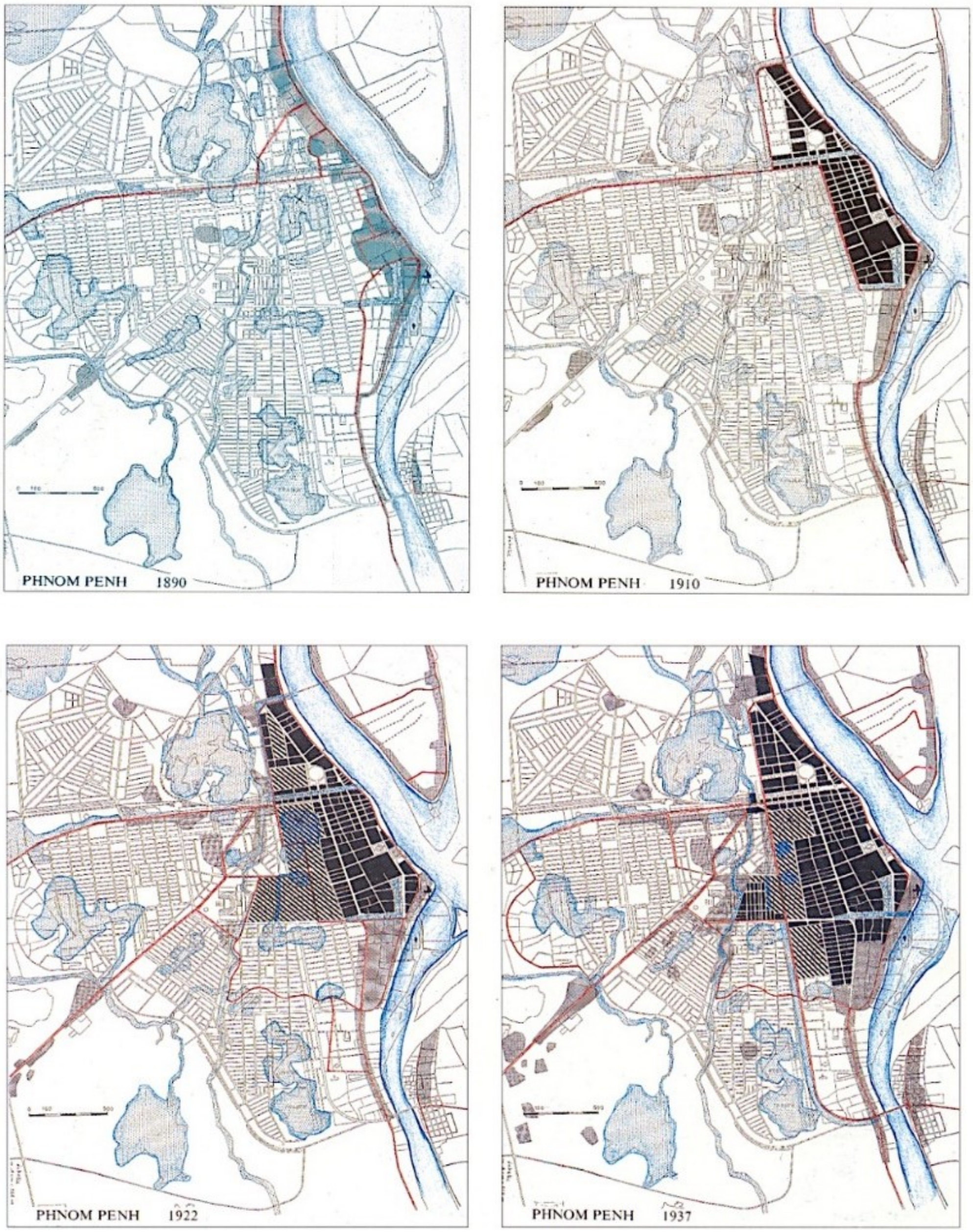
As shown in **Table 2.2**, history of urban development in PPC is closely involved with 6 remarkable periods[11]: Pre-colonial period (1432-1863), Colonial period (1863-1953), Independence period (1954-1975), Khmer Rouge period (1975-1979), Vietnamese Occupation period (1979-1989) and Peace and rehabilitation period (1989-1995).

Table 2.2 History of urban development in PPC.

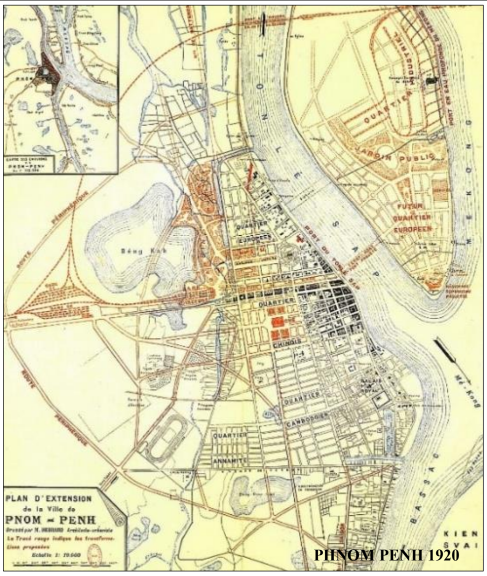
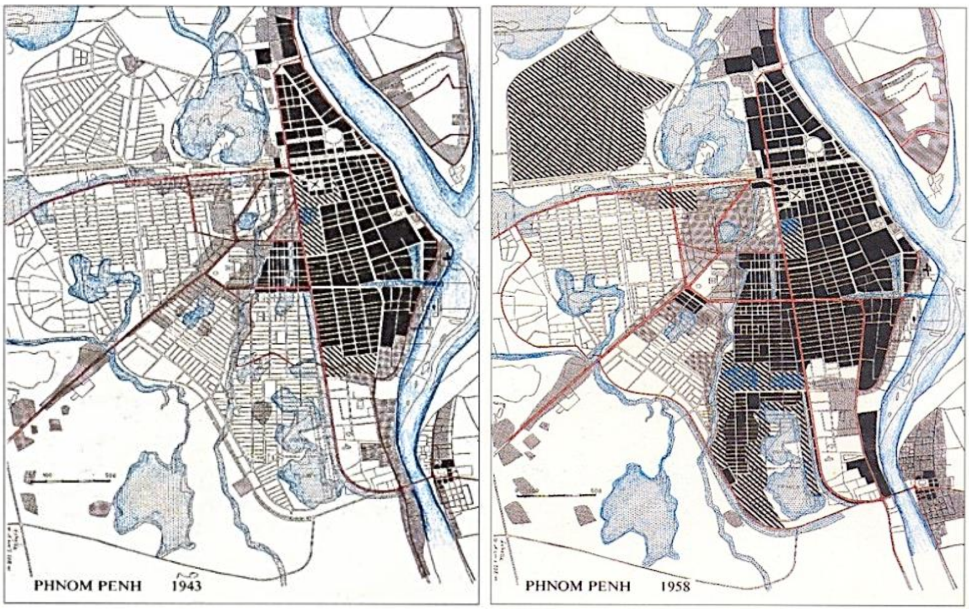
Period/Year	Description of each urban development stage in PPC
1432-1863 **Pre-colonial period**	● Establishment on the Mekong River bank. ● Canals, reservoirs, and banks were made for flood prevention. ● Houses were built on stilts. ● Only Preah Sisowath Quay was the only inner road in the city.

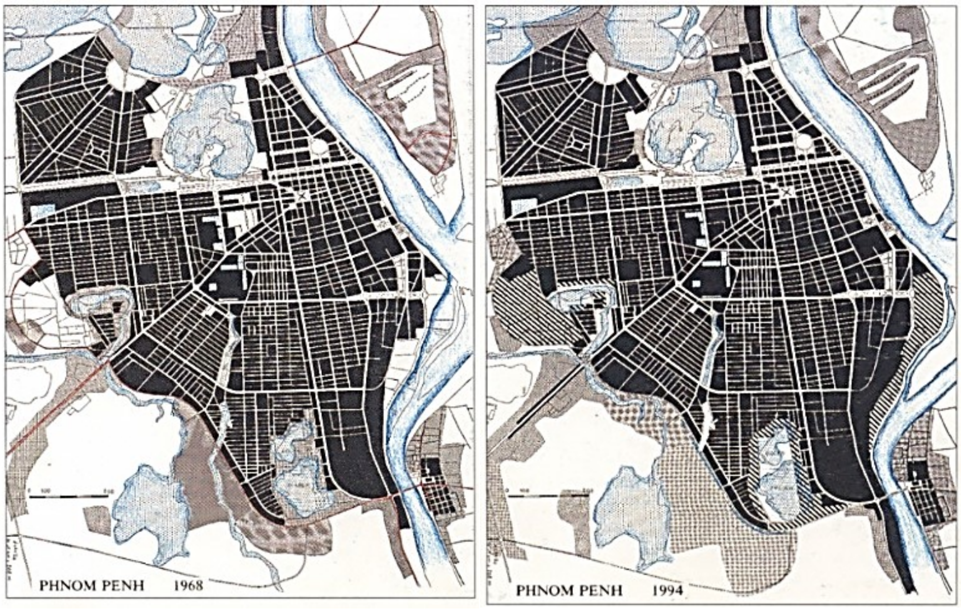
1863-1953

Colonial period



Historical City 1900-1940[12)].

	 Phnom Penh City in 1920[13]. This stage called “Historical City”, the development of PPC’ land use was mainly focused on[12]: ● Creation of multimedia centers. ● Expansion of city by filling the flood plain area. ● Strategic planning of land use planning based on creation of public spaces and large official buildings.
1954-1975 **<u>Independence period</u>**	 Dike City 1955-1970[12]. ● Planning of land use was based on the land division for flat houses. ● International Airport, Olympic Stadium, and the theater were constructed. ● The establishment of first urban planning was identified.
1975-1979 **<u>Khmer Rouge period</u>**	All component of the city were destructed and neglected during the Khmer Rouge[11]

1979-1989 **<u>Vietnamese Occupation period</u>**	Areas of slum settlements were develped[11].
Beginning of the 90s **<u>Peace and Rehabilitation period</u>**	The beginning of the reformation of the historical city took place in 1991 after several years of civil war[11]. The sign of peaceful appeared in terms of restoration and development of the city after the arrival of United Nation in election period (1993) took place. ● Villas, the majority of Government Official Buildings were restored. ● Warehouses along Mekong River bank were rebuilt as gardens.  Reconstruction and Urban Expansion (1979~) [12].

2.2.2 Urban development in PPC (1995-current)

In mid of the 90s, thanks to international sponsors and collection of the first mobilization of funds, many development plans were implemented[13].

- Landfill of the low-lying plain area in front of the river, Bassak River, which is one of the intersected rivers where PPC is located, enabled the connection of one main boulevard named Preah Sihanouk to the Riverside, was carried out.
- Public and open space named "Hun Sen Garden" and construction of some new buildings in

the north part of the hotel named “Cambodiana Hotel”, which is located at the embankment of Tonle Sap River and in the heart of PPC, was created.

- Renovation of public open space named “Wat Phnom Garden” with the tallest religious structure and located in the central point of the PPC was realized.
- Expansion of Riverside in the Chruy Changvar, the opposite side of PPC, which is located along the riverside, was made. Restoration of the infrastructure began including various roads in Sangkat (one hierarchy territorial division in PPC, which is under the district division) located in core zone of the city, clean water and electricity system, repair of dikes outside the city and water pumping station.

At the end of the 90s, the development of economic and foreign investment in the city had begun, which brought many development plans to the city.

- Garment factories were established along each district located nearby the suburb areas.
- Land divisions along the main boulevards and public spaces (for example, Phnom Penh National Olympic Stadium) have been gradually increasing.
- Villas made of brick-concrete had gradually replaced the wooden houses in Sangkat located in the southern part of PPC.
- Big house with higher fence buildings primarily appeared.

In 2001, disorderly of land use development had occurred everywhere.

- 2 or 3 floors flat house buildings and villas have been gradually increasing.
- Along with the development of land use, most requested construction area (1,200,000 m^2) was used to build houses for Cambodia citizen mainly are government officers, businessmen, and craftsmen in exchange for their houses in the core city, which were found too crowded and too noisy. The new houses normally have quite environment, different land use types (abandon agricultural land) of the previous house and large size in a new Sangkat of PPC.
- Rapid increasing of factories has found located along the width road like national road toward the city.

In brief, areas for constructing houses have been steadily increasing year after year from 2001 afterwards.

In 2003, the presence of local and foreign investments (Canadia, Seoul, Manila, Singapore), urban development in PPC has been progressively developed as follows:

- Many mega projects with the high demand of land have been rapidly increasing.
- Purchasing of public spaces (area of the railway station, public universities, and lakes used for stocking rain water) and land reclamation have been gradually growing in number among the investors and private sectors.
- Development plans named "New City" composed of offices, residential, and other usable buildings etc. with high-security service, were introduced. Most of these plans have been carried out nearby suburb areas (not too far from the core center).

Requesting of areas for the buildings was dramatically growing from 1,200,000 m^2 in 2001 to 4,500,000 m^2 in 2007.

From 2007 to current, urban development in both core zone and suburbs is as follows:

- Historical City-Core zone of PPC
  - Building density of each district in the city's been increasing, particularly in the high-rise buildings.
  - Certain areas including Wat Phnom, Royal Palaces, Independence Monument, Central Market, and natural resorts in Chatomok Area along the riverside, are preserved.
  - A notable landfilled natural reservoir inside the city center, Boeung Kak, is currently developed as a satellite city.
- Suburbs of Phnom Penh City
  - Transformation of agricultural land to land for construction is rapidly growing in number.
  - Crafts, warehouses, factories, enterprises and special economic zones surrounding the Phnom Penh International Airports, which is along the national road from PPC to other provinces, have been rising.

- Many new development zones have been gradually formed.

2.3 Current condition of urban development in PPC

2.3.1 Law of urban relative development in PPC

As of 2010, about 189 of laws and legal regulations concerning land issues in Cambodia have been enacted since 1985[14)], which are including land law, land ownership, state property, land concession, economic land concession, concession, urban planning, construction permits, environmental protection, and environmental impact assessment[6)].

In this dissertation, descriptions concerning about two of the most important laws used to discuss sustainable development in PPC are extracted:

- Law on Land Use Planning, Urbanization and Construction (LLUPUC), No04NS94, August 10, 1994[14)].
- Law on the Environmental Protection and Natural Environmental Resource Management, NS/RKM/1296/36, December 24, 1996[14)].

a) Law on Land Use Planning, Urbanization and Construction (LLUPUC) No04NS94

Fundamentally, land use zoning plans enable the planner to regulate, form, design and attempt to control and manage the development to seek for the better living, and sustainable land use development[6)]. In the contrast, with the lack of zoning, instead of taking into account for the future development, immediate profits are considered. Therefore, without zoning regulations laid out by the access for the basic service and infrastructure in the urban master plan, the sustainability of the city, and the quality of city life will decrease as the urban development continues.

In Phnom Penh City, the establishment of Law on Land Use Planning, Urbanization and Construction was created in August 1994 with the procedures for both formulations of development plans and land use plans based on the national and local levels. Issued articles in urban planning are focusing on the formulation of the development master plans and land use master plans under the development plans are required for Phnom Penh City at provincial and municipal levels. The land use master plans with zoning system comprising areas for allocation of national defense, agriculture, commerce, industrial, handicraft, culture, tourism, religion and administrative, and public facilities shall be established while construction work conducted based on the development plan, land use plans, and relevant documents[6)]; however, the application seems not exactly following the enacted law.

Some important and basic articles in general land use rules focusing on natural, location and sideboard to the construction area in chapter 1 and location and site of constructions in chapter 2 of Sub-Decree #86[15)] are described as following:

- **Natural, Location, and Sideboard to The Constructions Areas[15)]**

  - Article 32: Prohibited zone

    Each province and municipality shall establish without delay a plan of prohibited zones. This plan shall integrate the protection of agricultural and forestry and mining zones which shall not be changed by reason of their ecological and economic benefits. This plan shall integrate natural sites, such that seaside, riverside, preks and pongs by reason of their patrimonial and ecological benefits. This plan shall integrate all inundated zones which are preserved by reason of their usefulness for draining rain waters and their role in preventing floods. Local authorities shall take adequate measures in order to preserve and promote these declared prohibited zones. All construction permits shall be denied on these zones.

    In the event of illegal constructions within these zones, local authorities shall demand the demolition of the constructions and the restoration to its initial state. In the event of non-completion, local authorities shall impose fines and demand to demolish and restore to its initial state on the cost of the offenders or in necessary case the local authorities could request to the court to enforce it. This plan shall be approved by the National Committee of Land Management, Urban Planning and Construction, and be made known to the public officials responsible for the protection of these prohibited zones who would not take necessary *measures to enforce it shall be sanctioned by the administrative authority. The Khmer version is the official version of this document.*

➢ **Location and Size of Construction**[15)]

- Article 35: Building to ground ratio

The constructions ratio as compared to the surface of the lot shall not in away event exceed 75% for the" apartments "and collective living quarters. For residential houses, the constructions to ground ratio shall not exceed 50% of the surface of the area of a lot. The unbuilt area of the lot shall be used for garden with a water absorbed ground on at least half of its area. For building of at least 15 living units, hotels, offices buildings and factories, the construction to ground ratio shall be not exceed 50% of the area of the lot. The Khmer version is the official version of this document. The unbuilt area of the lot shall be used for garden with a water absorbed ground on at least half of its area. The Municipality and Provincial administrative shall define the urban zones in which this rule shall apply and shall determine special rules for actual situation. The Khmer version is the official version of this document.

- Article 36: Height

Every Municipal and Provincial administration shall have in place within a period of 1 year from the date of the approval of this Anukret a master plan determining for each zone of the city a maximum construction height.

This plan shall take into account.

- Existing average height of each zone.

- The main characteristics of the zone (commercial, residential, factory, downtown or outskirts, elevated or non-elevated terrain, servitudes linked to infrastructures, etc.)

- The type of constructions (apartment, houses, buildings, warehouses and industrial buildings etc…)

This plan shall be approved by the National Committee of Land Management, Urban Planning and

Construction and be made known to the public.

b) Law on Environmental Protection and Natural Resource Management (LEPNRM) NS/RKM/1296/36

Significant beneficial of land use can be added as long as the sustainable environment is maintained. Remarkably, with the increasing concerns on the sustainable environment took place in the early 1970s; in PPC, the Law on Environmental Protection and Natural Resource Management was promulgated in 1996.

The purposes of the law are mainly based on the following points:

- Through the prevention, reduction and control of pollution, protection and promotion, environmental quality, and public health are ensured.
- All proposed projects are subjected to the assessment of the environmental impacts, which are prior to the insurance of the decision by the Royal Government.
- Rational and sustainable conservation, development management, and use of the natural resource management are ensured.
- The public to participate in environmental protection and natural resource management is allowed and encouraged.
- Any acts cause harm to the environment is suppressed.

In addition, in February 2008, the protected area law was enacted; however, no protected area was found in Phnom Penh Capital City[6)].

2.3.2 Land use data and master plan in PPC

a) Land use data in PPC

In October 2007, under the Bureau des Affairs Urbaines (BAU) supported by Embassy of France, the final report of "White Book on Development and Planning of Phnom Penh" was formulated[3)]. Available land use map and summary of land use types in 2004 can be found in **Fig.2.12** and **Table 2.3**

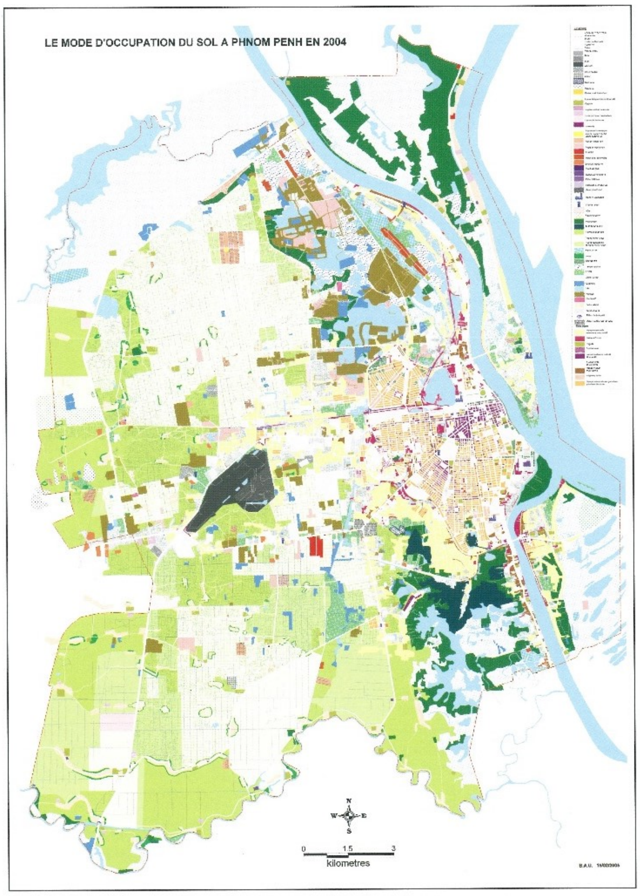


Fig.2.12 Land use map of PPC in 2004[3), 6)].

Table 2.3 Summary of PPC's Land use types in 2004.

Land use types	Total surface %
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

b) Master plan in PPC

- **Master plan in PPC from 1956-1987**

Certain master plans from the independence period in 1956, 1972 and 1987 are expressed in **Fig. 2.13**, **2.14**, and **2.15**, respectively.

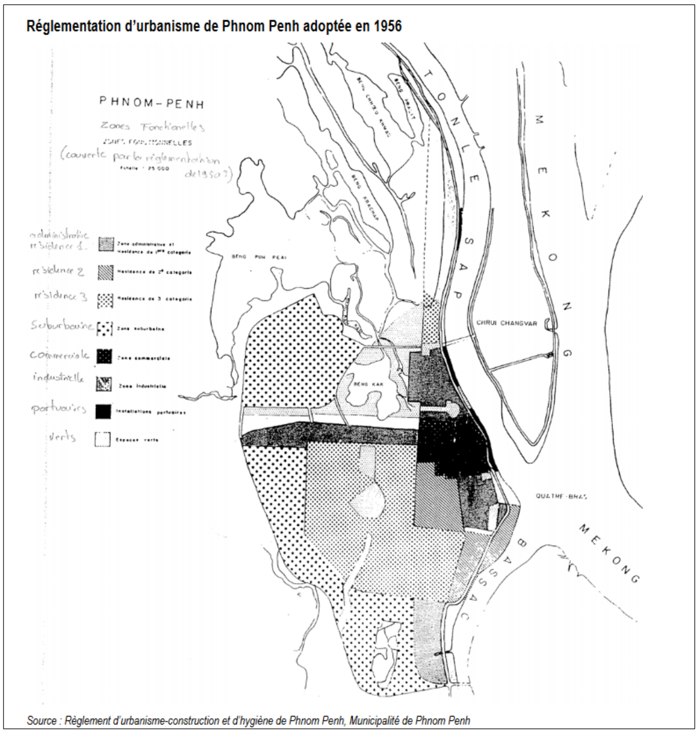


Fig. 2.13 Master plan in 1956[3].

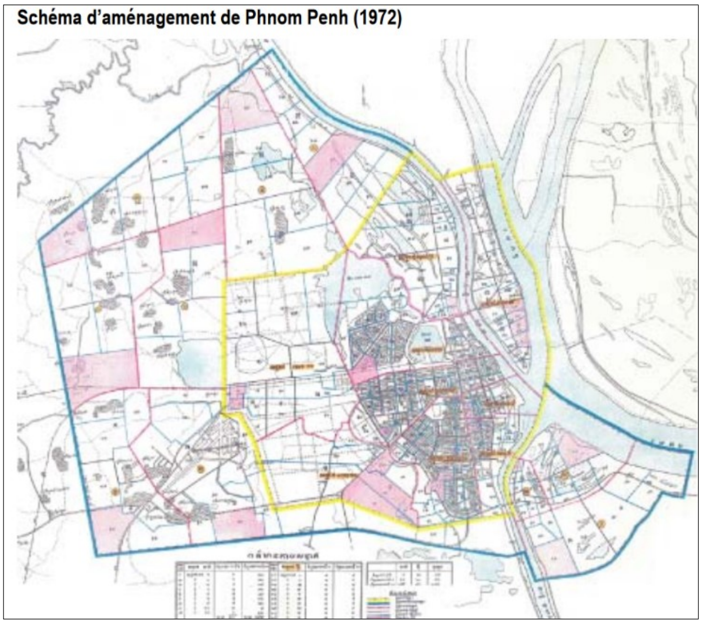


Fig. 2.14 Master plan in 1972[3].

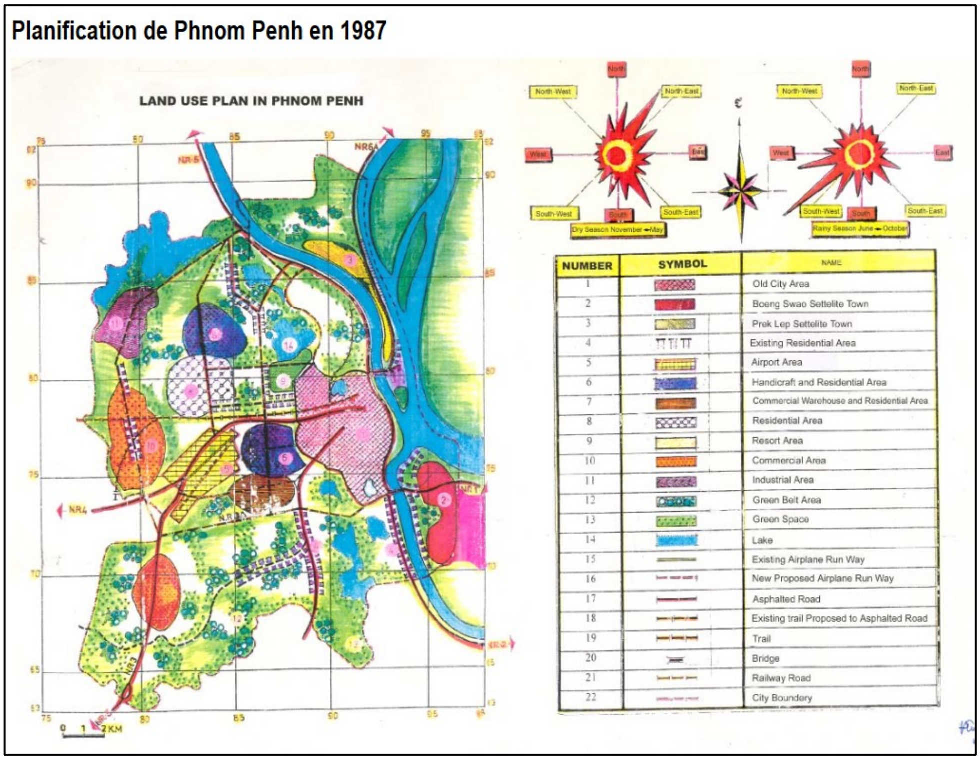


Fig. 2.15 Master plan in 1987[3)].

➢ **Master plan 2020 in PPC**

Phnom Penh Master Plan 2020[12), 13)] is demonstrated in **Fig.2.16**. With some important points had been presented regarding to master plan in 2020 as following[6)]:

- To comply with the rectangle strategy of Cambodia government, Phnom Penh City development was oriented by master plan until 2020.
- Under national level, formulation of master plan referring to territorial arrangement planning of PPC's administrative boundary and surrounding relevant center areas which help to push not only the development to free market economic but also administration management to democracy.
- With respond to the private investment and population growth, planning of public investment is oriented by master plan in 2020, which is an ambition of state's strategic document to develop and expand the city.
- With regard to environmental protection law and balance the act on natural resource, master plan in 2020 is formulated taken account into many natural resources including land, water,

energy, ecology system, and forest.

- For economic development, orientation on the development including major physical infrastructure, clean water, sewage system, road network, green space, city heritage conservation, etc. is guided by state and private investment in terms of location determination.

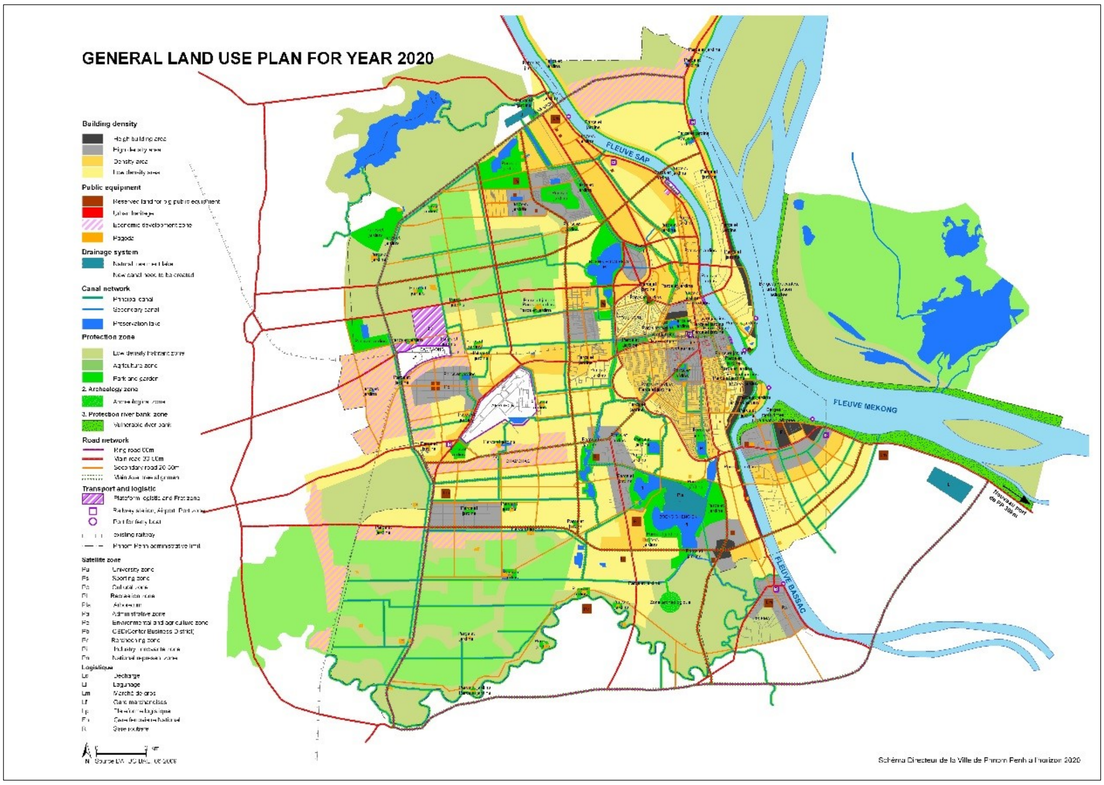


Fig.2.16 Master Plan of PPC in 2020[6), 13)].

2.3.3 Limitation of sufficient data in PPC

Generally, lack of the sufficient data is inevitable for the developing countries. Likewise, in PPC, land use data or most of the urban relative development data is not widely provided through the relevant web pages, and mainly are not considered as open source.

To obtain relevant hard and soft documents to carry out this research, personal communication was applied to the related ministries and institutions; however, only a few data mainly hard documents are available while some soft documents are available through the open source provided by the private organization. Under these circumstances, the challenge of manually creating of the necessary data is needed.

2.3.4 Ongoing project development plan

Some examples of large-scale development spots have taken place in both the center and the suburb of PPC mostly invested by private sectors are demonstrated in **Fig.2.17** with corresponding development area[6] expressed in **Table 2.4**. Historical and characteristics of three development spots in PPC with the corresponding transformation of land use in 2005 and 2015 are illustrated.

Table 2.4 Large-scale urban development by private sectors[6].

Project name	Area (ha)	Company Name
1. Grand Phnom Penh International City	233	YLP & Ciputra Group
2. Satellite City	380	OCIC
3. Camko City	119	World City (Korean)
4. Boeung Kak	133	Sukaco Inc.
5. Koh Pich (Diamond Island)	80	Canadian Bank
6. Boeng Chhouk	238	Sokimex
7. Green City (Satellite City)	2634	AZ

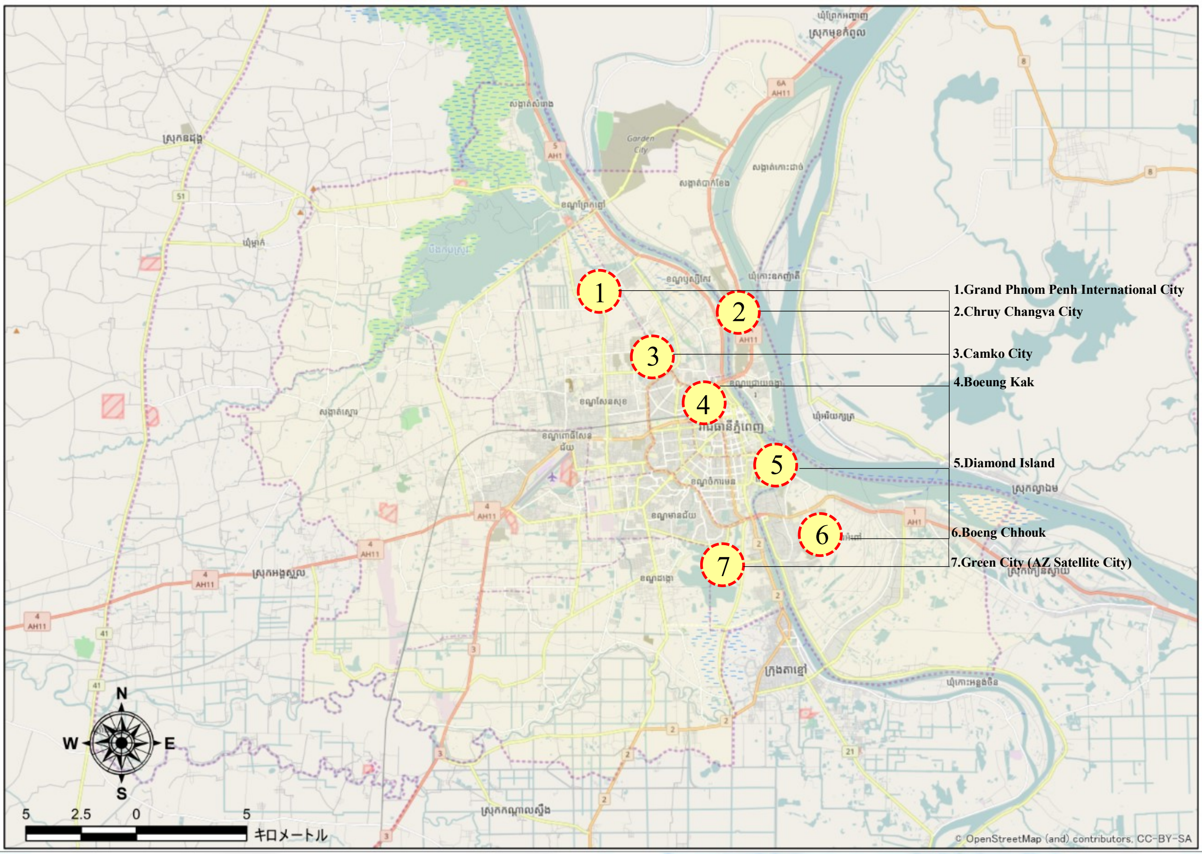


Fig.2.17 Land reclamation in some development spots in PPC.

a) Boeung Kak area

Natural lake located in the core zone of PPC known as Boeung Kak covers a 133 ha (including water surface and its surrounding land area).

In 1987-1988, without any housings, this area was under the administration of Municipal People's Revolution Committee in Phnom Penh (currently known as Phnom Penh Capital Hall). Since 1993, this area became anarchical as the results of illegally occupied and built shelters without any construction plans. In late 2003, Boeung Kak model development plan as shown in **Fig.2.18** was selected for bidding under the support from Embassy of France and Phnom Penh Capital Hall and participated by all relevant agencies. Consequently, authorization of development in this area belongs to Shukaku Inc. The company was approved by the Royal Government of Cambodia. To deserve as a Pearl City as it's been known before, this area is developing as commercial, cultural, tourism, housing, and resort hubs along with infrastructure including road, drainage system, green space, and amusement parks[6)].

Geographically, Boeung Kak is bordered mainly 4 main boulevards:

- North is close to road number 70 called street Oknha Kleang Moeung.
- South is approach to Russia Boulevard.
- East is near Monivong Boulevard.
- West is nearby Street Samdach Penn Nouth intersected with Monivong Boulevard.

Essential infrastructure including Embassy of France, public hospital, Municipality of Phnom Penh City, Muslim church, the Ministry of Information, the National University of Management, railway station, Wat Phnom Garden etc, in which some of these areas are the preservation areas existing from the first forming of the city. **Fig.2.19** shows the transformation of land use in Boeung Kak area in 2005 and 2015 in terms of this development.

Fig. 2.18 Master plan of development in Boeung Kak area[16].

Fig.2.19 Transformation of land use in Boeung Kak area in 2005 (left) and 2015 (right) [17].

b) Camko City area

Under foreign investment from Korea, development of "Phnom Penh New Town" known as Camko City is located in the Pong Peay Lake development zone, and it is located about 3 km from the heart of PPC as shown in **Fig.2.20**.

In February 2003, Bureau of Urban Planning in Phnom Penh City appointed this city as a development zone for the "New Satellite City" with the project site of 119 ha.

The main characteristics of this city are composed of:

- Advance urban complex such as residential, commercial and public facilities[18].
- Modern infrastructures including (1) 4 to 6 lanes paved roads, water supply & sewage system and system of stable electrical, (2) High-speed information and telecommunication lines and systems, (3) System of electronic security, and (4) System of sustainable environment [18].

Enhancement of lifestyle through a system of new residential including (1) The first introduction of modern high-rise condominiums, and (2) Newly developed housing system[18]. Transformation of land use in Camko City area from 2005 to 2015 is presented in **Fig.2.21**.

Fig.2.20 Master Plan of development in Camko City area[18].

Fig.2.21 Transformation of land use in Camko City area in 2005 (left) and 2015 (right) [17].

c) Chruy Changva City area

Under local investment, Overseas Cambodian Investment Company (OCIC), Chruy Changva City is located in the northeast of Chruy Chang Va Bridge, previously known as Sunway City[6] as shown in **Fig.2.22**.

3 Sangkats including Chruy Chang Va, Prek Leap and Prek Ta Sek of Khan Russey Keo in PPC are covered by this project with the total area of 387 ha.

Development is divided into 4 zones with it occupying areas:

- Zone 1 is composed of the Botanic garden with an area of 60 ha[6].

- ➢ Zone 2 is an International Standard Stadium with an area of 45 ha[6].
- ➢ Zone 3 is called ASEAN plus 3 zones for the meeting or events of ASEAN plus 3 countries[6].
- ➢ Zone 4 is used as a housing complex, business centers, banks, schools, theaters, etc., with the total area of 162 ha[6].

Transformation of land use in Chruy Changva City area from 2005 to 2015 is presented in **Fig.2.23**.

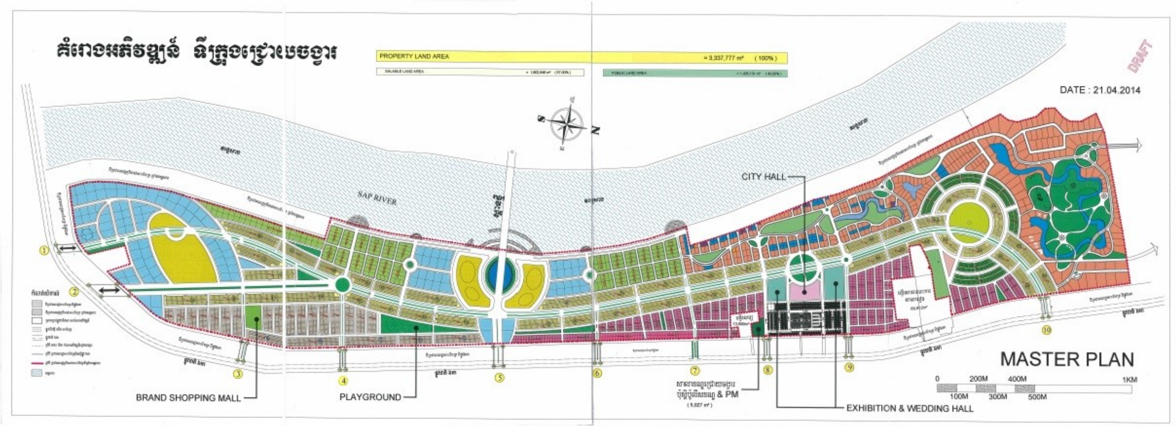


Fig.2.22 Master Plan of development in Chruy Changva City area[12].

Fig.2.23 Transformation of land use in Chruy Changva City area in 2005 (left) and 2015 (right) [17].

d) Comments on existing ongoing development plans

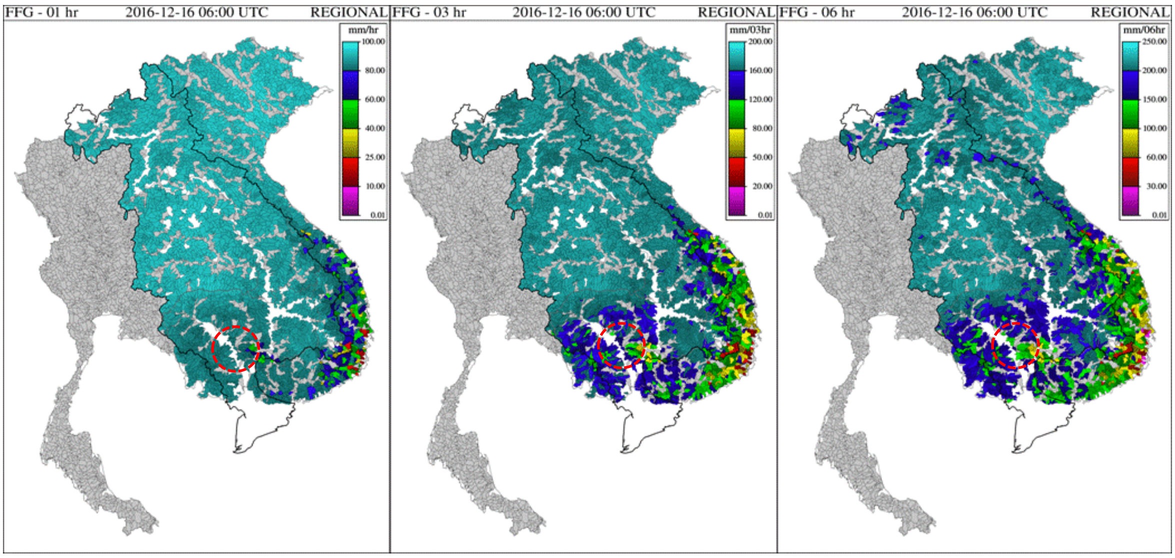
Existing ongoing development plans show that the developments pay high attention to the aesthetic with ideal infrastructure shaped geometrically and symmetrically; however, very little concerns have been paid either to the aspect of ecological, water stream or relation to the outside of the development area.

2.3.5 Flooding Issues

a) National level, flooding in Cambodia

In Cambodia, there are two types of floods happened including river flood and rainfall flood. Rainfall flood is found as the most prominent occurrence in PPC.

As one of the countries located at Lower Mekong Basin, the vulnerability to suffering from flooding is relatively high. Flash Flood Guidance based on 1 hourly, 3 hourly, and 6 hourly taken place on 16 December 2016, beginning of drying season in Cambodia, covering 4 countries including Thailand, Laos, Cambodia, and Vietnam are expressed as **Fig.2.24**. Based on these figures, several high-risk areas to flash flood are identified [1]. Along with several high-risk areas to flash flood occurrence at Southern of Vietnam, this occurrence also happened to PPC as expressed in **Fig.2.24** with red circles.



1 hourly Flash Flood Guidance. 3 hourly Flash Flood Guidance. 6 hourly Flash Flood Guidance.

Fig.2.24 Flash flood guidance on 16 December 2016[1]

Based on past record of flooding, along with two rivers: Mekong and Tonle Sap, eighteen out of twenty provinces in Cambodia were suffered from annual river flooding[19]. Timeline of flooding taking place in Cambodia during 1996 to 2014 can be seen in **Fig.2.25**. It demonstrated that Mekong flooding in 2000 was the worst case during the last 70 years in Cambodia. Whereas in **Table 2.5** illustrates the rainfall average level during 2000 to 2011.

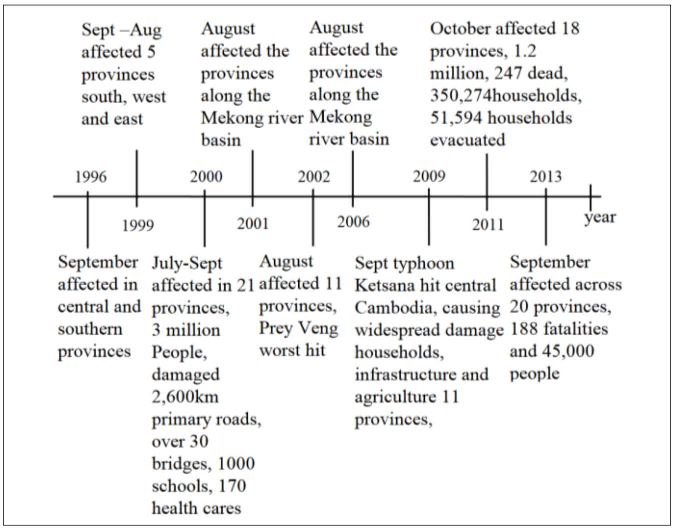


Fig.2.25 Timeline of flooding in Cambodia from 1996 to 2014[19].

Table 2.5 Rainfall data in Cambodia during July, August, and September[19].

Month	Year		
	2000-2010 average (mm)	2010 (mm)	2011 (mm)
July	244.0	218.9	226.4
August	259.6	245.8	275.9
September	272.6	218.3	338.6
Average	258.7	227.7	280.3

b) City level, flooding in PPC

PPC is always suffering from regular flooding during the rainy season (May-October) with major flood risk area of PPC[1] as shown in **Fig.2.26.**

Unlike other provinces in Cambodia, PPC is not affected by river flood but frequently rainfall flood since much of excessive runoff are generated in every storm event. Stormwater and wastewater are not separated in PPC. In accordance with former drainage system in both center and suburb area of PPC as expressed in **Fig.2.27** and **Fig.2.28**, the system of ponds, streams, canals, and lakes as shown in **Fig.2.29** are very important for managing the stormwater in PPC[3), 12)]; either storm water or waste water[20] (**Fig.2.30**) is collected through underground pipes with distinct size of sections and open canals before discharging to wetlands surrounding PPC.

The function of dikes is used not only to protect flood but also utilized as roads in PPC. In the point of fact, North part of “Chartomok area” located in the core zone of PPC, especially the plain area nearby the intersection of the rivers (Mekong River and Tonle Sap), is protected by National Road 5, as shown in **Fig.2.31**. Generally, increasing of flood extent is taken place from “Kompong Chnang” to “Kompong Luong” (first term is a province’s name while the second term is a village in Cambodia). In the West part of National Road 5, the flood is spreading from the Kompong Luong to the dike named Kob Srov. Many creeks also drain the floodwater from the northern part of PPC. In the southern part of PPC, the floodwater is spreading in the buffer of 15-20 km from the Basak River and National Road 3, and the west part drains to the west part of the country. Therefore, dikes and natural reservoirs used as drainage system play as the important roles in terms of flooding disaster protection as well as mitigation in PPC[20). As aforementioned, the “Chartmok area” seems quite safe from the flooding phenomena. However, certain places also have been suffered from the regular flooding. In this context, this flooding problem can be figured out as the result of poor drainage system management in terms of built environment, which has brought about the gradually decreasing of natural reservoirs functioned as water collectors as well as stockers during the rainy season.

The establishment of the drainage system is an essential step to be realized before the expansion of PPC. Since the beginning of expansion taken place in PPC, appropriate drainage system fulfilled the demand was prepared in terms of dikes, water collectors, and stockers. Not long afterwards, water-pumping stations were created. Dikes are used for flood protection from Mekong River. While drainage system including collectors such as sewage system and canals are used for gathering rainwater to the stockers, which is called natural reservoirs, and it’s known as “Lake”. Whereas water pumping stations are utilized not only for transporting rainwater across the dikes but also acts as the function of balancing the water level in the lakes.

In spite of increasing the impervious covers while decreasing of natural reservoirs in the current development trends in PPC, the economic development in this city has been raising; however, these actions have been causing many critical problems and negative effects exposed to the social and environmental aspects as the result of intensifying the flow velocity of rainwater to the lower-lying plain area. In addition, surrounding this issue, certain reclamation areas are found flooding during the rainy season due to the lack of drainage system[12].

In brief, the integration of both poor management of drainage system and disorderly of land reclamation makes the city be high vulnerability to flooding risk.

Compounding of this flood risk issue taken place in PPC, two main factors can be considered:

- The lack of parks or open spaces to absorb the rainfall during rainy season as the result of built environment.
- The drainage system is still poor, which cannot cope with the rapidly increasing of the population.

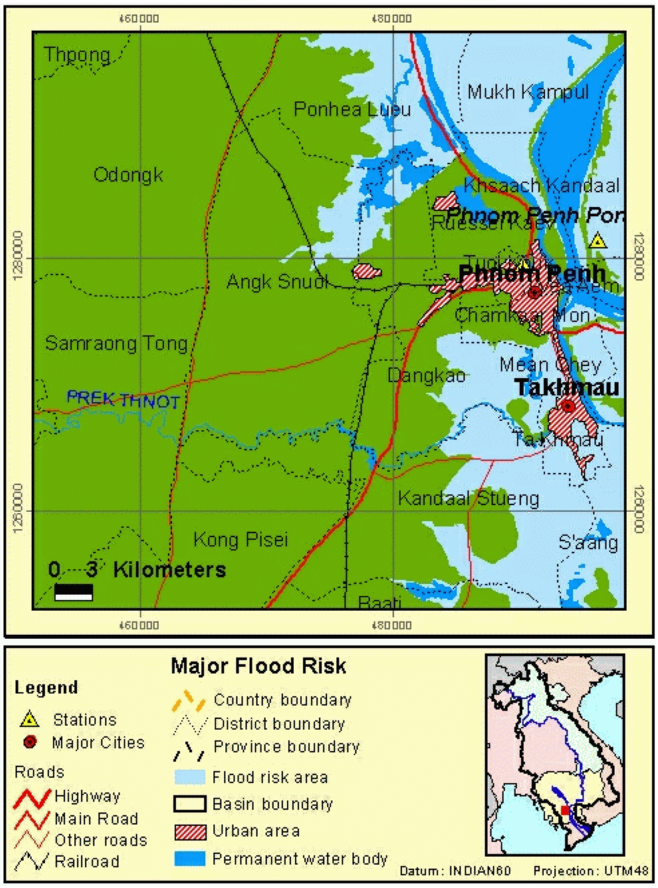


Fig.2.26 Major flood risk in PPC[1]

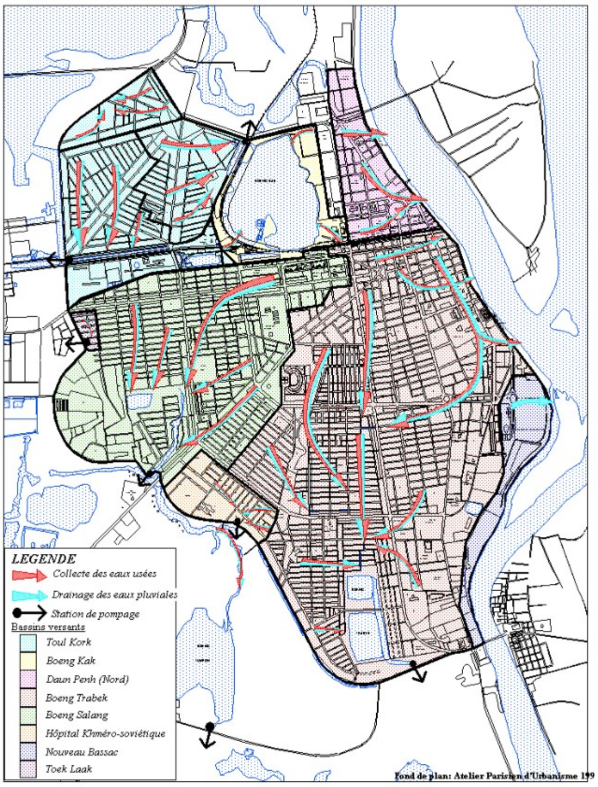


Fig.2.27 Drainage system[3] (center area of PPC).

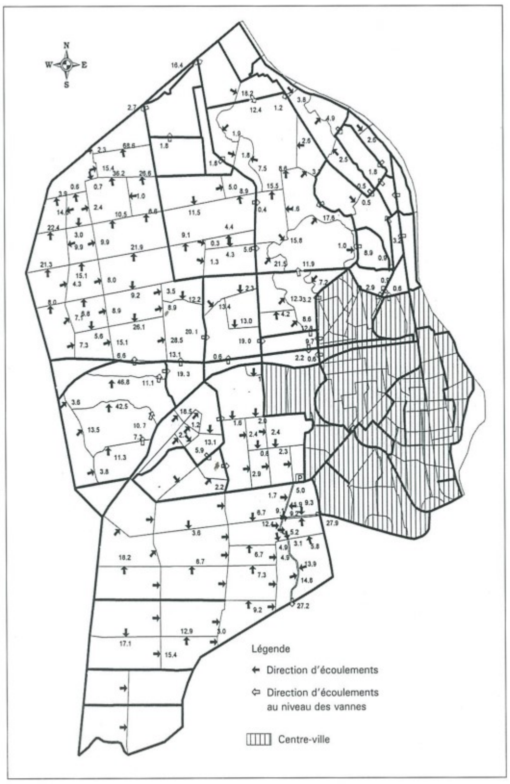


Fig. 2.28 Drainage system [20] (suburb of PPC).

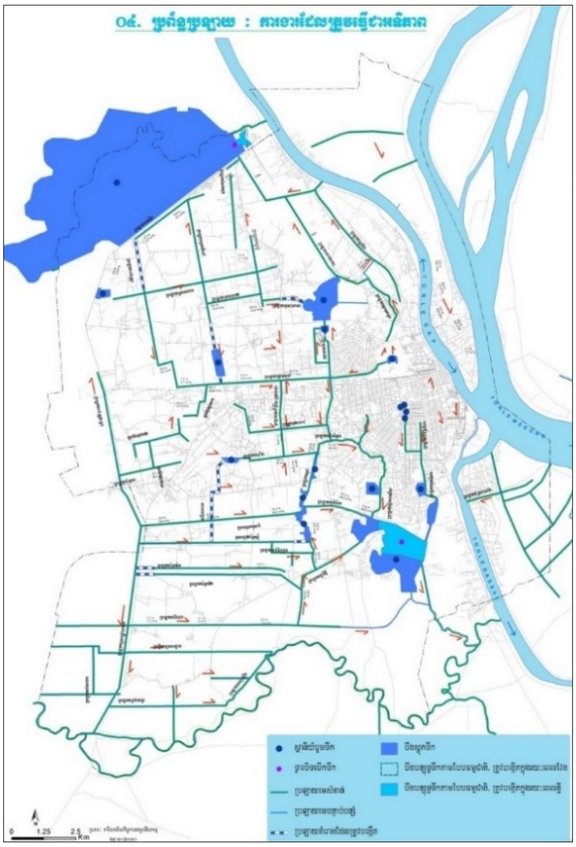


Fig. 2.29 Drainage system of PPC[12].

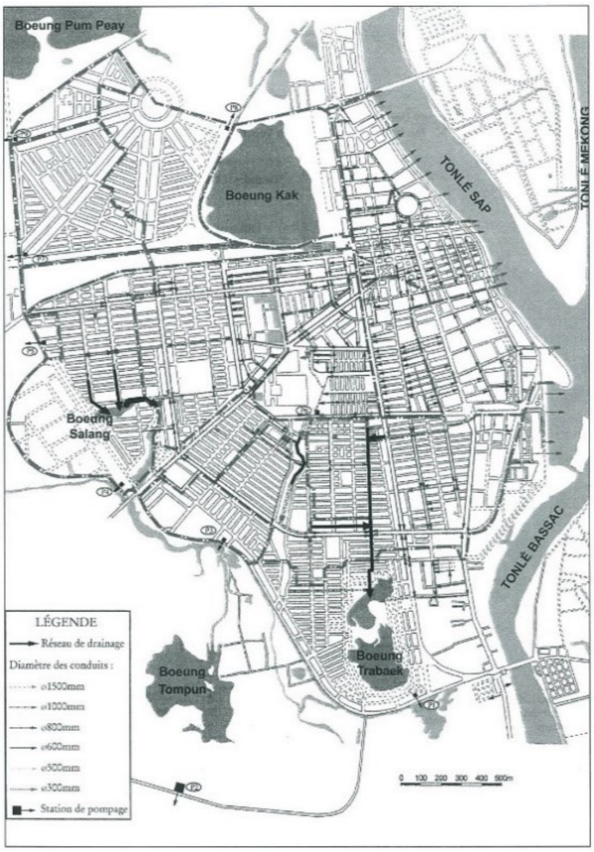


Fig. 2.30 Sewage system of PPC[20].

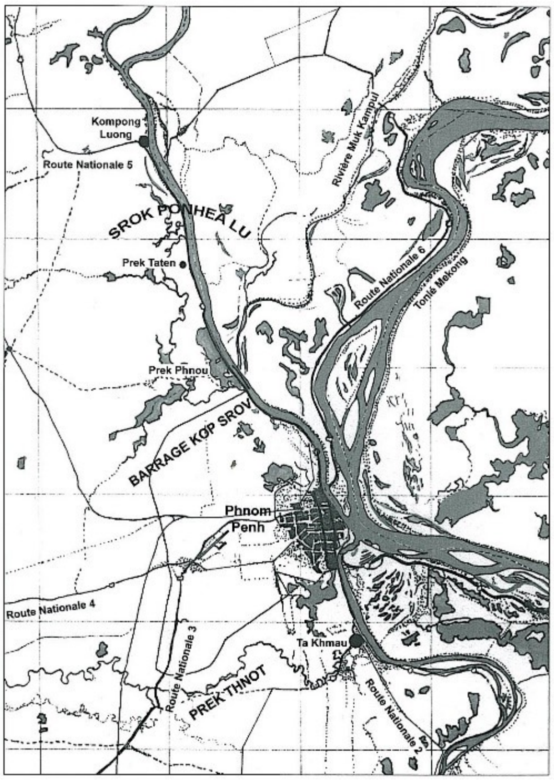


Fig. 2.31 Urban flooding issues in PPC[20)]

2.4 Conclusions of chapter

Based on the basic information, historical perspectives of urban development, existing master plans, and law on urban relative development, careful consideration of sustainable stormwater management in PPC was defined. However, after a cutting edge of economic growth, a tremendous land use development has been taking place in PPC since 2003; the policy regarding sustainable stormwater management has no longer been followed.

Current situation of urban development in PPC shows the trends of ongoing large-scale projects mainly taken place on natural reservoirs, lakes, functioned as water collectors and stockers. The manner of current development by replacing lakes into impervious cover has been posing a severe problem to the quality of life and environment particularly during the rainy season (May-October) because of the increasing of urban flooding extent.

With this concern, the appropriate developed methodology, which not only adapts for current development but also for future sustainable development, is introduced in the later chapter of this dissertation.

References

1. Mekong River Commission. *Flood Information*, viewed 01 May 2017, from http://ffw.mrcmekong.org/topo.htm#here.
2. JICA Report, 1999, *Sector B meteorology and hydrology*, viewed 01 October 2015, from http://open_jicareport.jica.go.jp/pdf/11527900_02.pdf.
3. Municipality of Phnom Penh, Bureau des Affaires Urbaines, Ambassade de France au Cambodge & Ambassade de France au Cambodge, 2007, *Livre blanc du développement et de l'aménagement de Phnom Penh*, viewed 05 November 2015, from https://www.iau-idf.fr/fileadmin/NewEtudes/Etude_142/Livre_blanc_du_developpement_et_de_l_amenagement_de_Phnom_Penh_avec_signets.pdf. (French Language).
4. United Nations, 2015, *Population Division: World Population Prospects, the 2015 Revision*, viewed on 28 April 2017, from https://esa.un.org/unpd/wpp/Graphs/DemographicProfiles/.
5. Open Development Cambodia, 2010, *Population projections for 2030 in Cambodia*, viewed on 03 October 2015, from https://opendevelopmentcambodia.net/layers/page/4/.
6. JICA: *Overview of urban development in Phnom Penh Capital City*, 2011.
7. National Institute of Statistics, 2013, *12 Phnom Penh Municipality*, viewed 01 May 2017, from http://www.stat.go.jp/info/meetings/cambodia/pdf/ec_pr12.pdf.
8. Wikipedia, *Phnom Penh,* viewed 02 May 2017, from https://en.wikipedia.org/wiki/Phnom_Penh.
9. Wikimedia commons, *Phnom Penh Tower*, viewed 01 May 2017, from https://commons.wikimedia.org/wiki/File:Phnom_Penh_Tower.jpg.
10. Wikipedia, *List of tallest buildings in Cambodia*, viewed 01 May 2017, from https://en.wikipedia.org/wiki/List_of_tallest_buildings_in_Cambodia.
11. Englund, G. and Ryttar, S.: The blue pearl of Asia: Flooding as an urban asset-a beautiful and resilient future Phnom Penh, *Final thesis in landscape planning 30+30 hp*, *Swedish University of*

Agricultural Science, 2008.

12. Personal communication, *Water way of Phnom Penh City and Urban Development*, interviewed May 2015.
13. City Hall and JICA, 2009, *Phnom Penh Croissance et Transformation*.
14. Laws and legal regulations concerning land issues in Cambodia, viewed 28 April 2017, from https://phalthy.files.wordpress.com/2006/11/laws-and-legal-regulations-concerning-land-issues-in-cambodia.pdf.
15. Council for the Development of Cambodia, CDC, Cambodian Investment Board, CIB & Cambodian Special Economic Zone Board, CSEZB, Sub-Decree #86 on Construction Permit_971219, viewed 02 February 2017, from http://www.cambodiainvestment.gov.kh/sub-decree-86-on-construction-permit_971219.html.
16. Phnom Penh Post, *Boeung Kak master plan*, viewed 02 February, from http://www.phnompenhpost.com/post-property/shukaku-opens-new-boeung-kak-lake-chapter.
17. Google Earth. *Land use in 2005 and 2015 in some development spots: Boeung Kak area, Camko City, and Chroy Changva City in PPC*, viewed 01 February 2017, from https://www.google.com/intl/ja/earth/explore/products/desktop.html.
18. World City Co., Ltd, *Master plan*, viewed 02 February, from http://www.worldcitycambodi a.com/master_01.html.
19. Sovannara, C. and Sharp, A.: Flood Management in Cambodia: Case studies of flood in 2009 and 2011, 2015, *International Conference on Environment and Civil Engineering*, pp. 89-94, 2005.
20. Molyvan, V.: Modern Khmer Cities, *Reyum Publishing, Phnom Penh*, 2004 (Khmer Language).

CHAPTER 3
Review of research trends in watershed-based land use analysis

3.0 Summary of chapter

With increased awareness of the importance of land use change at both local and regional scales within watershed-based planning, the study of land use analysis has become the focus of several international scientific endeavors. Since land use change has become a major issue in this century due to global urbanization, the study of watershed-based land use analysis will play an important role in a sustainable future. In this chapter, a comprehensive review of watershed-based land use analysis is undertaken to clarify the research trends in this area, including basic tools, factors, methodologies, study regions, scales and areas.

3.1 Purposes of review

Land use change is a major issue for this century, and urbanization is considered to be one of the dominant forms of land use change in terms of increasing surface runoff, impervious cover, and non-point source (NPS) pollution, which are accompanied by water pollution components[1), 2)]. Consequently, it causes urban flooding and degradation of water quality and the natural environment, leading to further changes in land use patterns.

Watershed-level planning is inherently concerned with land use issues and their impact on watershed interests, such as stream quality and biological diversity. Watersheds have been used as physical, biological, social, economic, and political units for the planning and implementation of land management activities[3)]. In the United States, the use of watersheds as planning units originated from defining the best hydrological planning units for land, water, and ecosystem management, then defining governmental boundaries based on watersheds, and finally delineating the boundaries of district planning based on watersheds[4)]. For example, in New York, a watershed management agreement was signed in 1997 to protect the quality of drinking water while promoting environmental sustainability compatible with economic development[5)]. Japan has based planning for ecosystems, cultural landscapes, and disaster prevention on the watershed unit; it has also introduced watershed-based planning in the master plans for parks and open space in some municipalities[6)]. Therefore, for city and regional planning, the watershed can be considered as a reference even though its boundaries do not necessarily coincide with the administrative boundaries.

In watershed-based research, the study of land use is considered to be one of the most prominent issues. Many studies have focused on the influences and impacts of land use practices due to urban development, which have a major impact on the natural environment and consequentially on the watershed. These studies have been discussed widely in the fields of hydrology, water resource management, environmental management, agriculture, geography, geology, land use, landscape, green space, and disaster prevention planning. They differ in their purposes, methodologies, available data, and applications, since the nature of land use analysis is dependent on many driving forces, especially the interaction between human activities and natural resources. Therefore, this multifaceted issue requires a multidisciplinary approach to resolve its associated problems, which are introduced in this chapter.

As the rate of global urbanization is constantly increasing, and the study of watershed-based land use analysis is broad and deals with complicated issues, it is essential to clarify research trends in this realm. Therefore, the aim of this chapter is to: (1) identify the research trends of basic tools, and (2) identify the research trends of the factors, methodologies, study regions, scales and areas, and the relationship of these factors in watershed-based land use analysis, which can be used for better future planning and research.

3.2 Review methodologies and process

3.2.1 Selection of target academic paper

In the selection process for the academic papers targeted in this chapter, we used web search engines and publishers' websites, input keywords, and criteria for selecting target academic papers.

The selection process for target academic papers is shown in **Fig. 3.1**. First, 15 combinations of two keyword terms were inputted into web search engines and publishers' websites based on the criteria shown. The obtained watershed-based papers were concerned mainly with three fields: landscape, ecological environment, and land use, with dates ranging from 1977 to 2015. Second, the target papers were filtered and selected for the studies related to watershed-based land use analysis, excluding the two other fields. The dates of the resulting papers ranged from 1991 to 2015, as shown in **Table 3.1**. These papers come from international journals and conference papers and various academic journal publishers. These publishers covered almost the whole globe including Europe, Asia, and North America, which shows that various publishers were involved in the academic paper selection process. The study regions were mainly defined according to the continents; these studies have been carried out in Asia, Europe, North America, South America, Africa, Australia, and Oceania.

Web Search Engines:

Google Scholar, Scopus, Web of Science, J-Stage

Publishers:

ScienceDirect, ASCE library, Wiley Online Library

Input two keyword terms in the web search engine=a_ib_j $(0<i\leq 5;\ 0<j\leq 3)$

a_1. Land use	
a_2. Land use analysis	b_1. Based on watershed
a_3. Land use planning	b_2. At a watershed scale
a_4. Land use change	b_3. At watershed level planning
a_5. Land cover	

Note: No limitation to the publishing year

Criteria for academic paper selection

1. Based on the background of each academic paper relating to the issues of urban development, urban expansion, urbanization and its associated influences, impacts and consequences in terms of various research fields.
2. Selecting the related papers in the references of each academic paper in 1.

Selection of academic papers

Around 70 academic papers including landscape, environmental ecology and land use, which are based on watersheds, were identified, with the publishing years ranging from 1977 to 2015.

Criteria for target academic papers selection

Filtered and selected for papers mainly related to watershed-based land use analysis 55/70

Note: 15 of the 70 papers are not referred to in the references.

Fig.3.1 Target academic paper selection process.

Table 3.1 Publisher and journal name of target academic papers.

Publishers	Journal name (total papers) (publishing year of target academic paper)
Elsevier	Agriculture, Ecosystems and Environment (2) (2001; 2003) CATENA (1) (2003) Computers & Geosciences (1) (2010) Environment International (1) (1997) Journal of Environmental Management (2) (2001; 2005) Journal of Hydrology (1) (2002) Land Use Policy (1) (1995) Landscape and Urban Planning (6) (2000-2015) Physics and Chemistry of the Earth (1) (2001) Procedia Environmental Sciences (1) (2011) Science of the Total Environment (1) (2015) The Egyptian Journal of Remote Sensing and Space Sciences (1) (2015)
John Wiley & Sons	Hydrological Processes (2) (1991; 2006)
Springer	Environmental Management (2) (2000; 2009) Environmental Monitoring and Assessment (2) (2006; 2011) Sustainability Science (1) (2014)
American Society of Civil Engineering (ASCE)	Journal of Hydrologic Engineering (1) (2013) Journal of Urban Planning and Development (2) (2014) Journal of Water Resources Planning and Management (1) (1995)
American Water Resource Association (AWRA)	Journal of the American Water Resource Association (JAWRA) (1) (2004)
Association of American Geographers	Middle States Geographer (1) (2007)
Japan Society of Civil Engineering (JSCE)	Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering) (1) (2012)
Japanese Institute of Landscape Architecture	Journal of The Japanese Institute of Landscape Architecture (6) (2002; 2012)

Architecture Institute of Japan (AIJ)	Journal of Architecture and Planning (2) (2007; 2009)
Ecology and Civil Engineering (ECES)	Ecology and Civil Engineering (1) (2003)
GIS Association of Japan	Theory and Applications of GIS (1) (2010)
Japan Society of Erosion Control Engineering (JSECE)	Journal of the Japan Society of Erosion Control Engineering (1) (2005)
Japan Society of Tropical Ecology (JASTE)	Tropics (2) (2004; 2011)
Scientific Research, International Lake Environment Committee Foundation (ILEC)	Journal of Lakes & Reservoirs: Research and Management (1) (2002)
International Research Operation in Sciences & Social Sciences (IROSSS)	International Journal of Advancement in Remote Sensing, GIS and Geography (1) (2014)
Japan Society of Geoinformatics (JSGI)	Geoinformatics (1) (2002)
Scientific Research	Journal of Geographic Information System (1) (2012)
Others	Asia Conference of Remote Sensing (1) (2010) The International Symposium on Cartography in Internet and Ubiquitous Environments (1) (2015) Environmental Design Research (1) (2012) The 15th Science Council of Asia Conference and International Symposium (1) (2015) World Water and Environmental Resources Congress (1) (2001)

3.2.2 Historical review of the target academic papers

Watershed-based studies, which have received far more attention within the biological and physical sciences than the social science framework, have long been used by researchers in landscape as well as ecological and environmental management studies.

Once filtered, the dates of the selected papers began in 1991. Watershed-based land use analysis became prominent during the 1990s, when many watershed geographical information (GIS) applications were developed[7] and growing concerns about urban development's effects on the natural environment began prompting efforts to find more sustainable solutions to the problems arising from the built environment.

3.2.3 Contents of this review

Section 3.3 examines the general trends in the target academic papers. All target academic papers were categorized based on publisher, characteristics of study regions, and research fields.

Section 3.4 covers research trends in the basic tools applied in watershed-based land use analysis. This section discusses basic tools including land use detection methods, land use modeling and thresholds in the watershed delineation process.

Section 3.5 discusses research trends in the factors used in watershed-based land use analysis. In this section, target academic papers were summarized based on background, purpose, target watershed scale, data type, methodology, findings, limitations, and future research. These factors were identified based on the research purposes of each summarized paper and then grouped in order to clarify methodologies, study region, area, scale, and the relationship of these factors in watershed-based land use analysis in different research fields.

3.3 General trends in the target academic papers

A total of 55 target academic papers were categorized according to publisher, characteristics of the study region, research field and journal name, with the publishing year of each target academic paper, as shown in **Figs. 3.2, 3.3,** and **3.4** respectively.

Among the target academic papers, as shown in **Fig. 3.4**, four main research fields were defined: (1) environment and management, (2) hydrology, (3) planning and development, and (4) remote sensing, GIS applications, and others.

Figures 3.2 and **3.3** show trends in the study regions and publishing years. Before 2002, few papers were defined in Asia; however, from 2003 a fluctuation in the number of studies seems to have taken place in Asia.

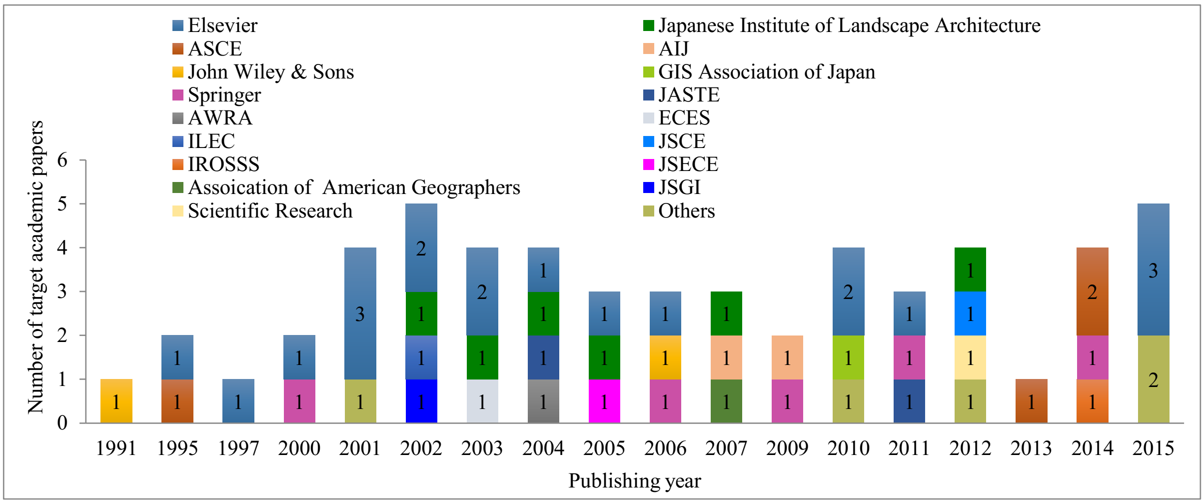


Fig. 3.2 Publishers and publishing year of target academic papers.

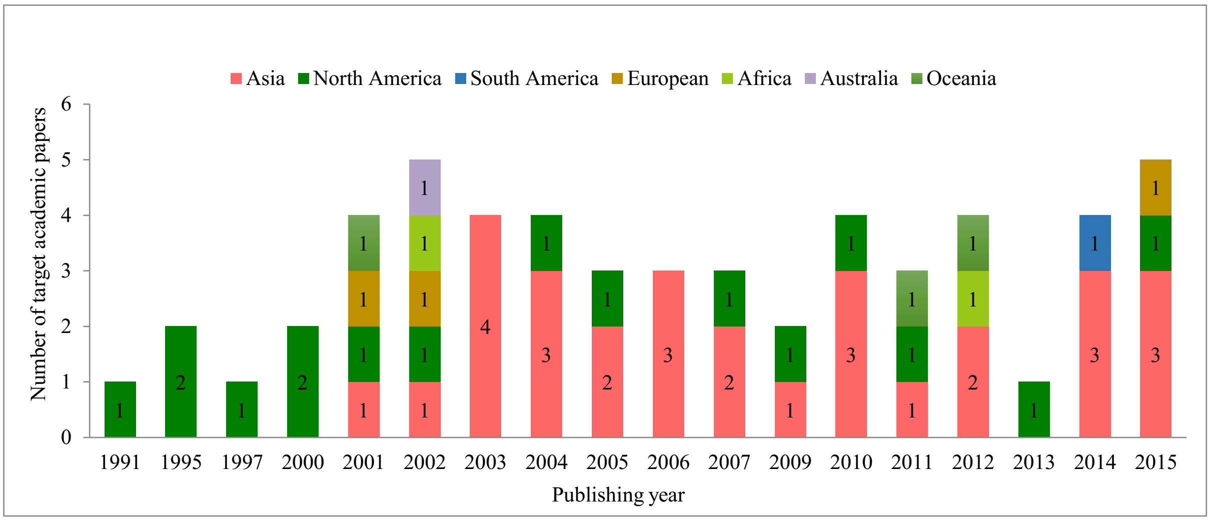


Fig.3.3 Study region and publishing year of target academic.

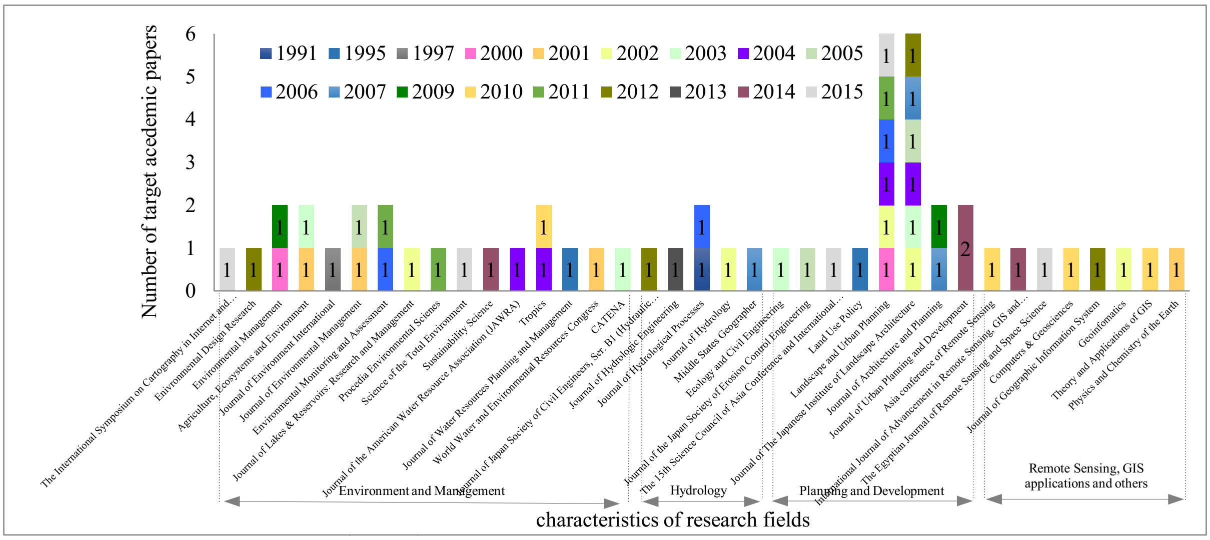


Fig. 3.4 Characteristics of research fields and publishing year of target academic papers.

3.4 Research trends in basic tools

In the study of watershed-based land use analysis, land use detection methods, land use modeling, and watershed delineation methods are considered basic tools, and are applied widely by researchers using watersheds as the planning unit.

3.4.1 Trends in watershed-based land use detection and modeling

The progressive worsening of urban environments, and the destruction of ecosystems due to the rapid pace of urban development, have led to awareness of the important role of land use and land cover in overcoming those problems[8)]. Therefore, it is essential to understand the trends related to the study of land use applied at the watershed scale. Among the 55 target academic papers, watershed-based land use analysis has been carried out in two forms: land use detection methods and land use modeling.

a) Trends in watershed-based land use detection methods

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 very high, high, and medium spatial resolution, respectively. These databases are used to carry out land use and land cover analysis with the integration of geographical information systems for understanding and defining land use and land cover dynamics[9)], understanding land use change, and predicting land use in the future[10)]. Many studies have shown that studies of land use detection have made extensive use of satellite imaging such as the Landsat Multispectral Scanner System (MSS) and Landsat Thematic Mapper (TM), with remote sensing software ERDAS IMAGINE[9), 10), 11), 12), 13), 14), 15)], while a few studies also applied image-processing software IDRISI[16)] and Geographical Information System (GIS) with image processing[17), 18)] for the detection of land use through Landsat data with six important steps in image classification[19)]. However, in detecting land use using remote sensing data, there are some shortcomings for tropical areas, where the cloud cover is high. Some studies have developed a method to overcome these shortcomings[9), 13), 20)]. In addition to land use detection by remote sensing, land use detection may also be conducted with land use data sheets and historical geographical maps using the PLUR program[21)].

In brief, remote sensing and GIS are considered essential technologies, which enable temporal analysis and qualification of spatial phenomena with less time and low cost.

b) Trends in watershed-based land use modeling

Watershed-based land use modeling has proved to be a useful tool for land use scenarios studies, as it provides not only the spatial distribution of land use based on the basic spatial data of land use and topography, but also the basic data for calculating landscape pattern metrics and hydrological components. It also provides useful information about the possible environmental impacts of future urbanization[22), 23), 24)].

In watershed-based land use analysis, six types of land use modeling have frequently been applied. The first model, Conversion of Land Use and Its Effects (CLUE-s), is based on an empirical model measuring the conversion of land use and its effects combined with other models for an integrated approach to simulate and evaluate land use changes, landscape patterns, and their effects on hydrological processes at the watershed level[22)].

The second model, the Land Use Change Modeling Kit (LUCK), is an approach to scenario generation using a grid-based discretization mode at catchment scale. It presents the spatial distribution of land use types in a landscape based on an evaluation of the characteristics of each grid, as well as on its neighborhood relationship. It is used for land use scenario generation providing a spatially distributed specification of land use changes in meso-scale catchments[25)].

The third model, SLEUTH, is an urban growth model with cellular automation. It is used to estimate present and future surface runoff and peak discharge in small- and medium-sized urban watersheds through land use information derived from satellite images[11)].

The fourth model, Cellular Automata (CA), is a well-known land use change approach used among peer-reviewed journals. It models urban sprawl by simulating complex dynamic processes through relatively simple rules, and can be applied for urban growth simulation and predicting the extent of an urban area[26)].

The fifth model, Land Use Transformation (LTM), is applied for forecasting and assessment of the impact of land use changes on runoff, as well as long-term runoff and NPS pollution[24), 27), 28), 29)].

The sixth model, Markov, is applied for predicting land use structure in the watershed[10)].

All land use modeling can be categorized based on eight core methodologies: Markov Chains, Economic-Based, Statistical Analysis, Cellular Automata (CA), Geographic-Based, Artificial Neural Network, Agent-Based, and Integration Modeling[30)]. Not all of these methodologies are applicable to watershed-based land use planning. The relationship between the major methodologies and watershed-based land use modeling is shown in **Fig. 3.5**.

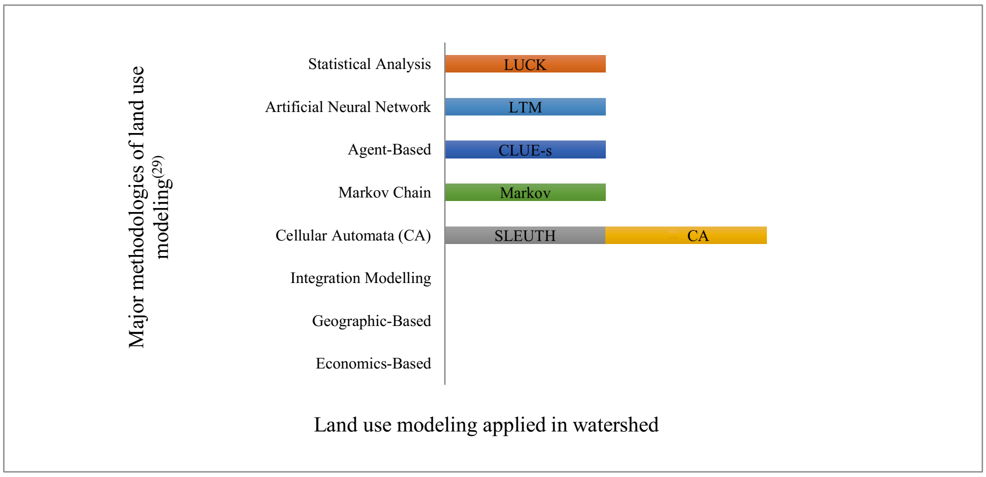


Fig. 3.5 Relationship between the major methodologies of general use modeling and watershed-based land use modeling

3.4.2 Trends in threshold definition methods in the watershed delineation process

Due to advances in desktop GIS capabilities, programming languages, and data availability, many watershed geographical information system (GIS)-based applications have been developed since the early 1990s. Hydrological modeling is a well-developed technology that has been widely applied with GIS in various studies, in particular those related to geomorphology, soil science, hydrology, and land use planning[7)]. In hydrological modeling, Digital Elevation Models (DEMs) are important and useful sources for automatically generating the flow direction, flow accumulation, stream direction, drainage line, catchment, sub-watershed, and watersheds. This system depends mainly on the input of thresholds in order to identify watersheds.

In brief, the smaller the chosen threshold, the more catchments it produces, which makes the channel complicated. However, the appropriate and reasonable stream threshold for defining the watershed remains unclear, since the only way to determine a reasonable stream threshold is by trial and error, which consumes much time[31)].

In watershed-based planning, the chosen threshold, which identifies the watershed unit of planning, influences and impacts the planning process. Thus, threshold issues should be discussed clearly in the planning process. Among the 55 target academic papers, two types of watersheds were defined from the planning perspective: rural watersheds and urban watersheds.

a) Rural Watersheds

Rural watersheds refer to original terrain where the natural topography conditions such as landform, surface shape, and the natural drainage pattern and network are not superimposed by infrastructure, such as streets, roads, and buildings. Rural watershed delineation, drainage pattern, and flow calculation have been shown to be capable of being automatically generated through digital terrain models. Of the computer-based terrain representations, grid algorithms such as DEMs were found to be better at defining large rural watersheds than the other two methods, Triangle Irregular Network (TIN) and Contours[32)]. Eight types of applications have been used for watershed-based land use studies. These applications are: GIS-ARC/INFO[32), 33), 34)], GIS-GRASS[35)], TNTmips[36), 37)] GIS-Hydrological Modeling[6), 38), 39), 40), 41), 42)], Terrain Processing in ArcHydro[43), 44)], and WinGrid system[31)]. In addition, certain researchers manually identified the watershed boundary by using topographical maps[12), 45)]. The majority of researchers tended to use the hydrological modeling tool in GIS to delineate the stream network. However, the threshold for defining stream network analysis was not discussed widely in the existing literature, though certain researchers were interested in discussing the identified thresholds in rural watersheds[31), 38), 39), 40), 41), 43), 46), 47)].

Five types of existing threshold-defined methods were identified in the target academic papers. The first method was applied using a trial threshold value and used natural topography as the reference for studies carried out to evaluate the green space environment in small watersheds, based on the water cycle[40), 41), 46)].

The second method involved trialing threshold values for obtaining corresponding average area of watersheds. Threshold was decided on the basis of comparing between the total average areas of administrative boundary with obtained average area of watersheds, for basic studies of land use planning[38)].

The third method, constant threshold, was defined according to flow accumulation automatically generated by using GIS. This method employed two conditions. The threshold value was set at the lower limit of the generated flow accumulation using hydrological modeling in GIS to identify the potential water flow path[39)], and the threshold value was set equal to one percent of the upper limit of the generated flow accumulation using Terrain Processing in ArcHydro. This method was used to evaluate the urban spatial characteristics of traditional cities such as a Japanese castle town based on watershed analysis[43)].

In the fourth method, the smallest weighted support area threshold was identified through a defined channel network where the mean stream drop in the first order stream is not statistically different from the mean stream drop in the higher order stream. It was used to define the threshold through an advanced mapping of the flow network from DEMs[47)].

In the fifth method, the threshold was defined through two modified algorithms: the headwater-tracing method and the fitness index[31)].

From the five aforementioned methods, it can be confirmed that the definition of thresholds is variable and differs between planners.

b) Urban Watersheds

In urban watersheds, the stream network cannot be automatically delineated in its urban terrain since the flow no longer follows its natural path. In urban watersheds the drainage flow path tends to encounter hindrances to flow such as street gutters, which is a result of urban development in the built environment, including buildings, roads, highways, subways, railways, and sewage lines. Basically, the surface drainage system flows through gutters and channels into storm water inlets, which are installed for the purpose of draining the excess runoff from impervious surfaces, namely artificial structures such as paved streets, roofs, sidewalks, and parking lots. The subsurface drainage network of storm sewer pipes, into which the surface water is directed by storm water inlets, is the other drainage network considered in urban watersheds.

For urban watershed planning, the computer-based terrain representation TIN was used with GIS-ARC/INFO to model the storm water flow. It serves as a valuable tool for urban planning and design, especially as it can be used to predict the impact of proposed land use changes and to evaluate land use management strategies. In addition, a tool was developed for further incorporating the GIS spatial analysis into the hydrologic analysis of an urban watershed[32]. The change of land use in a single lot with a city block corresponding to the nearest storm drain was defined through urban storm watershed modeling[33].

These methods can be effective for developing countries, in which the urban flooding associated with surface and subsurface drainage systems is the main urban watershed management issue. Though the applied data are different in scales and resolution, this shortcoming can be minimized through selection of the data sources with minimal scale differences, with the exception of soil maps. However, this method still has some limitations, including digital format availability[33]. These limitations are even more significant in developing countries, where digital data are less available.

3.5 Research trends in factors considered in watershed-based land use analysis

In this section, 36 of the 55 papers are analyzed and categorized according to each factor in their analysis, while the other 19 papers employ mainly basic tools.

Certain papers have two or more purposes defined in a single paper, while some papers have only one purpose associated with the factors. The factors are counted as the basis of all purposes in each target academic paper.

Two main issues are discussed: (1) research trends in factors considered in watershed-based land use analysis, and (2) the relationship of these factors as shown in **Table 3.2**.

In this section, two scales were used in the context of watershed-based land use analysis. 'Local scale' refers to city, regency, district, town, township, ward and village scales, while 'regional scale' refers to province or county scale. These scales depend on the territorial division of each country.

Table 3.2 Relationship of factors, characteristics of study region, scale and area in watershed-based land use analysis

(*) Size of the study area is watershed or catchment area/ (**) is drainage area/ (***) is watershed area corresponding to administrative area

Factors	Purposes	Research trends in factors considered in watershed-based land use analysis: Methodologies	Ref. N°	Study region and size of study area (km^2)		Scale
Land use polices	Identification of the effectiveness of green space and local land use policies at a watershed scale	▪ Quantification of percolation based on land use policies, green conservation policy scenarios	40)	Asia	435^{***}	City
		▪ Quantification of forest and farmland ratio	6); 41)		784^{***}; 21^{*}	City and Ward
		▪ Quantification of percolation based on first and second stream order by Horton Strahler	46)		41.3^{*}	Ward
	Studies of current policies on watershed conservation	▪ Based on land use policies documents and interviewing	3); 42)	North America and Oceania	2776^{**}; 365^{***}	Regional
	Analysis of the influence of land use policies on land use structure	▪ Considering slope degree as the most important factor	48)	Asia	3.9^{*}	Village
Water Quality	Exploring the relationships between water quality and land use	▪ Biology, water chemistry and habitat were used to demonstrate the relationship between the quality of the receiving river and land use	51)	North America	4550^{**}	Regional
		▪ Electrolytic conductivity as indicator	34)		9700^{**}	

		▪ The parameters of the water quality such as total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), and biochemical oxygen demand (BOD)	10)		2840.7 **	
		▪ Water Quality Index as indicator	12)	Asia	50*	District
	Assessment of the impact of land use and land cover changes (LUCCs) on the surface water quality	▪ Water quality parameters (WQPs) such as pH, TAN, BOD5, FCs, TCs, EC, NO^{-3}, and NO^{-2} as indicators	52)	Europe	5063.9 *	Regional
Surface runoff	Identifying, estimating, analyzing, quantifying, and simulating the impact of land use change	▪ Estimation of the increase of annual average runoff from watershed using the L-THIA model	2)	North America	70.5*	Regional
		▪ Estimation of surface runoff using the combination between the LTM and L-THIA model	27)		7032*	
		▪ Surface runoff simulation defined through the combination of the SCS model and storm water management model	29)		1963*-4007*	
		▪ Qualification of the impact of land use change on surface runoff with the aid of the SWAT hydrological model	23); 53)	North America and Europe	0.26*-82*; 316*	Regional and District
		▪ Calculating surface runoff from satellite image information by three methods	11)	North America	373*	Town

	Defining the runoff generation mechanism	▪ Defining the runoff generation by using WASIM-ETH	25)	Europe	100^{*}-500^{*}	Regional
Flooding control	Defining the characteristics of flood-prone areas	▪ Raster format map with derived hydrological products and field investigation	35)	Africa	1152^{***}	Regional
		▪ Identification of potential water paths	39)	Asia	21.54^{***}	Town
	Analyzing the effectiveness of planning approaches	▪ Study of two drainage design methods under different scenarios	54)	South America	726^{***}	Regional
		▪ Analyzing Ian McHarg's ecological planning approach	55)	North America	94.2^{**}	Township
Land suitability and allocation analysis	Land suitability analysis for establishing the most appropriate desirable direction for future land use development	▪ Criteria were defined through an ecological inventory in terms of primary, secondary, and unsuitable suitability	56)	North America	$62{,}160^{*}$	Regional
		▪ Criteria considered slope degree using the relative land use suitability index	48)	Asia	3.9^{*}	Village
	Define the best spatial location, considering economic, natural resource, and social factors	▪ Criteria including the maximization of housing and employment capacity, capability between land use and the minimization of NPS pollution were set as objectives in association with the global spatial trend	26)	Asia	180.75^{*}	District
		▪ Integration of GIS and an optimization model to define the future land use allocation based on the inexact-fuzzy multi-	57)	Asia	2565^{*}	Regional

		objectives linear programming (IFMOP) model				
		▪ Land suitability evaluation focused on soil types, slope gradient, landform, and slope aspects for rain-fed agriculture. A comparison of land suitability, current land use, and the potential land use scenarios based on surveys on biophysical, socio-economic parameters in the catchment and plans by authorities, was used for further evaluation of their effects on soil erosion, economic feasibility, and social acceptance	58)	Asia	3.5*	Village
		▪ With the aid of GIS Multi-criteria analysis in modeling future land use planning for resource planning and management based on biophysical parameters	59)	Africa	12,225*	Regional
		▪ Estimation of soil erosion and economic feasibility analysis based on the cost-benefit ratio of land use types in the watershed	60)	Asia	583.3*	Regency
	Identification of site prioritization	▪ Identification of site prioritization for low-impact development	61)	North America	666*	Regional

		(LID)				
		▪ Defining the potential sites for the placement of the conservation buffer and riparian restoration in the watershed	62)	North America	80.29*	Township
Landscape structure	Clarifying landscape structure and its relationship with land use	▪ Using landscape indices such as patch number per unit area, mean patch area of different land use types, diversity index (H)	12); 45); 63)	Asia	50*; 50.97*; 153.35*	District
			48)		3.9*	Village
			16)		190*	Regional
		▪ Using the characteristics of the natural environment such as topography, slope, and vegetation conditions	37); 42)	Asia and Oceania	1043*-3720*; 365***	Regional

3.5.1 Trends in factors considered in watershed-based land use analysis

The research trends in watershed-based land use analysis were analyzed and categorized into six factors: land use policies, water quality, surface runoff, flooding control, land suitability and allocation analysis, and landscape structure.

a) Land use policies

Many methods contribute to the study of watershed-based land use analysis in terms of land use policies. Three main methods focusing on the influences, impacts, and consequences of land use practices on watershed-based land use policies were identified.

First, in order to identify the effectiveness of green space and local land use policies at a watershed scale, the quantity of percolation was quantified based on the land use policy and greenery conservation policy scenarios. The effectiveness of the current conservation of green space was revealed[40)]. Quantifying the forest and farmland ratio was also used for environmental conservation and disaster prevention. The effectiveness of using the watershed as a planning unit to reflect finer level planning in terms of natural conditions and social background was defined[6], and the environment of small watersheds was evaluated[41]. Percolation, with the index of the water cycle focusing on the first and second stream order by Horton-Strahler, was quantified. Transformation of the green space environment on both scales made it possible to consider the restoration of the policy[46].

Second, in studies of current policies on watershed conservation, studies of land use policy documents were conducted, and policy-makers were interviewed. Negligible numbers of land use planning measures for protecting forest and open space through the watershed were found[3]. In addition, state officers and local community organizations were interviewed, and delivers urgent issues were carried out[42].

Third, the influence of land use policies on land use structure was analyzed using slope degree as the defining factor. The new land use system was found to be better than the previous one[48].

b) Water Quality

Generally, the study of stream quality and function depends on five variables: climate, geology, soil, land use, and vegetation. Land use is considered to have direct control of and impact on watershed health[49, 50]. These impacts are dominated by contaminants released into the natural environment, which are normally classed as point source and non-point source pollution. Water pollution affects two separate resources: surface water and groundwater. However, in the study of watershed-based land use analysis, surface water pollution is the primary focus among researchers. This pollution is mainly due to the gradual progression of the urbanization process, in terms of discharge from wastewater treatment plants (WWTP), excess fertilizers from agricultural lands, causing a number of ecological effects and adverse health due to an overabundance of nutrients including nitrogen and phosphorus in the water, residential areas, and toxic chemicals from urban runoff.

Many researchers have studied and discussed water quality as one of the factors considered in watershed-based land use analysis. This research can be classified as having two main purposes, each with different corresponding methodologies.

The first purpose is to explore the relationship between water quality and land use. In this context, biology, water chemistry, and habitat were used to demonstrate the relationship between the quality of the receiving river and land use, which showed that increasing population pressures have resulted in increasing loads of nutrients and other pollutants in the watershed[51)]. Electrolytic conductivity, a general indicator for water quality, is more appropriately used to diagnose the impacts from point pollution sources rather than non-point pollution sources, in order to define the relationship between water quality and land use[34)]. Parameters measuring water quality such as total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), and biochemical oxygen demand (BOD) revealed that change in land use types have led to a tendency towards moderate decline in water quality[10)]. The water quality index (WQI) demonstrates that with proper land use planning, water quality can be protected and economic goals can be achieved[12)].

The second purpose is to make an assessment of the impact of land use and land cover changes (LUCCs) on the surface water quality. Water quality parameters (WQPs) such as pH, total ammoniacal nitrogen (TAN), 5-day biochemical oxygen demand (BOD5), fecal coliforms (FCs), total coliforms (TCs), electric conductivity in field (20°C) (EC), total nitrate (NO^{-3}), and total nitrite (NO^{-2}) were used as indicators. These showed that higher water quality protection can be achieved with greater forest occupation in water reservoirs[52)].

c) Surface Runoff

In general terms, surface runoff is defined as the flow of water occurring when excess storm water is generated during precipitation and snowmelt. It can infiltrate, evaporate, and its runoff can end up in nearby water bodies such as streams, rivers, lakes, and other surface water sources. Moreover, it occurs when there is heavy rain whose flow amount is beyond the absorption capacity of the soil. The increase in the size and number of impervious areas, which is a direct result of land use change and urban development, increases surface runoff. Surface runoff can cause not only water erosion and pollution, but is also the primary cause of urban flooding.

Being aware of and responding to those negative outcomes, many studies have carried out watershed-based land use analysis using surface runoff as a factor. Two main purposes and their corresponding methods were identified in this category of the target academic papers. Surface runoff was used as an indicator in 7 of the 36 target academic papers.

The first purpose is identifying, estimating, analyzing, quantifying, and simulating the impact of land use change on surface runoff. In this context, a long-term hydrological impact assessment, the L-THIA model, was developed for estimating the increase in annual average runoff from the watershed due to land use change. Owing to the intensified pressure on the natural environment due to the increase in impervious areas in the urban environment, the traditional short-term local-scale surface hydrological models focusing on estimating peak discharges and high-magnitude NPS pollution are not sufficient. An increase in annual average runoff volume and metals but decrease in nitrogen and phosphorus load were estimated in terms of increasing urbanization[2)]. Estimation of surface runoff for land use in different periods was defined using a combination of the LTM and L-THIA models. Essential information about future urbanization and the possibility of environmental impacts can be generated; this could be a potential research direction for the future[27)]. Simulation of surface runoff before and after urbanization was defined using a combination of the soil conservation service (SCS) and the storm water management models. A risk of increased flood discharge and decreased quality of aquatic systems was identified[29)]. Surface runoff from satellite image information was also calculated using three methods existing in numerous literatures, namely the SCS, Arthur's, and Peak surface runoff models. Increased inefficiency in the use of land was also identified as a factor that increases surface runoff[11)]. Moreover, quantification of the impact of land use changes on surface runoff can be conducted with the aid of the SWAT hydrological model, a river basin scale model developed to estimate the impact of land management practices in large and complex watersheds with varying soil types, land use, and management purposes over a long period of time. Surface runoff was identified as the factor most susceptible to land use change in both artificial and natural catchments[23)]. Decreased forest cover led to an increase in surface runoff in the studied watershed[53)].

The second purpose is to define the runoff generation mechanisms, including infiltration excess overland flow, saturation excess, subsurface storm flow, and quick groundwater outflow, which are likely to be affected by land use change and its influence on storm runoff generation. This study used an extension of the hydrological model, WASIM-ETH, including most of the processes relevant to runoff generation, by considering the spatial distribution of catchment characteristics and spatial temporal dynamics of climate variables, and improving the representation of the influence of land cover and the unsaturation zone on the infiltration process. High dependency on rainfall event characteristics and their spatial scale were identified[25)].

d) Flooding Control

Flood control is becoming one of the major questions in urban planning as well as land use planning. The urbanization process lowers the infiltration rate by substituting impervious cover for natural vegetation, and increases in discharge rate are the direct result of high water velocity. These lead to increased vulnerability to urban flooding; moreover, these problems are even worse for developing countries since industrialization has concentrated the urbanization process in the past half century[54)]. Considering these problems, flood control as a factor in watershed-based planning and land use analysis was categorized with two main purposes.

The first purpose is to define the characteristics of flood prone areas. These were defined through raster format maps with derived hydrological products and field investigation. Flood-prone areas were identified[35)]. From the viewpoint of geography and urban disaster prevention, flood-prone areas can be used as hazard maps defined through the identification of potential water paths[39)].

The second purpose is to define the effectiveness of planning approaches. Two drainage system design methods were analyzed: traditional channelization intervention or end of pipe solutions, and the distributed storm water management approach, based on sustainable urban drainage systems (SUDS). The objectives of this is to minimize the quality and quantity problems related to urban development's effect on the natural environment, and maximize amenities and biodiversity opportunities under different scenarios, considering distinct future urban development possibilities. The traditional approach distributes floods downstream at any time, while the distributed measures over the basin showed a high possibility of adaptation to the future urban pattern[54]. Ian McHarg's ecological planning approach based on hydrological properties related with land use change, storm water, runoff and discharge was evaluated for its effectiveness for flooding control, and the best solution among the development approaches compared in the study was identified[55].

e) Land suitability and allocation analysis

Among the target academic papers, two types of analysis were identified considering the influence and impact of land use practices on the natural environment and their related consequences on a watershed scale.

The first type is land suitability analysis, an approach establishing the most appropriate desirable direction for future land use development. In order to identify the most appropriate site, the suitability of various land uses for exploring the growth direction was identified. Criteria for four different types of land use, namely low-density housing, commercial development, industrial development, and recreation were defined using an ecological inventory of the Gila river watershed in terms of primary suitability, secondary suitability and unsuitability for certain land uses. This method can be applied to other rural areas of the American West[56]. Slope degree was considered to be the main factor in the suitability analysis, in particular, for the area dominated by soil erosion by using the relative land use suitability index (R), which was then used to define the suitability of the land use structure. It was clarified that the current land use structure was suitable[48].

The second type is land allocation analysis, which is conducted to integrate land use planning with effective environmental management, considering economic and social conditions. Land allocation analysis has two general objectives.

The first objective is to define the best spatial location taking consideration of economic, natural resource and social factors. In this sense, the land use optimization plan was defined, focusing on four criteria: the maximization of housing, employment capacity, compatibility between land uses, and the minimization of NPS pollution. It was demonstrated that these models were appropriate for use in areas undergoing urban expansion[26]. Integration of GIS and the optimization model was used to define the future land use allocation based on the inexact-fuzzy multi-objectives linear programming (IFMOP) model, allowing uncertainties including decisions, objectives, and constraints to be communicated in the program and generate solutions. However, this method is for real-time planning; environmental and socio-economic conditions change[57]. An approach to sustainable land use planning satisfying natural eco-environmental conditions, economic conditions, and local farmers' acceptance and participation, was conducted, where the land suitability evaluation focused on soil types, slope gradient, landform, and slope aspects for rain-fed agriculture. A comparison of land suitability, current land use, and potential land use scenarios based on surveys of biophysical and socio-economic parameters in the catchment and plans by authorities, was used for further evaluation of the effects on soil erosion, economic feasibility and social acceptance. A good choice of land use scenarios with respect to ecological/biological factors was defined[58]. The best allocation of land for future agriculture and forest development was identified with the aid of GIS multi-criteria analysis in modeling future land use for resource planning and management based on biophysical parameters[59]. A realistic soil conservation plan and its implementation in Indonesia was analyzed by conducting an estimation of soil erosion and economic feasibility analysis based on the cost-benefit ratio of land use types in the watershed. It was demonstrated that land use to optimize economic profit/benefit was the preferred option[60].

The second objective is site prioritization. In this context, the site prioritization was conducted for low-impact development (LID), a land use planning method used to improve water quality in the urban watershed and mitigate urban impacts to the environment at the sub-catchment level. Hydrological sensitive areas (HSAs) were identified using a multi-variable topographic index and calculation of suitability for LID application in terms of land use, spatial scale, position in the stream network and the effectiveness of impervious areas. This method enables the mitigation of the effects of urban land use and allows cost-effective land use planning decisions to be made regarding stream ecosystems across diverse landscapes[61]. Potential sites were identified for the placement of the conservation buffer and riparian restoration in the watershed, in which the delineation of the exact extent and boundary of the riparian landscape was often difficult, remaining an issue of debate. A power-screening tool for defining potential sites for conservation buffers and riparian restoration placement in watersheds was defined[62].

e) Landscape structure

Landscape structure is defined as the result of the complex interaction between physical, biological, political, economic, and social driving forces; change in landscape structure causes change in its function.

In recognition of the complex interactions involved, watershed-based land use analysis with landscape structure as an indicator primarily focused on clarifying landscape structure and its relationship with land use through two methods.

The first method is to use landscape indices. In this method, landscape indices such as patch number per unit area, mean patch area of different land use types, and diversity index (H), are used for describing information change and landscape pattern analysis. Fractal dimensions for measuring patch shape complexity, the evenness index derived from the Shannon Evenness Index, and the landscape fragmentation index, were analyzed with related land use types. The reliability of using these indices for measuring and evaluating land use/land cover change was illustrated[12]. The impact of urbanization on landscape characteristics and their consequences were elucidated in an urban lake watershed[16]. In addition, landscape structure and land use change can be identified with a fixed 50-m width buffer zone for all stream orders, in which the stream networks were derived from Strahler's stream ordering system[45]. Moreover, the land use and landscape structure were also identified through patchiness and degree of irregularity of different land use plots focusing on a shape complexity index (SCI) for investigating the change in forest patch complexity at the polygon level. This technique works by comparing the SCI of existing forest polygons with the optimum SCI polygon shape. Essential information of change occurred in forest areas and other major land uses in the studied watershed were identified[63]. The relationship between land use and landscape factors was defined using landscape indices such as area, areal percentages, and patch number per land use type. Fragmentation in the study area after land reform was shown[48].

The second method is to use the characteristics of the natural environment such as topography, slope, and vegetation conditions to clarify the relationship between land use and landscape structure. Types of land use changes and main components in terms of topography, land use, and soil were determined[37]; Landscape structure, function, and change were clarified[42].

3.6 Conclusions of chapter

First, in recognition of the land use detection method trends, several sources of information including current satellite data and corresponding software were demonstrated to be in use. Furthermore, for high-precision land use detection, the integration of remote sensing (RS) and GIS was proven to be an important technology for temporal analysis and qualification of spatial phenomena, particularly as it allowed for land use analysis with less time and low cost. However, higher spatial resolution satellite data are needed for detecting land use change in detail. Moreover, it has proved to be a useful tool to apply to watershed-based land use analysis with the major methodologies of land use modeling.

Second, terrain analysis based on the digital elevation model has been used widely not only in the fields of hydrology, water resource planning, and other fields, but also in city and regional planning. As the study of the watershed as a planning unit has moved into a new age with the aid of geographical information systems, the definition, application, and the use of a variety of indicators, particularly in rural watersheds, will become even more critical. From the viewpoint of watershed scale planning, the nature of using an application to analyze watersheds is not static. There is much variation among planners because the threshold values, used for stream definition differ. Therefore, close attention should be paid to the process of watershed analysis. With these concerns as a basis, it is proposed that instead of using constant thresholds, more appropriate and standard methods should be defined in order to bridge the gap between the actual watershed and the watershed delineated in the application. On the other hand, in urban watersheds, where the output information of the modeling is necessary to solve the problem of urban flooding, it is essential for future research to give more attention to the methods, in particular, for the majority of developing countries, where data are lacking and urban flooding is the main issue.

Third, from the review of these academic papers have shown that the research trends in factors considered in watershed-based land use analysis and the relationships between these factors, characteristics of study areas, scales, and areas are generally discussed at both the regional and the local scale.

Knowing the trends of both basic tools, lack of land use data in the research has been solved while discussion on threshold definition methods to define each scale of planning is introduced in **Chapter 4**. One factor known as land suitability and allocation analysis defined above is used for the development of watershed-based methodology for land use planning in this research as introduced in **Chapter 5**.

References:

1) DeFries, R. and Eshleman, K. N.: Land-use change and hydrologic processes: A major focus for the future, *Hydro. Process,* Vol. 18, pp. 2183-2186, 2004.

2) Bhaduri, B., Harbor, J. O. N., Engel, B. and Grove, M.: Assessing watershed-scale, long-term hydrologic impacts of land-use change using a GIS-NPS model, *Environmental Management*, Vol. 26, No. 6, pp. 643-658, 2000.

3) Erickson, D. L.: Rural land use and land cover change, *Land Use Policy*, Vol. 12, No. 3, pp. 223-236, 1995.

4) Kauffman, G. J.: What if the United States of America were based on watersheds?, *Water Policy,* Vol. 4, pp. 57-68, 2002.

5) National Research Council (U.S.): Committee to Review the New York City Watershed Management Strategy: Watershed management for potable water supply: Assessing the New York City Strategy, National Academy Press, pp. 45-87, 2000.

6) Katagiri, Y. and Ishikawa, M.: A study on landscape planning based on watershed unit in Sendai metropolitan area, *J. Japanese Institute of Landscape Architecture*, Vol. 75, No. 5, pp. 673-676, 2012.

7) Strager, M. P., Fletcher, J. J., Strager, J. M., Yuill, C. B., Eli, R. N., Petty, J. T. and Lamont, S. J.: Watershed analysis with GIS: The watershed characterization and modeling system software application, *Computer & Geosciences,* Vol. 36, Issue 7, pp. 970-976, 2010.

8) Anderson, J. R., Hardy, E. E., Roach, J. T. and Witmer, R. E.: A land use and land cover classification system for use with remote sensor data, *U.S. Geological Survey Professional Paper*, No. 964, USGS, Washington, D.C. 1976.

9) Rawal, H. S., Rawat, J. S., Kumar, M., Pant, N. C. and Rani, N.: Land use/ cover dynamics of Kail watershed, central Himalaya, India using remote sensing and GIS technique, *Int. J. Advancement in Remote Sensing, GIS and Geography,* Vol. 2, No.2, pp. 55-59, 2014.

10) Hong, Z., Hailin, L. and Zhen, C.: Analysis of land use dynamic change and its impact on the water environment in Yunnan Plateau lake area— A case study of the Dianchi Lake drainage area, *Procedia Environmental Sciences,* Vol. 10, pp. 2709-2717, 2011.

11) Carlson, T. N.: Analysis and prediction of surface runoff in an urbanizing watershed using satellite imagery, *J. American Water Resources Association*, Vol. 40, Issue 4, pp. 1087-1098, 2004.

12) Yunus, A. J. M., Nakagoshi, N. and Ibrahim, A. L.: Application of GIS and remote sensing for measuring and evaluating land use change and its impact on water quality in the Pinang River Watershed, *Ecol. Civil. Eng.,* Vol. 6, No. 1, pp. 97-110, 2003.

13) Butt, A., Shabbir, R., Ahmad, S. S. and Aziz, N.: Land use change mapping and analysis using remote sensing and GIS: A case study of Simly watershed, Islamabad, Pakistan, *The Egyptian Journal of Remote Sensing and Space Sciences,* Vol. 18, Issue 2, pp. 251-259, 2015.

14) Ghimire, S. K. and Higaki, D.: Study of recent changes in land use and stream course with reference to geomorphologic characteristics in the Siwalik Hills of Nepal, *J. the Japan Society of Erosion Control Engineering,* Vol. 57, No. 5, pp. 25-31, 2005.

15) Wen, Y., Khosrowpanah, S. and Heitz, L.: Land cover change of watersheds in Southern Guam from 1973 to 2001, *Environ. Monit. Assess.,* Vol. 179, pp. 521-529, 2011.

16) Li, Y., Zhao, S., Zhao, K., Xie, P. and Fang, J.: Land-cover changes in an urban lake watershed in a

mega-city, central China, *Environ. Monit. Assess.,* Vol.115, pp. 349-359, 2006.

17) Senevirathne, N., Mony, K., Samarakoon, L. and Hazaraki, M. K.: Land use/land cover change detection of Tonle Sap Watershed, Cambodia, *31st Asian Conference on Remote Sensing (ACRS)*, Vol. 1, pp. 852-857, 2010.

18) Apan, A. A., Raine, S. R. and Paterson, M. S.: Mapping and analysis of changes in the riparian landscape structure of the Lockyer Valley catchment, Queensland, Australia, *Landscape and Urban Planning,* Vol. 59, Issue 1, pp, 43-57, 2002.

19) Lu, D. and Weng, Q.: A survey of image classification methods and techniques for improving classification performance, *International Journal of Remote Sensing,* Vol. 28, No. 5, pp. 823-870, 2007.

20) Kunihiko, Y., Yudi, S. and Eikichi, S.: Land use analysis using time series of vegetation index derived from satellite remote sensing in Brantas River watershed, East Java, Indonesia, *The International Symposium on Cartography in Internet and Ubiquitous Environments,* 2015.

21) Luo, P., Takara, K., Apip, He, B., Nover, D. and Yamashiki, Y.: Land use change analysis and paleo-flood in the Kamo River basin, Kyoto, Japan, *J. Hydrologic Engineering,* Vol. 68, No. 4, pp. 127-132, 2012.

22) Lin, Y. P., Hong, N. M., Wu, P. J., Wu, C. F. and Verburg, P. H.: Impacts of land use change scenarios on hydrology and land use patterns in the Wu-Tu watershed in Northern Taiwan, *Landscape and Urban Planning,* Vol. 80, pp. 111-126, 2007.

23) Fohrer, N., Haverkamp, S., Eckhardt, K. and Frede, H. G.: Hydrologic response to land use changes on the catchment scale, *Phys. Chem. Earth (B),* Vol. 26, No. 7-8, pp. 577-582, 2001.

24) Takamatsu, M., Kawasaki, A., Rogers, P. P. and Malakie, J. L.: Development of a land-use forecast tool for future water resources assessment: Case study for the Mekong River 3S Sub-basins, *Sustain Sci.,* Vol. 9, pp. 157-172, 2014.

25) Niehoff, D., Fritsch, U. and Bronstert, A.: Land-use impacts on storm-runoff generation: Scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-

Germany, *J. Hydrology,* Vol. 267, pp. 80-93, 2002.

26) Huang, B. and Zhang, W.: Sustainable Land-use planning for a downtown lake area in central China: Multi-objective optimization approach aided by urban growth modeling, *J. Urban Planning and Development,* Vol. 140, Issue 2, 2014.

27) Tang, Z., Engel, B. A., Pijanowski, B. C. and Lim, K. J.: Forecasting land use change and its environmental impact at a watershed scale, *J. Environmental Management,* Vol. 76, pp. 35-45, 2005.

28) Pijanowski, B. C., Shellito, B., Pithadia, S. and Alexandridis, K.: Forecasting and assessing the impact of urban sprawl in coastal watersheds along eastern Lake Michigan, *J. Lakes & Reservoirs: Research and Management,* Vol. 7, 2002.

29) Yan, H. and Edwards, F. G.: Effects of land use change on hydrologic response at a watershed scale, Arkansas, *J. Hydrologic Engineering,* Vol. 18, pp. 1779-1785, 2013.

30) Nguyet, D. A. and Kawasaki, A.: Review of current approaches and new trends in land-use change projection modeling, *Seisan Kenkyu,* Vol. 65, No. 4, pp. 509-515, 2013.

31) Lin, W. T., Chou, W. C., Lin, C. Y., Huang, P. H. and Tsai, J. S.: Automated suitable drainage network extraction from digital elevation models in Taiwan's upstream watersheds, *Hydro. Process,* Vol. 20, Issue 2, pp. 289-306, 2006.

32) Djokic, D. and Maidment, D. R.: Terrain analysis for urban stormwater modeling, *Hydro. Process,* Vol. 5, pp. 115-124, 1991.

33) Greene, R. G. and Cruise, J. F.: Urban watershed modeling using Geographic Information System, *J. Water Resources Planning and Management,* Vol. 121, Issues 4, pp. 318-325, 1995.

34) Wang, X. and Yin, Z. Y.: Using GIS to assess the relationship between land use and water quality at a watershed level, *Environment International,* Vol. 23, No.1, pp. 103-114, 1997.

35) Masoud, A. A., Raghavan, V., Masumoto, S. and Shiono, K.: Stream network and basin boundary extraction using GRASS GIS: EL-Barud Basin, Safaga Area, Red Sea Coast, Egypt, *Geoinformatics,* Vol. 13, No. 4, pp. 205-212, 2002.

36) Ohbi, K. and Suzuki, M.: A study on the watershed classification using grid cell data, *J. The*

Japanese Institute of Landscape Architecture, Vol. 66, No. 5, pp. 871-876, 2002.

37) Ohbi, K. and Suzuki, M.: An analysis of land-use transition based on watershed units using the national digital information data base, *J. The Japanese Institute of Landscape Architecture,* Vol. 65, No. 5, pp. 861-864, 2001.

38) Minami, J., Usui, N., Shimizu, H., Murayama, A. and Otsuki, A.: A Basic Study on land use planning focused on watershed: Case of Ise Bay basins area, *J. Architectural Institute of Japan*, Vol. 45, pp. 601-604, 2007.

39) Inoue, K., Shimizu, H. and Otsuki, A. and Murayama, A.: Development of a method to visualize a “Water Path Network” in an urban area using GIS, *J. Archit. Plann., AIJ,* Vol. 74, No. 635, pp. 107-112, 2009.

40) Katagiri, Y., Yamashita, H. and Ishikawa, M.: An evaluation method for the plan of greenery and open space based on small watershed unit, *J. The Japanese Institute of Landscape Architecture,* Vol. 70, No. 5, 2007.

41) Katagiri, Y., Yamashita, H. and Ishikawa, M.: A study on the database of the watershed unit based on the common data, and the analysis and evaluation method for the open space planning, *J. The Japanese Institute of Landscape Architecture,* Vol. 67, No. 5, 2004.

42) Iida, A.: A study on watershed-based landscape planning on Babeldaob Island in the Republic of Palau, *Environmental Design Research,* Vol. 1, 2012.

43) Lim, L. and Sasaki, Y.: Methodology to evaluate the urban spatial characteristics of traditional cities by watershed-based analysis, *The 15th Science Council of Asia Conference and International Symposium,* pp. 38-44, 2015.

44) Kawasaki, A., Takamatsu, M., He, J., Rogers, P. and Herath, S.: An integrated approach to evaluate potential impact of precipitation and land-use change on streamflow on Srepok River basin, *Theory and Applications of GIS,* Vol. 18, No.2, pp. 9-20, 2010.

45) Yunus, A. J. M., Nakagoshi, N. and Ibrahim, A. L.: Riparian land-use and land cover change analysis using GIS in Pinang river watershed, Malaysia, *Tropics,* Vol. 13, No. 4, pp. 235-248, 2004.

46) Katagiri, Y., Yamashita, H. and Ishikawa, M.: A study on the transition of open space in small watershed from the viewpoint of water cycle, *J. The Japanese Institute of Landscape Architecture*, Vol. 68, No. 5, Landscape Research Japan, pp. 913-918, 2004.

47) Tarboton, D. G. and Ames, D. P.: Advances in the mapping of flow networks from digital elevation data, *World Water and Environmental Resources Congress,* 2001.

48) Chen, L., Wang, J., Fu, B. and Qiu, Y.: Land use change in a small catchment of northern Loess Plateau, China, *Agriculture, Ecosystems and Environment,* Vol. 86, pp. 163-172, 2001.

49) Morisawa, M. and LaFlure, E.: Hydraulic geometry, stream equilibrium and urbanization, *Proceedings of the 10th Annual Geomorphology Symposium Series*, D. D. Rhodes and G. P. Williams (eds.), Binghamton, NY, 1979.

50) Brabec, E., Schulte, S. and Richards, P. L.: Impervious surfaces and water quality: A review of current literature and its implications for watershed planning, *J. Planning and Literature,* Vol. 16, No. 4, pp. 499-514, 2002.

51) Wang, X.: Integrating water-quality management and land-use planning in a watershed context, *J. Environmental Management,* Vol. 61, pp. 25-36, 2001.

52) Meneses, B. M., Reis, R., Vale, M. J. and Saraiva, R.: Land use and land cover changes in in Zêzere watershed (Portugal) — Water quality implications, *Science of the Total Environment,* Vol. 527-528, pp. 439-447, 2015.

53) Coutu, G. W. and Vega, C.: Impacts of land use changes on runoff generation in the east branch of the Brandywine Creek watershed using a GIS-Based hydrological model, *Middle States Geographer,* Vol. 40, pp. 142-149, 2007.

54) Miguez, M. G., Rezende, O. M. and Veról, A. P.: City growth and urban drainage alternatives: sustainability challenge, *J. Urban Planning and Development,* Vol. 141, Issue 3, 2015.

55) Yang, B. and Li, M. H.: Assessing planning approaches by watershed streamflow modeling: Case study of the Woodland, Texas, *Landscape and Urban Planning,* Vol. 99, pp. 9-22, 2011.

56) Steiner, F., McSherry, L. and Cohen, J.: Land suitability analysis for the upper Gila River watershed,

Landscape and Urban Planning, Vol. 50, pp. 199-214, 2000.

57) Wang, X., Yu, S. and Huang, G. H.: Land allocation based on integrated GIS-optimization modeling at a watershed level, *Landscape and Urban Planning,* Vol. 66, pp. 61-74, 2004.

58) Chen, L., Messing, I., Zhang, S., Fu, B. and Ledin, S.: Land use evaluation and scenario analysis towards sustainable planning on the Loess Plateau in China–Case study in a small catchment, *CATENA,* Vol. 54, pp. 303-316, 2003.

59) Nyeko, M.: GIS and multi-criteria decision analysis for land use resource planning, *Geographic Information System,* Vol. 4, pp. 341-348, 2012.

60) Aflizar, Saidi, A., Husnain, Ismawardi, Istijono, B., Harmailis, Somura, H., Wakatsuki, T. and Masunaga, T.: A land use planning recommendation for the Sumani watershed, West Sumatra, Indonesia, *Tropics,* Vol. 19, No. 1, pp. 43-51, 2010.

61) Martin-Mikle, C. J., de Beurs, K. M., Julian, J. P. and Mayer, P. M.: Identifying priority sites for low-impact development (LID) in a mixed-use watershed, *Landscape and Urban Planning,* Vol. 140, pp. 29-41, 2015.

62) Qiu, Z.: Assessing critical source areas in watersheds for conservation buffer planning and riparian restoration, *Environmental Management,* Vol. 44, pp. 968-980, 2009.

63) Gautam, A. P., Webb, E. L., Shivakoti, G. P. and Zoebisch, M. A.: Land use dynamics and landscape change pattern in a mountain watershed in Nepal, *Agriculture, Ecosystems and Environment,* Vol. 99, pp. 83-96, 2003.

CHAPTER 4
Preparation of GIS-based spatial databases for watershed-based land use analysis in PPC

4.0 Summary of chapter

Basically, this chapter is composed of three main parts. The terminology terms used in this research is firstly presented. The setting of watershed scale mainly including watershed delineation process with the demonstration of data collection and data processing are performed, afterwards methodology to define threshold values for identifying watershed scales: macro, middle, and micro are demonstrated. Lastly, land use detection using remote sensing image by the first level of remote sensing classification system is performed by using ArcHydro extension in ArcGIS 10.2 platform.

4.1 Definition of catchment, sub-watershed, watershed, river basin, drainage area and urban flooding

A catchment is a land area where all surface water (rain, melting snow or ice) drains into a common outlet, while a sub-watershed is composed of two or more catchments; a watershed is composed of many catchments and sub-watersheds[1)] as shown in **Fig.4.1**.

The term 'river basin' is defined as an area of land drained by a river or its tributaries.

A drainage area is the total surface area, upstream of an outlet of a stream, where water from rain, snowmelt, ice or irrigation not absorbed into the ground flows over the ground surface and back into streams, and finally flows into the outlet[2)].

Urban flooding is defined as the overflowed water in land or properties in the built environment. The lack of water storage, absorbable soil, and excess of high intensities rainfall over the capacity of canals and sewage system can result in urban flooding.

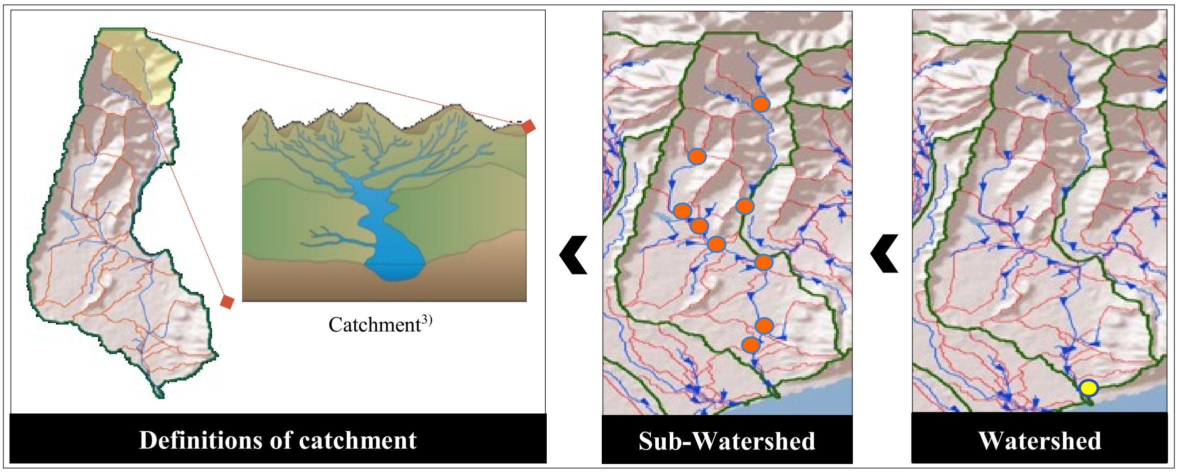


Fig.4.1 Terminology of catchment, sub-watershed, and watershed.

4.2 Watershed delineation

4.2.1 Data Source

This research uses the open source of Digital Elevation Model (DEM) known as Shuttle Radar Topography Mission (SRTM) with 90m resolution[4], as shown in **Fig. 4.2**.

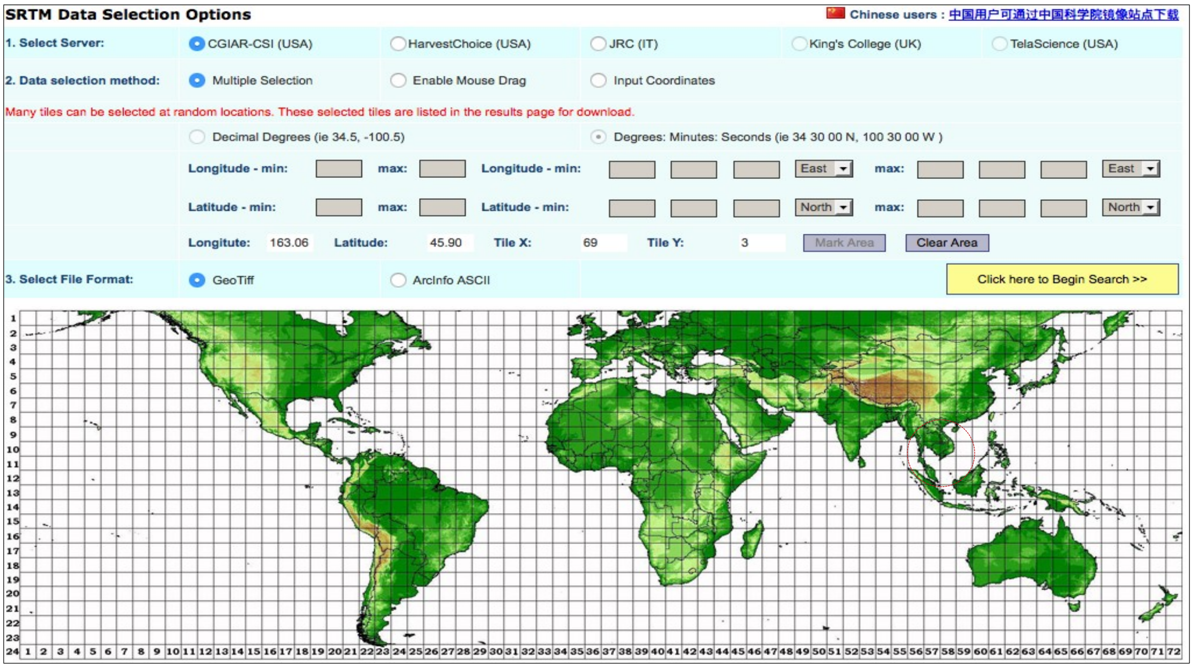


Fig.4.2 Interface of open source of SRTM[4].

4.2.2 Data processing

It's essential that fourth geo tiffs obtained from the open source are combined into single DEM with exact projected coordination system to perform the watershed analysis. In these respects, ArcGIS

10.2 platform is used to process the data with two important steps:

- With the procedures from "ArcToolbox-Data Management Tools-Raster-Raster Dataset-Mosaic to New Raster", 4 geo tiffs are combined into single DEM.
- Procedures of "ArcToolbox-Data Management Tools-Projection and Transformations-Raster-Project Raster with cell size 90" are performed with the projected coordination system of "WGS1984/UTM Zone 48N" for data preparation in this chapter.

4.2.3 Watershed delineation process

Generally, various watershed delineation procedures are found among the scholars with different computing software applications. In this chapter, ArcGIS 10.2 platform with ArcHydro extension is used to perform the watershed analysis.

The performance of watershed delineation method is based on some important steps including 1. fill sink, 2. flow direction, 3. flow accumulation, 4. stream definition, 5. stream segmentation, 6. catchment grid delineation, 7. catchment polygon processing, 8. drainage line processing, 9. adjoint catchment processing, 10. drainage point processing, 11. batch point generation, and 12. batch watershed delineation[5)].

4.3 Definition of threshold value

In terms of performing watershed analysis, the critical step known as stream definition, which requires to input the threshold value, is equal to the product of numbers of cell in flow accumulation and the square of cell size. It is the most crucial factor to define the size of the catchment units as well as sub-watershed units due to the fact that the smaller the threshold value of stream definition is, the denser the catchment units are.

From the watershed-based planning perspective, the watershed unit used as a scale of one study area is a vital issue to be discussed in the planning issue. In this respect, methodology to define a threshold value for identifying watershed unit is essential and explained in this chapter.

4.3.1 Methodology to define threshold value

Amongst five types of threshold values defined in **Chapter 3**, identification of threshold values based on one of the existing researches[6)] is demonstrated. Threshold value based on three important steps are illustrated as follows:

- The average output of watershed area is identified in terms of trialing threshold values performed in watershed delineation process with the aid of ArcGIS 10.2 platform.
- The average value of total administrative boundaries, for example, district boundaries, is simply derived from the division between the total area of districts and the number of districts.
- Comparison between the above two steps is performed to define the most approaching threshold value among these two steps.
- Linear Interpolation is performed to obtain the final threshold value.

4.3.2 Illustration of defining threshold value

Primarily, following the watershed delineation process using the DEM obtained from section **4.2.2**, 20 trialed threshold values are performed, as shown in **Table 4.1**. Secondly, a simple calculation of the average value of district areas, as **Fig.4.3**, is conducted.

Finally, the average value of 7603.76 ha was defined in the interval of 4000ha and 5000ha as shown in **Table 4.1**. By using linear interpolation, the defined threshold value (DTV)= [(5000-4000)/(8506.02-6875.97)] *(7603.75-6875.97) +4000=4446.48≈4447 ha.

Table 4.1 20 trailed threshold values.

Nº	Threshold (ha)	Number of cells	Number of catchments	Average area of catchment (ha)	Total area of catchments (ha)
1	25	30.86	832983	49.82	41495407.45
2	50	61.73	434383	95.39	41434421.71
3	100	123.46	225533	183.38	41357568.88
4	250	308.64	92244	446.91	41224903.02
5	500	617.28	46681	880.18	41087710.89
6	750	925.93	31452	1303.55	40999318.83
7	1000	1234.57	23706	1726.14	40919836.78
8	1250	1543.21	18977	2152.80	40853663.01

9	1500	1851.85	15902	2565.58	40797830.51
10	1750	2160.49	13676	2979.99	40754390.21
11	2000	2469.14	11942	3409.25	40713206.56
12	3000	3703.70	7899	5136.23	40571102.59
13	**4000**	**4938.27**	**5884**	**6875.97**	**40458195.07**
14	**5000**	**6172.84**	**4745**	**8506.02**	**40361063.95**
15	6000	7407.41	3924	10262.54	40270190.04
16	7000	8641.98	3390	11852.10	40178631.67
17	8000	9876.54	2971	13490.79	40081148.97
18	9000	11111.11	2614	15304.40	40005707.17
19	10000	12345.68	2322	17195.90	39928869.76
20	11000	13580.25	2101	18969.64	39855219.7

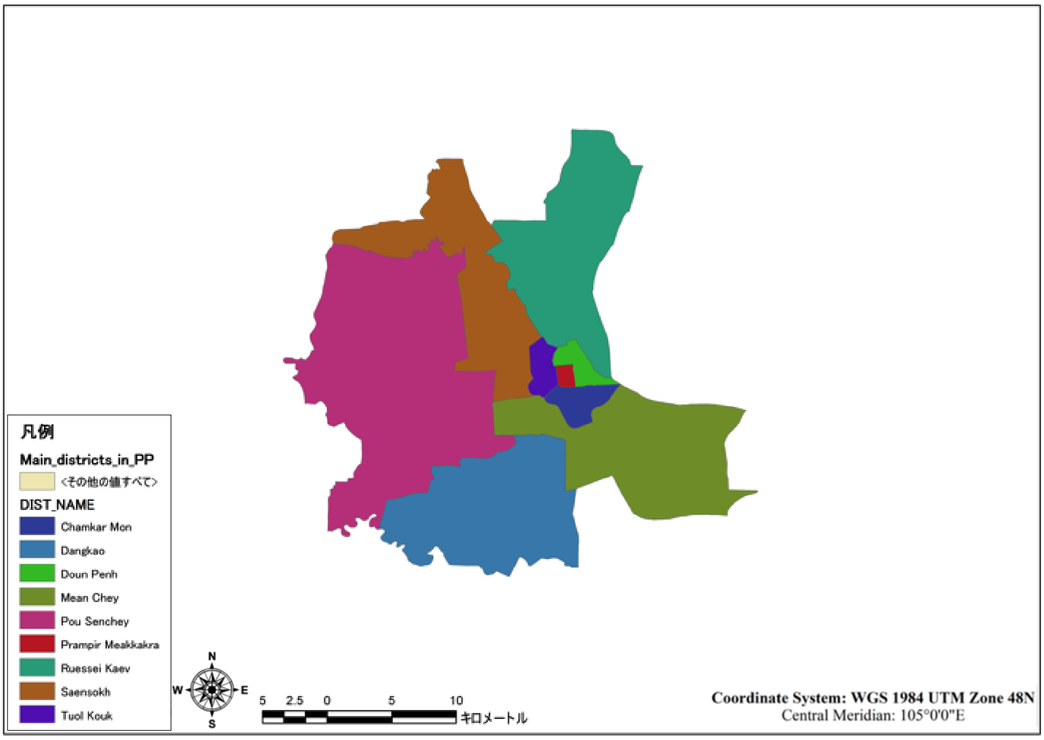


Fig.4.3 District area of Phnom Penh City[7].

4.3.3 Watershed scale

Fundamentally, the hierarchy of territorial division in Phnom Penh City (PPC) is based on the Khmer language known as Khans (Districts), Sangkats (Communes) and Kroms (Villages).

In this context, from the watershed-based planning perspective, two watershed scales including macro scale (Khan level) and middle scale (Sangkat level) are based on the hierarchy of territorial division in PPC. Whereas watershed unit with stream definition =100ha=1km^2 is used to define micro scale.

Figures 4.4 shows watershed unit and drainage networks defined based on the hierarchy territory division of Phnom Penh City (PPC) known as Khan level. Each number indicates watershed units' names.

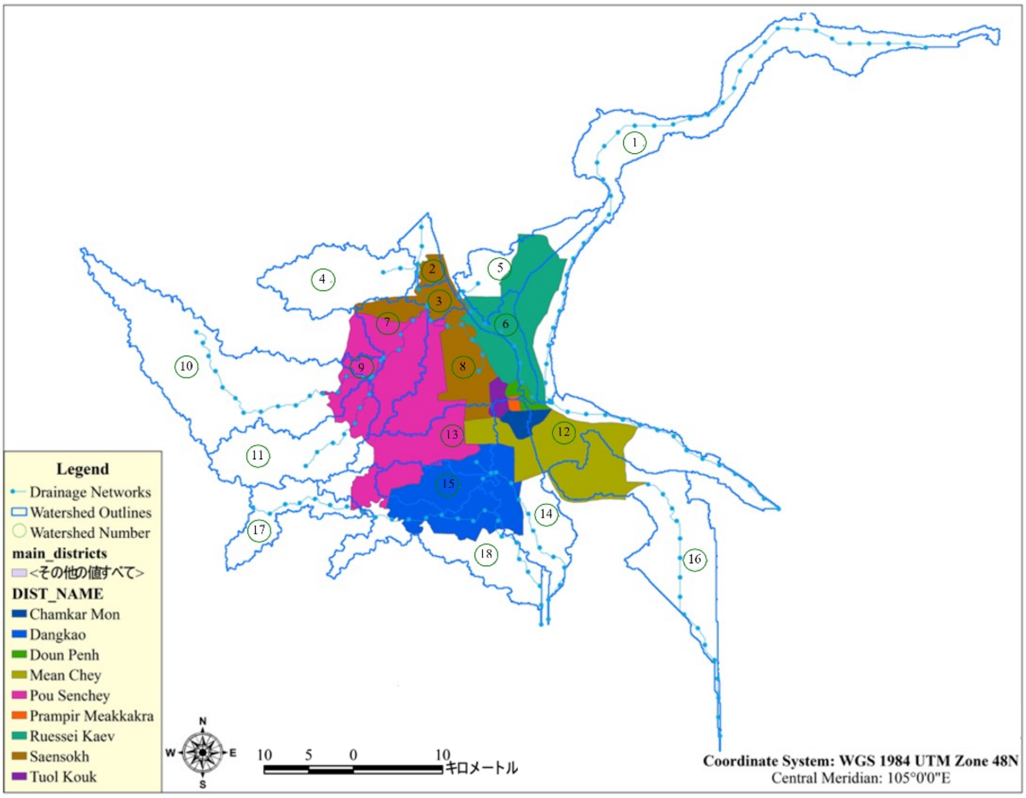


Fig.4.4 Watershed outlines, drainage networks, and PPC's district boundaries.

4.4 Land use detection using remote sensing image and GIS

Thanks to the rapid development of technology that enable both scientific communities and scholars to use the open source such as satellite image for further understanding and investigating of land use dynamic in the globe. Particularly, in many developing countries, the lack of land use data remains as crucial issues for the urban planning development. Likewise, PPC, as one among the cities in the developing countries, lacking data is inevitable.

In this respect, detection of land use using open source data called Landsat data is introduced with the expectation that it can be used as a tool for significantly improving the land use planning in PPC.

In terms of performing land use detection, land use classification system and land use detection process are the two key issues to be discussed hereafters.

4.4.1 Land use classification system

The land use classification system, which concerns about the level of classifying land use types, is essential to be identified before performing the land use detection.

In this chapter, decision on the level of the land use classification system is made by using available data source of Topographical map[8)] and Google Earth as the reference. In this respect, five types of the first level's land use classification system with remote sensor data, as shown in **Table 4.2**, is adapted based on the presented revision of the land use classification system[9)].

With the medium resolution of Landsat data and limitation of reference data, the first level of the land use classification system is sufficient to discuss about watershed-based land use planning for PPC in **Chapter 5**, **6** and **7**.

Table 4.2 Five types of the first level's land use classification system[8)]

Level I	Description of each land use
Urban or Built Up	Residential, commercial or service, industrial, transportation, communication, utilities and another urban land such as garden, waste dumps etc.
Agricultural Land	Cropland, pasture, orchards, and another agricultural land, 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

4.4.2 Land use detection procedures

a) Data source

Remote sensing images called Landsat data, which are obtained from the open source provided by U.S. Geological Survey (USGS)[10)] with essential criteria including Max cloud of 0% and target year from 2000 to 2015, are used in this research as shown in **Fig. 4.5**.

Consequently, Landsat data known as Landsat 4-5 Thematic Mapper (TM) in 2005 and Landsat 8

Operational Land Imager (OLI) in 2015 with 30 m resolution are obtained.

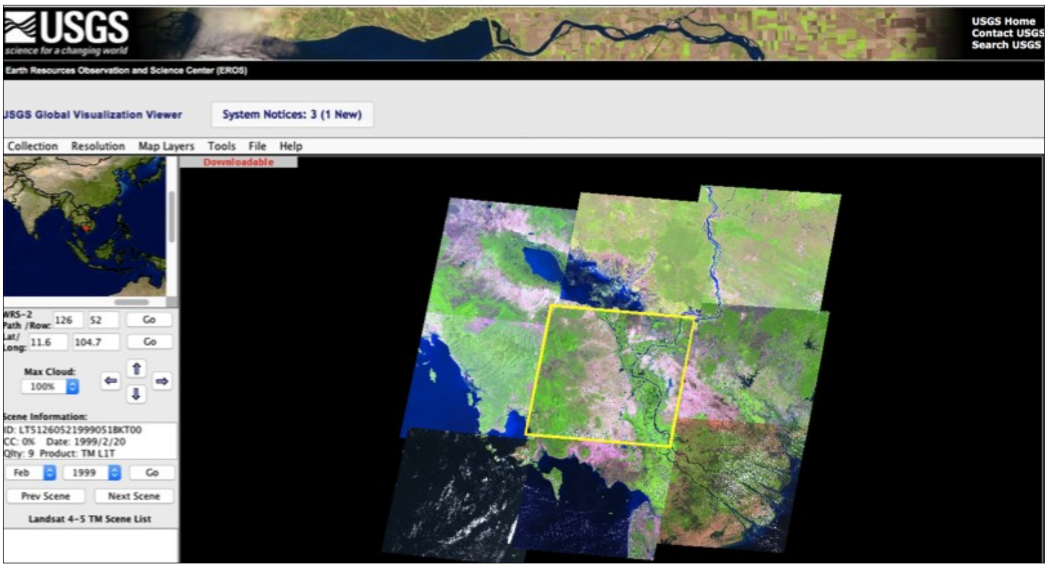


Fig.4.5 Source of Landsat data[10].

b) Data processing

Detection of land use data can be conducted with several types of detection tools. In this research, detection of land use data is performed by using Image Classification with ArcGIS 10.2 platform.

Basically, fourth important steps are essential to be performed.

- The composition of essential bands, which are defined based on the existing study[11], is conducted by using Image Analysis in ArcGIS 10.2 platform.
- Certain training samples are drawn manually and qualify by using training sample manager with ArcGIS 10.2 platform to reflect on the actual land use. These processes are carried out with the aid of existing topographical maps and time slider available from the year of 2000 in Google Earth.
- The maximum-likelihood algorithm of supervised classification is performed for pixel clustering based on the first level of classification with five types of land use (1. Urban or Built-Up, 2. Agricultural land, 3. Forest land, 4. Water, and 5. Wetland based on the definitions from existing study[9]).
- Accuracy assessment of land use detection is conducted. It begins firstly with the verification between detected results and actual condition based on the random points created in ArcGIS 10.2 platform. Secondly, Error Matrix conducted for defining overall accuracy called observed result,

and Product Matrix determined for the expected results, are calculated based on the results of those random points. Consequently, Kappa coefficient ((Observed-Expected)/(1-Expected)) is determined to judge for the accuracy of the detection (Kappa coefficient >0.8: high accuracy, 0.4-0.8: moderate accuracy, and <0.4: poor accuracy)[12), 13)].

c) Illustration of land use detection using remote sensing image and GIS

Primarily, the combination between the watershed defined in section **4.3.3**, which is used to define the boundary of detection and to composite the band 4, 5, and 6 of Landsat data 8 OLI, is used to demonstrate the detection of land use by Image Classification with the aid of ArcGIS 10.2 platform, as shown in **Fig.4.6**.

The result of land use detection is defined as shown in **Fig.4.7**. Calculations of both Error Matrix and Product Matrix are determined between detected results and actual condition based on the random points performed in ArcGIS 10.2 platform, as shown in **Table 4.3** and **Table 4.4**. As the results, Kappa Coefficient is determined as equal to 67% identified as moderate accuracy for the land use detection.

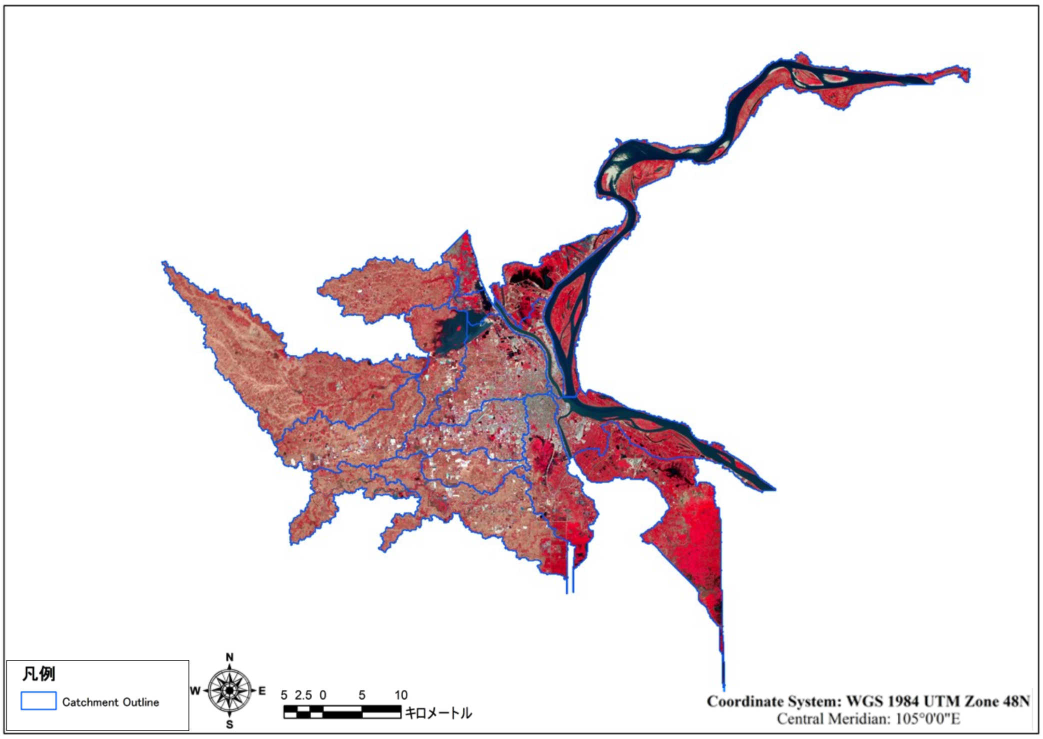


Fig.4.6 Landsat 8 OLI with detection boundary.

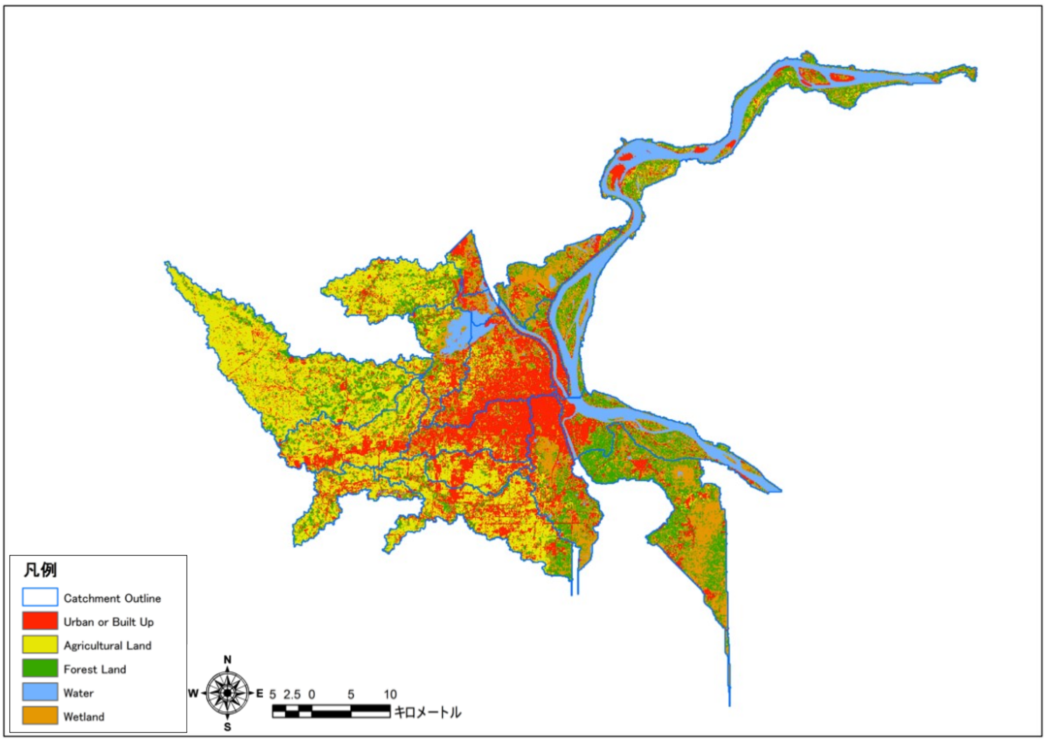


Fig.4.7 Results of land use detection.

Table 4.3 Error Matrix.

	Urban or Built-up	Agriculture Land	Forest Land	Water	Wetland
Urban or Built-up	26	1	3	0	2
Agriculture Land	10	52	7	0	3
Forest Land	4	5	18	0	3
Water	0	0	0	19	0
Wetland	7	1	2	1	26
Observed=Overall accuracy=141/190=74%					

Table 4.4 Product Matrix.

	Urban or Built-up	Agriculture Land	Forest Land	Water	Wetland
Urban or Built-up	1504	1888	960	640	1088
Agriculture Land	3384	4248	2160	1440	2448
Forest Land	1410	1770	900	600	1020
Water	893	1121	570	380	646
Wetland	1739	2183	1110	740	1258
Expected=8290/36100=67%					

4.5 Conclusions of chapter

The rapid development of technology makes further researches on developing countries, in which spatial databases are found lacking, constantly moving forward with the aid of GIS applications and some open sources including Digital Elevation Model and remote sensing image known as Landsat data.

In this chapter, scales of watershed including macro, middle, and micro applied in **Chapter 5**, **6**, and **7**, respectively are explained and identified using open source known as SRTM and base map with ArcGIS 10.2 platform. In the absence of land use data, the creation of land use data obtained from USGS is demonstrated using the integration of remote sensing and GIS with the first level of the classification system of remote sensor data, which are mainly utilized in **Chapter 5** and **Chapter 6**.

In brief, the spatial databases including scales of watershed and land use data created in this chapter are the essential information and data used for the main contents in this research.

References:

1. Lim, L. and Sasaki, Y.: Review of research trends in watershed-based land use analysis, *Journal of Infrastructure Planning and Management, JSCE,* Vol. 4, 227-242, 2016.
2. EcoWho, *Terms & Definition*, viewed 22 June 2016, from https://www.ecowho.com/defn/list.php?l=d.
3. Integration & Application Network, *River 3D: catchment-Freshwater-Vector Illustration/ Drawing/Symbol (SVG)*, viewed 08 September 2013, from http://ian.umces.edu/imagelibrary/disp layimage-6434.html.
4. CGIAR CSI, *SRTM 90m digital elevation model database v4.1*, viewed 11 September 2015, from http:// srtm.csi.cgiar.org.
5. Esri Support, *Arc Hydro Tools,* viewed 7 September 2013, from http://down loads.esri.com/archydro/archydro/Tutorial/Doc/Arc%20Hydro%20Tools%202.0%20-%20 Tutoria l.pdf.

6. Junichiro, M., Naoyuki, U., Hiroyuki, S., Akito, M. and Atsushi, O.: A Basic Study on land use planning focused on watershed: Case of Ise Bay basins area, *Journal of Architectural Institute of Japan*, 45, 601-604, 2007.
7. Open development Cambodia, *Base map*, viewed 6 July 2014, from http://www.opendevelopmentcambodia .net/.
8. Aruna Technology Ltd, *1: 100,000 Scale Topographic Map WGS84/UTM Coordinates*, viewed 10 October 2014, from http://arunatechnology.com/resources/downloads/.
9. Anderson, J.R., Hardy, E.E., Roach, J.T. and Witmer, R.E.: A land use and land cover classification system for use with remote sensor data, *U.S. Geological Survey Professional Paper*, No. 964. USGS, Washington, D.C, 1976.
10. USGS Global Visualization Viewer, *Landsat data*, viewed 10 November 2015, from http:// glovis.usgs.gov.
11. Rawal, H. S., Kumar, M., Pant, N. C. and Rani, N.: Land use/ cover dynamics of Kail watershed, central Himalaya, India using remote sensing and GIS technique, *International Journal of Advancement in Remote Sensing, GIS and Geography,* 2(2), 55-59, 2014.
12. Senevirathne, N., Mony, K., Samarakoon, L. and Hazariki, M.K.: Land use/land cover change detection of Tonle Sap watershed, Cambodia, *31st Asian Conference of Remote Sensing (ACRS),* Vol.1, pp. 852-857, 2010.
13. Congalton, R. G.: A review on assessing the accuracy of classifications of remote sensed data, *Remote Sensing Environment,* Vol. 37, pp. 35-46, 1991.

CHAPTER 5

Concept of watershed-based land use planning for PPC at macro scale

5.0 Summary of chapter

The methodology of watershed-based land use planning for PPC is developed based on three scales: macro, middle and micro. In this chapter, the concept of watershed-based land use planning for PPC at macro scale focusing on the district level is introduced[1)]. The relationship among watersheds is regarded as a primarily screening assessment for defining critical development area; grasping and analyzing land use planning based on watershed are essential. In this context, two key issues are discussed. Transformation of land use in 2005, 2015, and master plan in 2020 based on zoning area in each watershed are performed. Interaction of zoning area and outside of zoning area as part of the watershed is conducted, which reflects on the interaction between upstream and downstream of the watershed.

5.1 Transformation of land use in 2005, 2015, and master plan in 2020 based on zoning area in each watershed

To achieve the objectives in this chapter, fourth basic steps are performed as follows:

- Identification of watershed used for Phnom Penh City (PPC)
- Defining "Zoning area" and "Outside of zoning area" in each watershed
- Detection of land use in 2005, 2015, and manually creation of land use types for master plan in 2020 according to the first level of land use classification system.
- Computation of land use transformation in 2005, 2015, and master plan in 2020 based on zoning area as part of watershed

5.1.1 Data source

To carry out the analyses in this chapter, all spatial databases of PPC are collected with different scales and resolutions in the various source data as shown in **Table 5.1**.

Table 5.1 Data source and scales for Phnom Penh City.

Data	Source	Scale / Other
Shuttle Radar Topography Mission[2)] (SRTM) with 4 GeoTiffs	http:// srtm.csi.cgiar.org	90 m
Landsat 4-5 TM (01/03/2005)[3)] Landsat 8 OLI (01/15/2015) [3)] (Max cloud=0%)	http:// glovis.usgs.gov	30 m
Topographic Map 2002[4)]	http://www.arunatechnology.com	1:100,000
Base Maps[5)] (Districts, National Road, Provinces and Water Bodies)	http://www.opendevelopmentcambodia.net/	Shape files
Master Plan in 2020[6)]	DATUC-BAU, 06-2009 (Municipality of Phnom Penh)	JPEG Image

5.1.2 Identification of watershed used in PPC

To identify watershed used in PPC, overlaying maps between the defined watershed units, which can be found in **section 4.3.2**, are performed based on the district level and the administrative boundary of PPC. The results are shown in **Fig.4.4** of **Chapter 4**.

5.1.3 Definition of "zoning area" and "outside of zoning area" in each watershed

Based on the overlaying maps between the defined watershed units and master plan in 2020 as shown in **Fig.5.2**, obviously administrative boundary of PPC is found not overlapped with the master plan in 2020. Under these circumstances, it can be comprehended that the development plan until 2020 is not completely widespread the whole PPC. In this context, the common area is picked and called "Zoning area". Generally, land use planning is mainly discussed on zoning area; however, from the viewpoint of this research, it's essential to consider not only the zoning area but also another area as part of the watershed. So, the other area besides zoning area as part of the watershed is defined as "Outside of zoning area" in this context.

Therefore, as shown in **Fig.5.1**, in certain watersheds including 1, 3, 5, 7, 12, 13, 14, and 15 composed of zoning area and outside of zoning area are employed for the discussion hereafters.

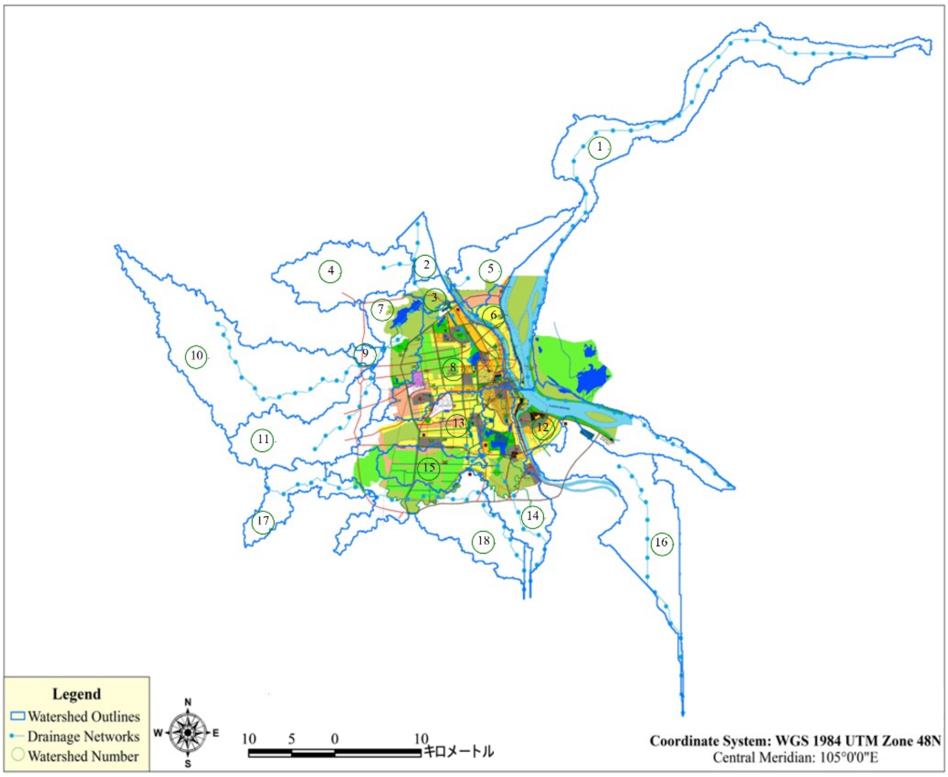


Fig.5.1 Overlaying maps of watershed outlines, master plan in 2020, and drainage networks.

5.1.4 Detection of land use in 2005, 2015, and master plan in 2020

The same method applied in **section 4.4.2** of **Chapter 4** is utilized for the detection of land use both in 2005 and 2015 as shown in **Fig.5.2**.

Since obtained master plan in 2020 is in the form of JPEG image, it's essential that two additional steps are made with the aid of ArcGIS 10.2 platform to determine land use type for comparing the land use within these 3-time frames as shown in **Fig.5.3**.

- "Georeferencing toolbar" in ArcMap is used to georeference JPEG image of master plan in 2020.
- Based on the first level of land use classification system for remote sensor data, land use types from master plan in 2020 are created. Manually tracing of land use following 5 types of land use including urban, agricultural land, forest land, water, and wetland is performed afterwards.

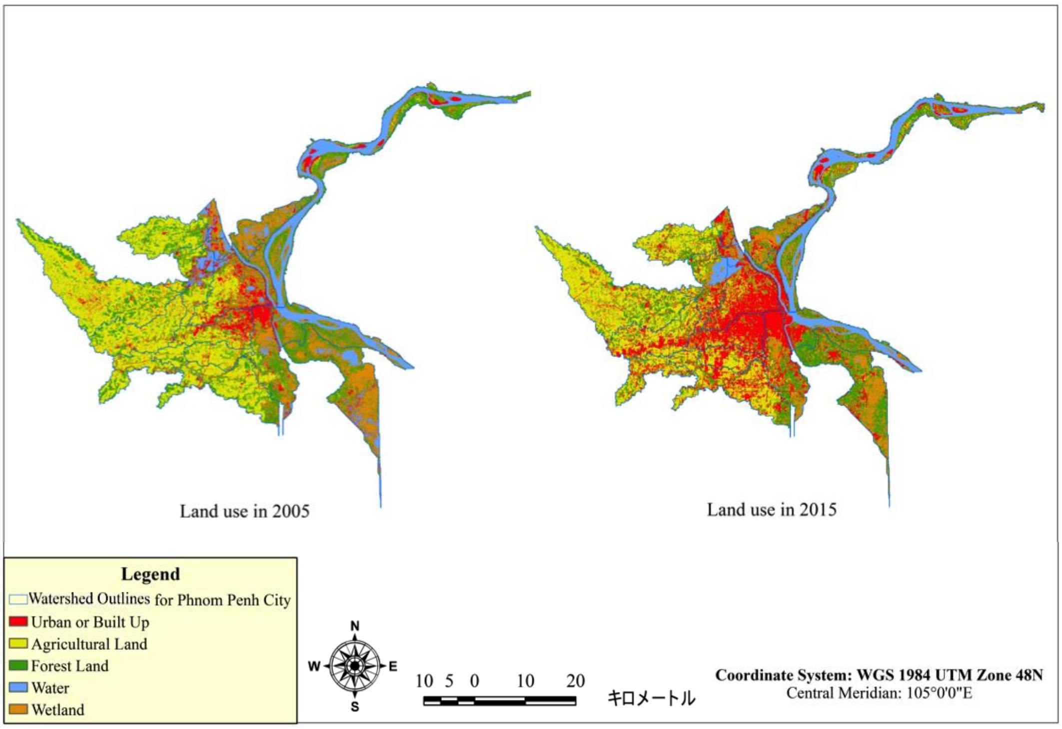


Fig. 5.2 Land use detection in 2005 and 2015.

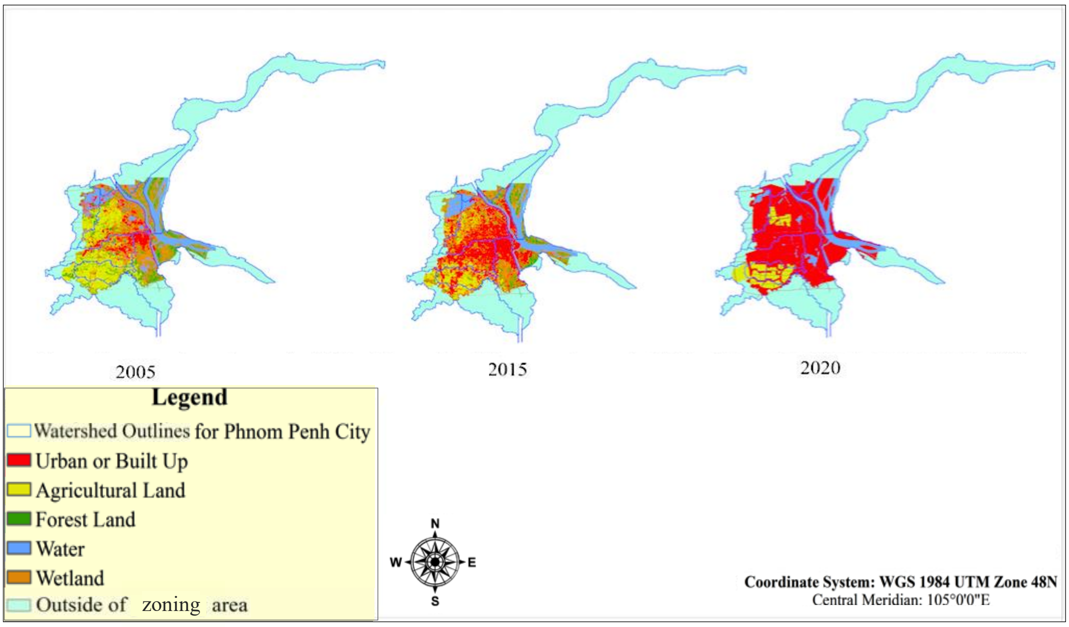


Fig.5.3 Land use in 2005, 2015, and master plan in 2020 in each watershed.

5.1.5 Computation of land use in 2005, 2015, and 2020 based on zoning area as part of watershed

As aforementioned in **section 5.1.3**, the area of land use in 2005, 2015, and 2020 located on certain watersheds including 1, 3, 5, 7, 12, 13, 14, and 15 are used for identifying the trends of land use changes in the zoning area. Computation of land use area within 3 periods is conducted by using ArcGIS 10.2 with the aid of transition matrix obtained from Tabulate Area in ArcMap. The results indicated that urban land use of zoning area in each watershed constantly increased among three periods as expressed in **Fig.5.4**. This result implies that the zoning area is urbanized.

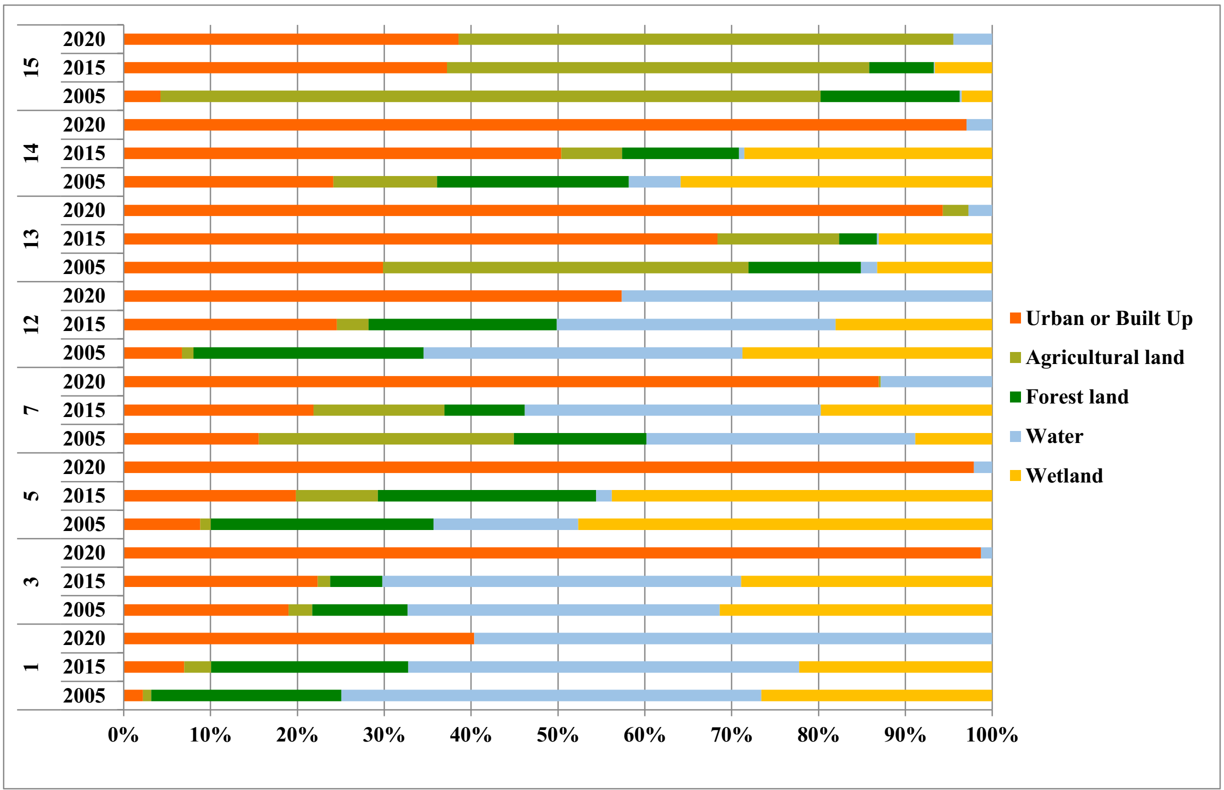


Fig.5.4 Results of land use transformation in 2005, 2015, and 2020 based on zoning area in each watershed.

5.2 Interaction of zoning area and outside of zoning area in each watershed

From the view point of watershed-based planning, the interaction between upstream and downstream is very important and critical issue to discuss in planning perspectives, particularly planning for flooding mitigation in developing countries. Parallel to this view point, the influence of the development area is discussed focusing on the zoning area and outside of zoning area as part of the watershed.

Both zoning area and outside of zoning area as part of each watershed in 2005 and 2015 are analyzed and computed for the change ratios of land use in the purpose of comparing the development taken place within these two periods (2005 and 2015) among these two areas.

Change ratios of urban land use are considered as the most negative effects that contribute to the social and environmental issues in the urbanized area. Particularly, urban flooding can occur as the result of increasing impervious covers in the urbanized area and consequently intensifying the flow velocity of runoff. In this sense, the change ratios in terms of urban land use are compared in both zoning and outside of zoning areas of land use in 2005 and 2015 as part of each individual watershed.

Basically, more attention should be paid, particularly to the outside of zoning area having a high tendency of change ratio compared to the zoning area in each individual watershed. Change ratio of urban land use in outside of zoning area located in upstream is greater than zoning area located in downstream of one watershed, this indicates that zoning area in downstream might be suffered large influence from water flow. So, the development has to pay more attention to the influence of upstream area. Whereas change ratio of urban land use in outside of zoning area located in downstream is greater than zoning area located in upstream of one watershed, the development should be considered of its influence to the downstream area.

Change ratios of urban land use between 2005 and 2015 in watersheds 1, 3, 5, 7, 12, 13, 14, and 15 are computed simply with the aid of transition matrix obtained from ArcMap. The results can be shown in **Table 5.2** and **Fig.5.5**. Examples of development area located at upstream and downstream are demonstrated and as shown in **Fig.5.6** and **Fig.5.7**, respectively.

4 outside of zoning areas having higher change ratios of urban land use from 2005 to 2015 compared to the zoning areas are defined. These areas occurred in watersheds 1, 3, 5, and 7. 3 of 4 outside of zoning areas are located in upstream while 1 of 4 is in downstream of its watersheds. This indicates that high attention should be paid when the development is taken place in these watersheds.

Table 5.2 Change ratios of urban land use in zoning area and outside of zoning area from 2005 to 2015 in each watershed.

Outside of zoning areas area are located *: in upstream /**: in downstream

Watershed	Change Ratio of zoning area from 2005 to 2015 (%)	Change Ratio of outside of zoning area from 2005 to 2015 (%)
1	0.42 to 1.32	**6.57 to 8.92***
3	9.53 to 11.23	**7.55 to 15.53****
5	1.25 to 2.81	**4.78 to 12.82***
7	8.19 to 11.53	**3.75 to 10.49***
12	3.85 to 12.40	1.25 to 2.80**
13	26.08 to 59.71	1.26 to 5.85*
14	14.01 to 29.24	3.52 to 8.29**
15	4.21 to 37.09	0.00 to 0.02*

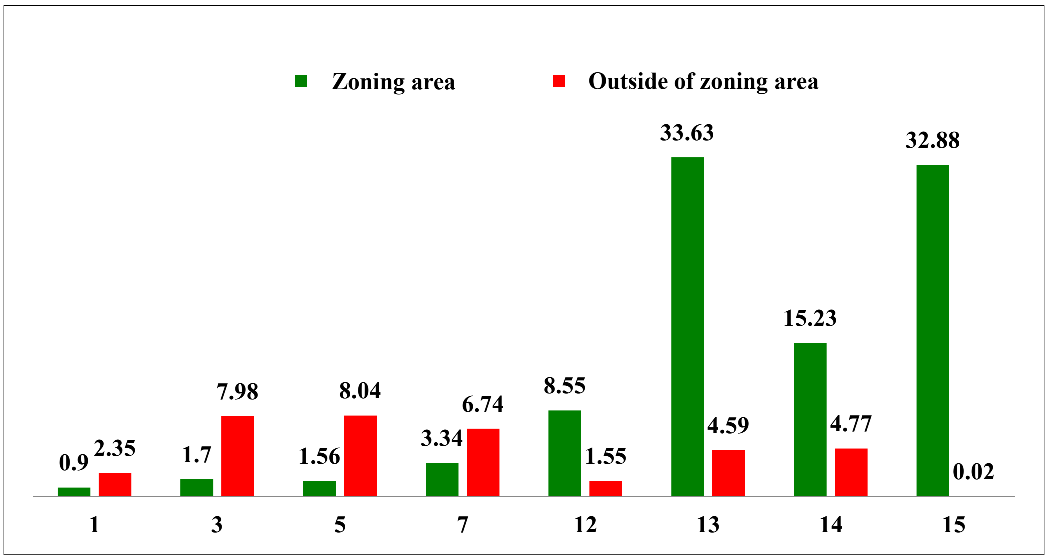


Fig.5.5 Difference of urban land use change ratios from 2005-2015 in each watershed.

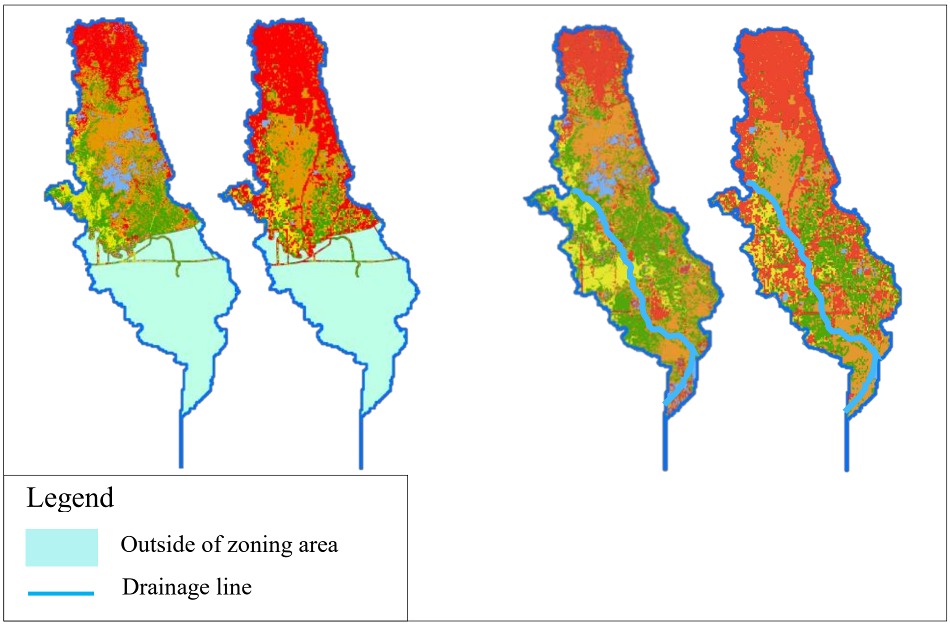


Fig.5.6 Zoning area and outside of zoning area in watershed 14

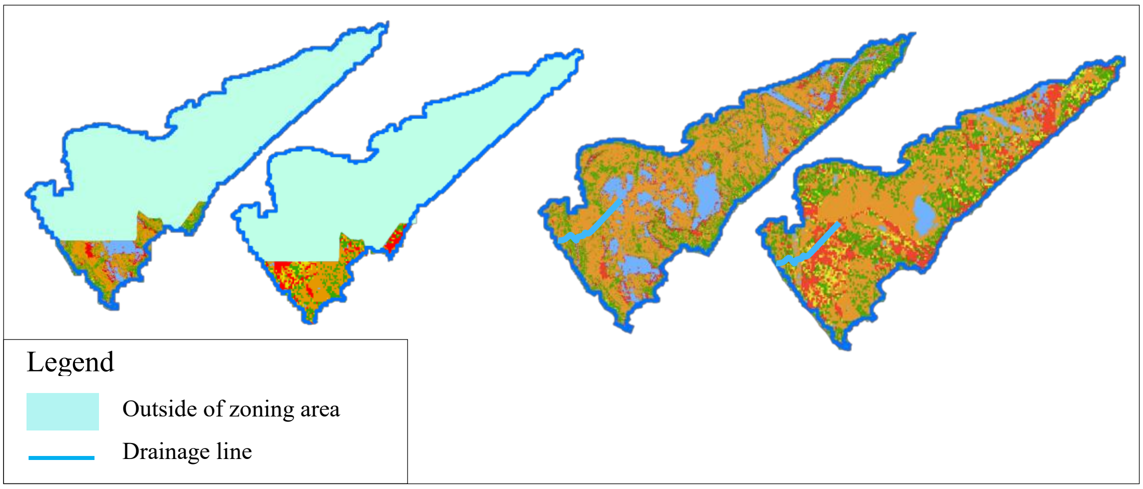


Fig.5.7 Zoning area and outside of zoning area in watershed 5

5.3 Conclusions of chapter

On the basis of the findings in this chapter, two conclusions can be made.

Firstly, this chapter showed the transformation of land use in Phnom Penh City in 2005, 2015, and 2020 based on the zoning area in each watershed. The results demonstrated that all urban land use of zoning area in each watershed is increasing and the master plan also intending to accelerate the trends. In this respect, it can be concluded that zoning area is urbanized.

Secondly, the interaction of zoning area and outside of zoning area as part of the watershed was analyzed. One can confirm that the interaction between zoning area and outside of zoning area in each watershed should be considered whenever the development is taken place.

Therefore, from the viewpoint of watershed-based planning for flooding mitigation in urbanized city like Phnom Penh, controlling land use change in upstream and downstream of the watershed is necessary to be implemented at macro scale. However, to adapt to the current development trends and to achieve for future sustainable development, the method proposed in this chapter is not sufficient. Complement concepts are introduced in the next chapters. By zooming into the critical development area as defined in this chapter, identifying zoning indicator, the source of runoff, at the middle scale is employed in **Chapter 6**. Design measures at micro scale including infiltration, vegetation, and retention/detention are applied in zoning indicators and adopted in **Chapter 7**.

References:

1. Lim, L. and Sasaki, Y.: Transformation of Land Use Pattern in Phnom Penh City at a Watershed Scale, *Civil Engineering Conference in the ASIAN Region CECAR 7*, 2016.
2. CGIAR CSI, *SRTM 90m digital elevation model database v4.1*, viewed 11 September 2015, from http:// srtm.csi.cgiar.org.
3. USGS Global visualization viewer, *Landsat data*, viewed 10 November 2015, from http:// glovis.usgs.gov.
4. Open development Cambodia, *Base map*, viewed 6 July 2014, from http://www.opendevelopmentcambodia.net/.
5. Personal communication, *Water way of Phnom Penh City and Urban Development*, interviewed May 2015.

CHAPTER 6
Concept of watershed-based land use planning for PPC at middle scale

6.0 Summary of chapter

Thanks to the rapid development of the technology, in this research, land use data is created using remote sensing image called Landsat data and GIS as explained in **Chapter 4**. Unlike other developed countries like United State of America using open source of the NRCS Soil Survey Geographic (SSURGO) soil databases to extract both saturated hydraulic conductivity (Ks) and depth to restrictive layer (D), this research creates the soil databases based on closed source of sub soil data, which is obtained from the existing research and permission from the owner of the source, with some assumptions illustrated in **Chapter 6**. Meanwhile, the creation of impervious and pervious covers under the poor condition of the public database in PPC is also demonstrated.

In this chapter, Hydrological Sensitive Areas (HSAs) is introduced for watershed-based land use planning for PPC. The idea of HSAs and its importance are explained. Computation of HSAs is illustrated including formulation of Topographical Index, Wetness Index, and Soil Water Storage with the creation of soil databases, impervious and pervious covers with the aid of ArcGIS 10.2 platform. A case study at middle scale planning is conducted to discuss about the trends of land use planning occurred in HSAs based on a master plan in 2020.

6.1 The idea of Hydrological Sensitive Areas (HSAs) and its importance

An area where can be defined as Hydrological Sensitive Area (HSA) is based on its tendency to generate runoff, which is prone to be saturated area during a rainfall event[1)]. **Fig.6.1** shows the schematic of the area considered as saturated areas. As shown in the **Fig.6.1**, saturation tends to occur in the areas where soil above restrictive layers are shallow as noted 1 or decreasing of down-hill topographic slope as noted 2 or area of topographical converging as noted 3[1)]. The probability of runoff or overland flow in particular location of the watershed which will be generated is also characterized as HSA[2)]. It is defined as the area in landscape actively contribute to runoff generation[3)].

In terms of urban development, the concept of HSAs is used for protecting watershed health. To maintain watershed health and landscape integrity from urban development, HSAs should be treated and protected as other sensitive environment resources such as riparian area or wetland within the watershed[3].

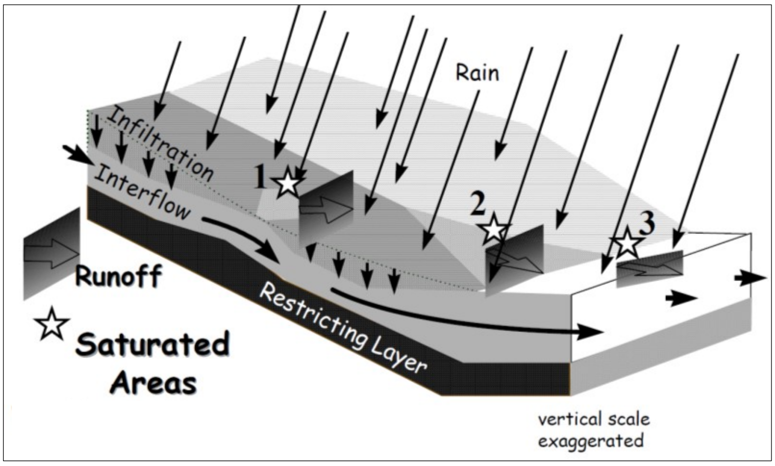


Fig.6.1 Schematic of the area considered as saturated area[1].

HSA concept is not only applied for implicating water quality risk assessment[1], but also used for the matter of solving land use issues like identifying site prioritization for Low Impact Development[4), 6)], identifying site potential for placement of the conservation buffer and riparian restoration in watershed[5), 6)], and evaluating of how effective of existing land use controls in protecting HSAs[3].

Generally, Hydrological Sensitive Areas (HSAs) are areas where Topographical Index (TI) is equal or greater than a given threshold value[5].

From HSA's idea and its importance, one can confirm that by knowing the areas of HSAs, controlling the development of one area can be conducted. This implies that development taken place in the area defined as HSAs allows planners to take into consideration of the development or planning that not exacerbates the runoff process. In this respect, instead of proposing planning full of building lots causing the increase of impervious surface, planning with open space or garden or greenery can be pondered in this area.

6.2 Computation of Hydrological Sensitive Areas (HSAs)

6.2.1 Definition and formula of Topographical Index (TI)

As a basis for rainfall-runoff model, Topographical Index (TI) is used for simulating the surface runoff contributing area's pattern based on the Variable Source Area (VSA) hydrology, in which the capacity of soil saturation is exceeded, and the generation of runoff is dominated by both expansion and contraction of the development in this saturated areas[7].

The tendency of a given point in a watershed, which is likely to become saturated area and served as source areas for surface runoff, is measured by TI [5, 4]. Topographically, this index was primarily known as Wetness Index, in which the distribution of soil moisture in the landscape is predicted. Basically, this index depends on the runoff contributing areas called flow accumulation and slope, which can be derived from Digital Elevation Model (DEM) performing in GIS. As a proven good indicator, it can be used for delineating area exposed to flood inundation[8]. However, in this research, from the viewpoint of watershed planning applied to the land use planning in the urban area, the heterogeneous with various soil types, land cover as well as land use, and slopes are essentially taken into consideration. In this respect, not only the index obtained based on topographically is required, but also soil water storage accounting for the soil hydraulic conductivity (Ks) and the restrictive layer of soil depth (D) proposed by existing researches is needed to be adapted[4, 5].

The combination of two terms: Wetness Index and Soil Water Storage are hereafters referred as the Topographical Index and defined as follows

$$\lambda = \ln\left(\frac{\alpha}{\tan\beta}\right) - \ln(K_s D_{ISA}) \quad (1)$$

where $\ln\left(\frac{\alpha}{\tan\beta}\right)$ is wetness index; $\ln(K_s D_{ISA})$ is soil water storage

$$\begin{cases} \ln\left(\frac{\alpha}{\tan\beta}\right) \begin{cases} \alpha \text{ is runoff contributing areas per contour length in m} \\ \beta \text{ is a slope in radian} \end{cases} & (2) \\ K_s = \frac{d}{\sum_1^n (d_i/k_i)} \begin{cases} d \text{ is total thickness of the soil above the restrictive layer} \\ d_i \text{ is the thickness of layer i} \\ k_i \text{ is the saturated hydraulic conductivity of layer i} \end{cases} & (3) \\ D_{ISA} = D - (D \text{ x } ISA);\ ISA: \text{proportion of pixel } (0-1) \text{ covered by impervious surface} & (4) \end{cases}$$

6.2.2 Wetness Index

Normally, the higher the value of this index, the more likely the saturation of the grid occurred in the storm events. In practices, one watershed is composed of many small grids, while this index is measured at each grid. Whereas this index is often derived from a DEM performing in GIS[5)].

a) Data source and processing

Fundamentally, calculation of Wetness Index is based on two essential factors including flow accumulation derived from the watershed analysis and slope obtained from a spatial analyst of DEM using ArcGIS 10.2 platform. However, conversion of cell size or spatial resolution of DEM is importance to be carried out before performing the calculation of Wetness Index[9)]. In this context, conversion of these data based on the DEM is conducted by using ArcGIS 10.2 platform as shown in **Table 6.1**.

Table 6.1 Conversion of DEM data in ArcGIS 10.2 platform.

Data source	DEM as parameter	ArcGIS 10.2 platform
Flow accumulation (m)	α= (flow accumulation +1)* cell size, cell size=90,	Raster calculator
Slope (radian)	(β*1.57076)/cell size, cell size=90	(1) Spatial Analyst – Surface-Contour in degree-(2) Raster calculator

b) Result of Wetness Index

By applying the formula in Eq. (2), wetness index is calculated using raster calculator in ArcGIS 10.2 platform. Wetness index is illustrated based on watershed defined in macro scale as shown in **Fig.6.2**. In addition to this figure, an area with no wetness index are lakes. All higher wetness indexes are overlapped with the drainage networks identified from the watershed analysis.

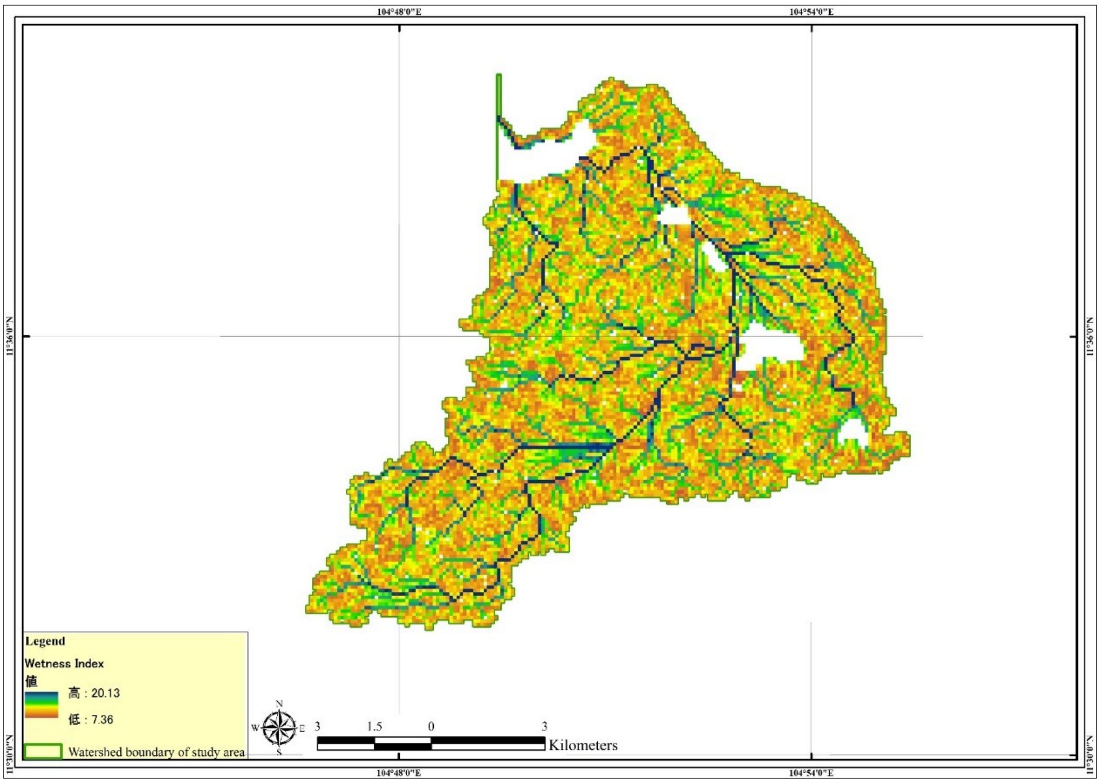


Fig.6.2 Wetness Index based on one watershed of PPC at macro scale.

6.2.3 Soil Water Storage

a) Assumptions for creation of soil databases

Two components including saturated hydraulic conductivity (Ks) of the soil profile and depth to restrictive layer (D) are two factors used for identifying the Soil Water Storage.

Saturated hydraulic conductivity (Ks) refers to the soil's ability measurement to transmit water when submitting to the hydraulic gradient[10)]. While depth to restrictive layer (D) is defined as the layer which water cannot surpass, usually is referred to the bedrock layer[10)]. Generally, the deeper the depth to restrictive layer, the higher the saturated hydraulic conductivity, but the lower the value of Topographical Index[4)] as stated in Eq. (1). In practices, several layers of soil depth with different saturated hydraulic conductivities are above the restrictive layer. In this respect, mean saturated hydraulic conductivity is determined by Eq. (3)[4)].

Unlike most of the existing researches in United State of America using open source of the NRCS Soil Survey Geographic (SSURGO) soil databases to extract both Ks and D, this research creates the soil databases based on closed source data of bore log, as shown in **Fig.6.3**, which are used for foundation design in construction field.

In terms of making these soil databases, the ideal method cannot be realized since the depth of most of the bore log data are tested below 50 m that made the bedrock cannot be figured out; some soil texture classes cannot be identified in the list of the saturated hydraulic conductivities' indicative values. However, some assumptions made in this research are based on the reliable source, methods, and logical way, in which the tolerance of output results can be accepted for conducting further research with the limitation of sufficient databases like PPC. Some assumptions are made as follows:

- Being known as having the smallest saturated hydraulic conductivity among the soil texture classes, clay layer is assumed as a restrictive layer.
- Saturated hydraulic conductivity of all soil texture classes is defined based on the indicative values of saturated hydraulic conductivity for various soil texture class[11)], as **Table 6.2**.
- Soil texture class in certain layers of sub-soil data is not defined in **Table 6.2**, this sub-soil texture type is identified as one of the main soil texture class (sand, clay, loam, or silt) it belongs to.
- Soil texture class in certain layer contained two of the main soil texture classes, the saturated hydraulic conductivity for this soil texture's type is assumed as equal importance. With this respect, the saturated hydraulic conductivity of this soil texture class is equal to 50% of both soil texture classes' saturated hydraulic conductivities.
- In the case of bore log data doesn't exist the clay layer, it's essential that the restrictive layer is assumed as the total depth of all layers at this point.

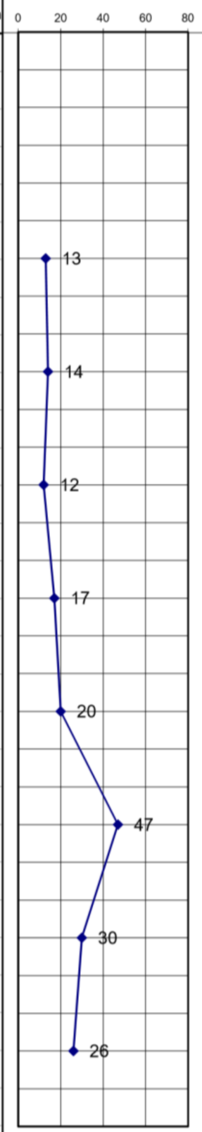
RESEARCH & DESIGN ENTERPRISE

SOIL TESTING LABORATORY

BORING LOG

PROJECT NAME: Villa Project.	**Borehole N°** 3
PROJECT SITE : Located at Lot No 33-35, Street No 122, Sangkat Veal Vong, Khan 7 Makara, Phnom Penh.	Date Started: 24/09/2009
Elevation of borehole: m — EQUIPMENT : ROTARY AUGER METHOD	Date finished: 24/09/2009

Depth (m)	Samples (No)	Sample Type	DESCRIPTION OF STRATA	Depth & Thick. (m.)	Pocket Test (kPa)	Vane Test (kPa)	Depth testing (m.)	N_0	N_1	N_2	SPT N- value (Blows / 300mm)	Recovery ratio (mm.)
0–2	-	-	Made ground	(2.00) / 2.00								
3	1	D	Yellow medium stiff Lean CLAY with sand		115		3.00 to 3.45	5	6	7	13	
4.5	2	D		(5.10)	75		4.50 to 4.95	4	6	8	14	
6	3	D		7.10			6.00 to 6.45	4	5	7	12	
7.5	4	D	Yellow medium dense SAND				7.50 to 7.95	6	8	9	17	
9	5	D		(3.20) / 10.30			9.00 to 9.45	8	10	10	20	
10.5	6	D	Yellow dense Clayey SAND				10.5 to 10.95	17	22	25	47	
12	7	D		(2.70) / 13.00			12.0 to 12.45	14	15	15	30	
13.5	8	D	Yellow very stiff Sandy Lean CLAY	(2.00) / 15.0			13.5 to 13.95	10	12	14	26	



LEGEND: D - Disturbed Sample	Water Strike: 6.00m	Sheet 1
U - Undisturbed Sample	Water level: 2.00m	**FIGURE 5**

Fig.6.3 Bore log data in PPC.

Table 6.2 Indicative values of saturated hydraulic conductivity for various soil texture class[6].

Soil texture class	Ksat (mm/hr)	Ksat Class
Coarse sand	360	Very rapid
Sand	208	Rapid
Loamy sand	61	Rapid
Loam fine sandy	36	Moderately rapid
Sandy loam	26	Moderately rapid
Fine sandy loam	19	Moderately rapid
Loam	13	Moderate
Silt loam	7	Moderate
Silt	7	Moderate
Sandy clay loam	4	Moderate slow
Clay loam	2	Moderate slow
Silty clay loam	1.5	Moderate slow
Sandy clay	1.2	Slow
Silty clay	0.9	Slow
Clay	0.6	Very slow

b) Data preparation and processing for Ks and D

The raw data of sub soil data called bore logs data, which are used in the existing research[12] and permission from the right holder of these data, is used for defining the mean saturated hydraulic conductivity and depth to restrictive layer in this chapter.

Originally, these bore logs data are composed of Excel files (English and Khmer), AutoCAD files, and JPEG images showing the location of boreholes.

Some necessary procedures are performed as follows:

- All the documents in Khmer are properly translated into English by using the existing original Khmer files as the references.
- Locations of available sub-soil data are measured based on the information of the given road number and distance measured in AutoCAD files. These available locations are created in Google Earth as KMZ extension and exported into ArcGIS 10.2 platform. As the results, a total of 378 points are defined, as **Fig.6.4**, and mostly these points are in the center area of PPC.

➢ Since the location of all available points is under the scope of the study area, in this respect, assumptions are made, particularly the points nearby the boundary of the study area. One of the watersheds defined at macro scale is set as the boundary. Due to the distance of the assumption points are approaching to the available points so that influence rate of these assumptions points can be ignored.

➢ Numerical calculations of mean saturated hydraulic conductivity and the depth to restrictive layer are performed, as shown in **Table 6.3**. Manipulation of both Ks and D with the aid of ArcGIS 10.2 platform is carried out afterwards.

➢ Surface interpolation known as Kriging method commonly used in soil science and geology[13)] is introduced in this research. Interpolation of the mean saturated hydraulic conductivity of soil profile (Ks) and the depth to restrictive layer (D) are conducted and as shown in **Fig.6.5** and **Fig.6.6**, respectively.

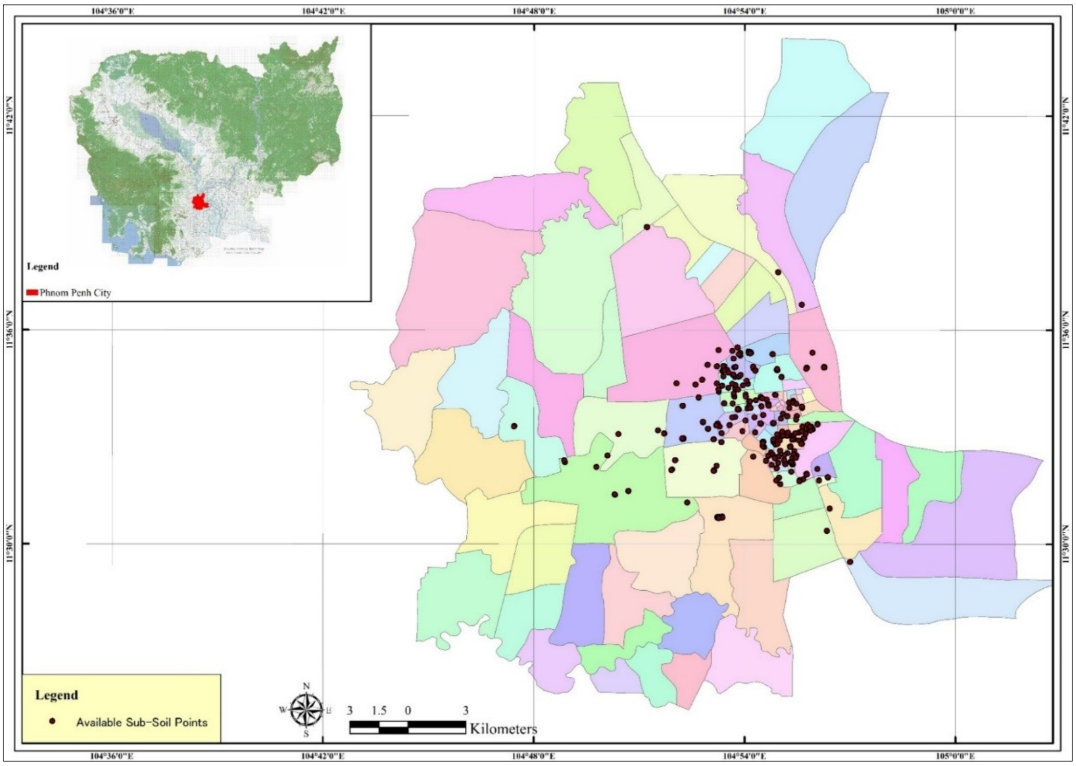


Fig.6.4 Available sub soil points.

Table 6.3 Calculation of mean saturated hydraulic conductivity (Ks) and depth to restrictive layer (D).

FID	Soil profiles	D (m)	Thickness of layer i(di)	Ki (m/day)	Ks for each layer (m/day)	Mean Ks (m/day)
0	Made ground	1.20	1.20	8.64000	0.13889	8.64000
	Very stiff lean clay		0.80	0.01440	55.55556	
1	Made ground	1.30	1.30	8.64000	0.15046	8.64000
	Very stiff fat clay		0.70	0.01440	48.61111	
2	Made ground	2.00	2.00	8.64000	0.23148	8.64000
	Red stiff lean clay		7.80	0.01440	541.66667	
3	Made ground	1.80	1.80	8.64000	0.20833	8.64000
	Brown very stiff lean clay		4.90	0.01440	340.27778	
4	Made ground	2.20	2.20	8.64000	0.25463	8.64000
	Brown soft lean clay		1.80	0.01440	125.00000	
5	Made ground	1.40	1.40	8.64000	0.16204	8.64000
	Yellow stiff lean clay		1.20	0.01440	83.33333	
6	Made ground	1.40	1.40	8.64000	0.16204	8.64000
	Red medium stiff sandy clay		1.10	0.01440	76.38889	
7	Made ground	4.30	2.20	8.64000	0.25463	3.93213
	Brown medium stiff lean clay with sand		2.10	2.50320	0.83893	
	Brown very stiff sandy lean clay		1.20	0.02880	41.66667	
8	Made ground	2.30	2.30	8.64000	0.26620	8.64000
	Medium stiff lean clay		0.70	0.01440	48.61111	
9	Made ground	2.60	2.60	8.64000	0.30093	8.64000
	Yellow medium stiff lean clay		1.60	0.01440	111.11111	
10	Brown medium stiff lean clay	0.00	3.00	0.01440	208.33333	0.00000

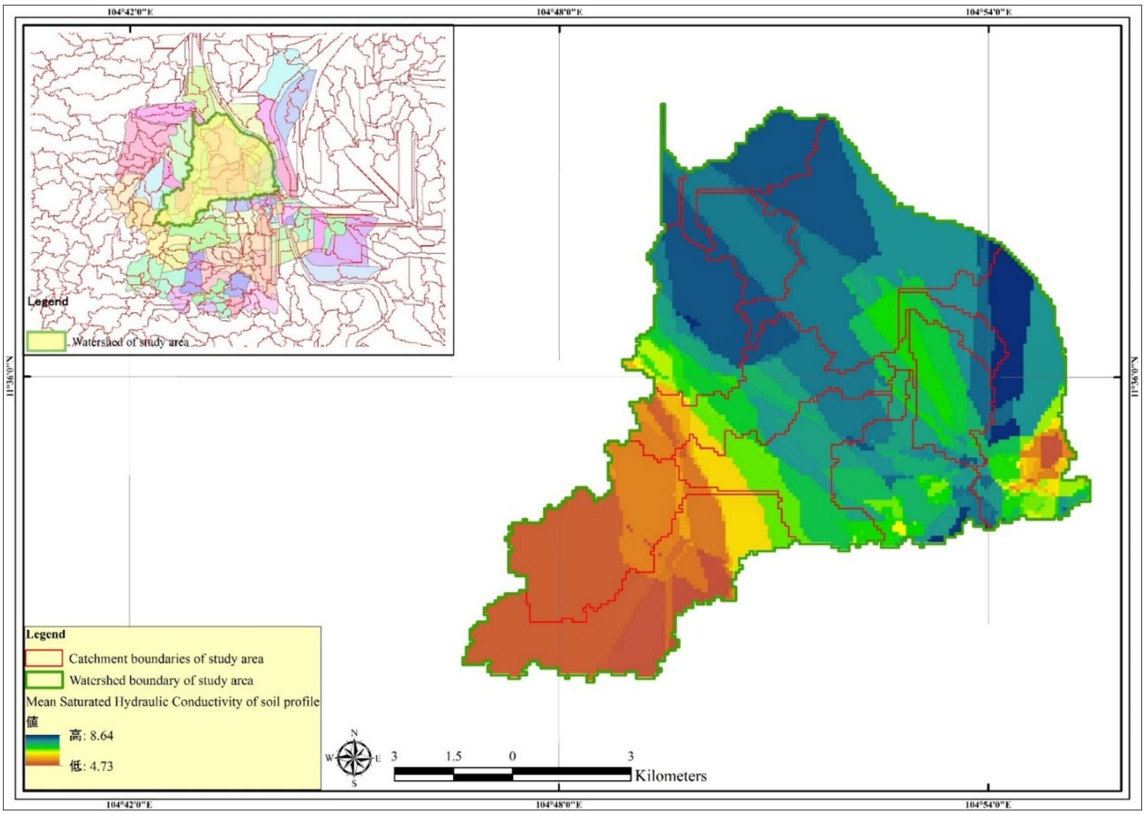


Fig.6.5 Mean saturated hydraulic conductivity of soil profile (Ks).

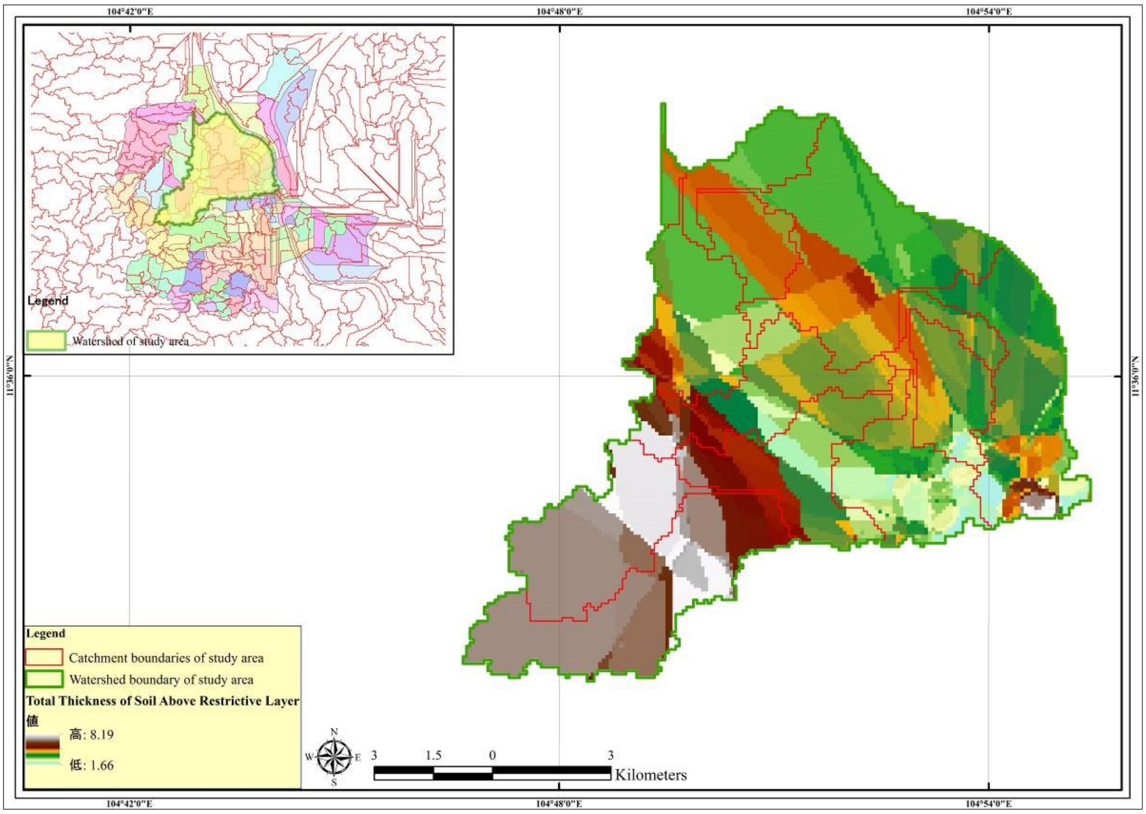


Fig.6.6 Total thickness of soil above restrictive layer (D).

c) Impervious and pervious covers

In this section, due to the lack of data in PPC, the creation of impervious and pervious cover is conducted manually. On the basis of land use detection with five types of land use, the creation of both covers is manipulated taking into consideration of land use types including agricultural land, forest, water, and wetland as pervious cover. Whereas urban or built-up land use type is sub-divided into pervious and impervious covers.

➢ **Creation of impervious and pervious cover ratios**

- **Data source**

  Redetection of land use in 2015 based on one watershed in macro scale, which is manipulated and performed in advance as expressed in **Fig.6.7** with the corresponding overall accuracy of 81% and Kappa coefficient of 68% as shown in **Table 6.4** and **Table 6.5**, is the main source for the creation of impervious and pervious cover ratios.

  Essentially, two data sources are needed to create the impervious and pervious covers.

  - Clipped Landsat data focusing only on urban land use, as shown in **Fig.6.8**, obtained after the redetection of land use limited to one watershed as shown in **Fig 6.7**, is prepared for redetection of land use according to impervious and pervious covers.

  - Population data based on a commune (hierarchy of territorial division of PPC known as Sangkat) is defined based on the open source[14)] and the report supported by Phnom Penh Capital Hall and JICA Urban Management Advisor[15)].

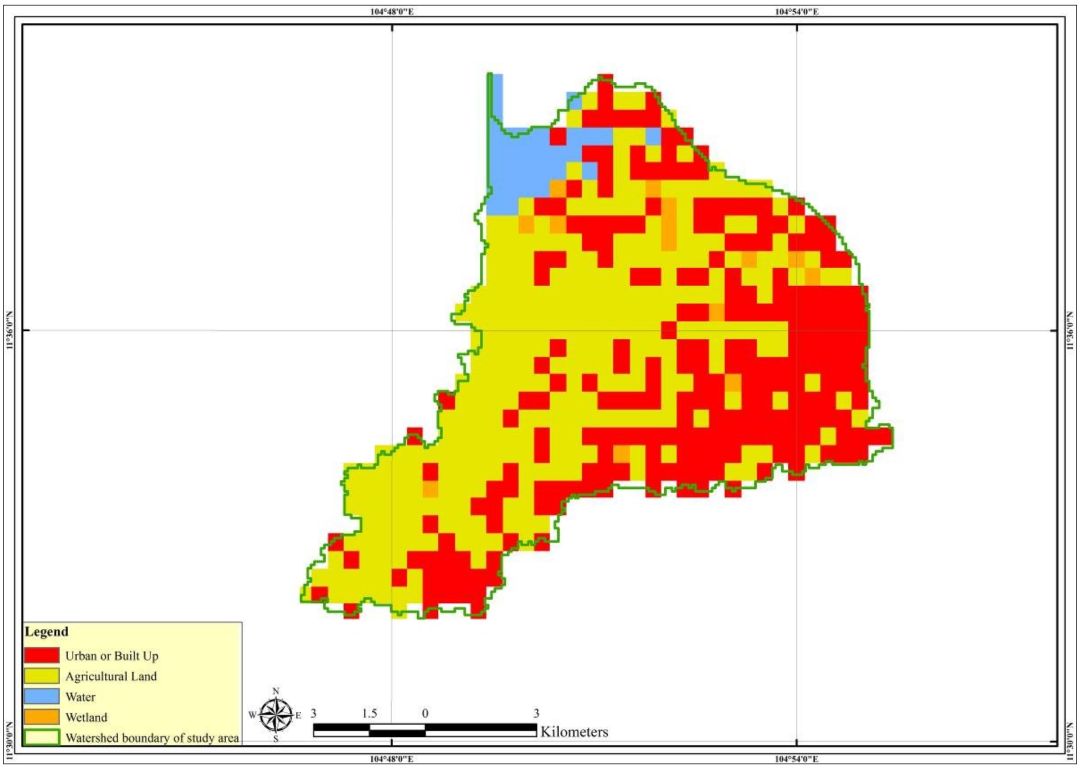


Fig.6.7 Detection of land use in one watershed at macro scale.

Table 6.4 Error matrix of land use detection in one watershed at macro scale.

	Urban	Agriculture Land	Water	Wetland
Urban	111	23	0	2
Agriculture Land	11	108	1	0
Water	2	0	16	0
Wetland	4	15	0	7
Total	128	146	17	9
Overall accuracy =81%				

Table 6.5 Error matrix of land use detection in one watershed at macro scale.

	Urban	Agriculture Land	Water	Wetland
Urban	17408	19856	2312	1224
Agriculture Land	15360	17520	2040	1080
Water	2304	2628	306	162
Wetland	3328	3796	442	234
Kappa coefficient =68%				

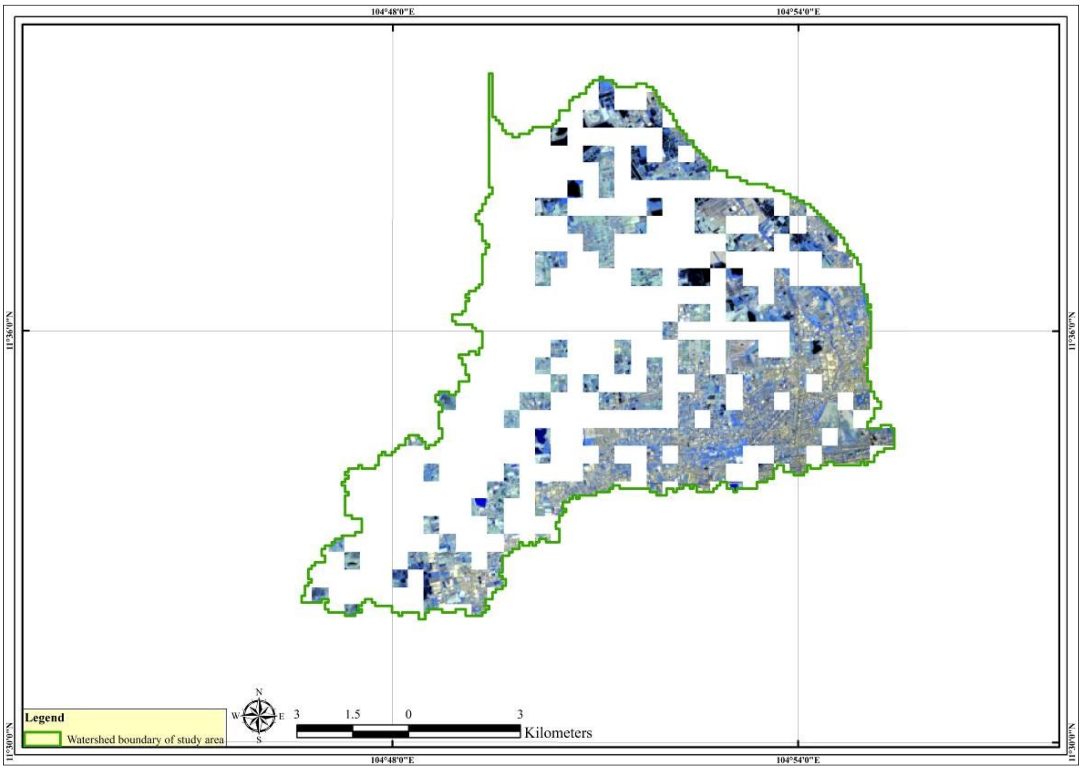


Fig.6.8 Clipped Landsat data for detection of impervious and pervious covers.

➢ **Data processing**

Basically, manually creation of impervious cover (buildings, roads, parking lots, etc.) and pervious cover (garden, trees, grass, etc.) undertakes essential steps as following:

● Redetection of urban land use (as shown in **Fig.6.8**) is carried out for defining both the impervious and pervious covers. The results are identified with the overall accuracy of 95% and Kappa coefficient of 89% as expressed in **Table 6.6** and **Fig.6.8**.

Table 6.6 Error and Product matrix of impervious and pervious cover.

		Impervious	Pervious
Error matrix	Impervious	67	2
	Pervious	7	92
	Overall accuracy=95%		
Product matrix	Impervious	5106	6486
	Pervious	7326	9306
	Kappa Coefficient =89%		

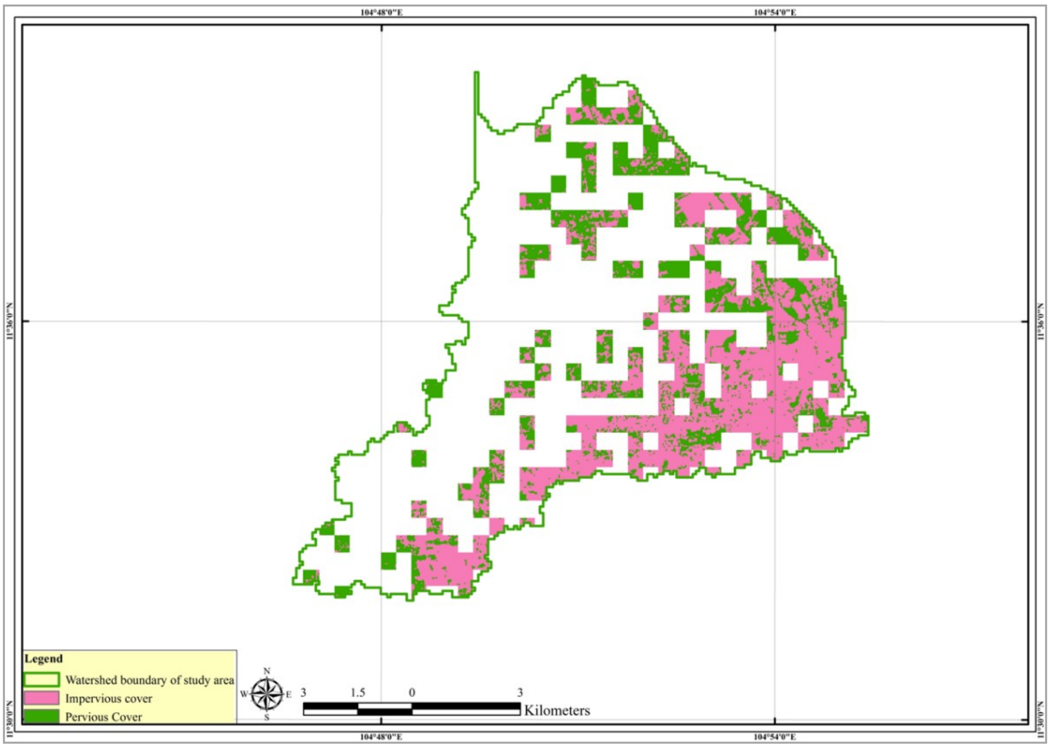


Fig.6.9 Impervious and pervious covers.

- Typical residential density[16], which is not found available in PPC, and impervious cover ratios index[17] and formula as Eq. (5)[17] are used to define impervious cover ratios for PPC with the combination of population density calculated based on the commune boundaries as shown in **Table 6.7** and **Table 6.8**, respectively.

Table 6.7 Typical residential density[16].

Land use Designation	Population Density Range (people/acre)
Low-Density Residential	11-16
Medium Density Residential	26-53
High-Density Residential	53-107
Mixed-Use	53-107

Note: Land use designation assumptions are made for missing values based on its close value of population density range of each land use designation.

Table 6.8 Impervious cover ratios index[17].

Land use	Impervious percentage range	Median
Residential low density	20-49	35
Residential medium density	50-79	65
Residential high density	80-100	90
Commercial/industrial/transportation	80-100	90

$$\text{Imperviousness} = \frac{\text{No}_{\text{low}}\times 35\% + \text{No}_{\text{medium}}\times 65\% + \text{No}_{\text{high}}\times 90\% + \text{No}_{\text{commercial/industrial/transporation}}\times 90\%}{\text{No}_{\text{watershed}}} \qquad (5)$$

- With ArcGIS 10.2 platform, polygons of both impervious and pervious are created according to **Fig.6.9**. To define the ratios of impervious covers for PPC, the intersection between the impervious polygons and population density contained each type of land use designation is overlaid. Based on the Eq. (5), impervious cover ratios are calculated and manipulated into raster data. While other land use types including agricultural land, water, and wetland known as pervious covers with the impervious cover ratios are 0% is as shown in **Fig.6.10**.

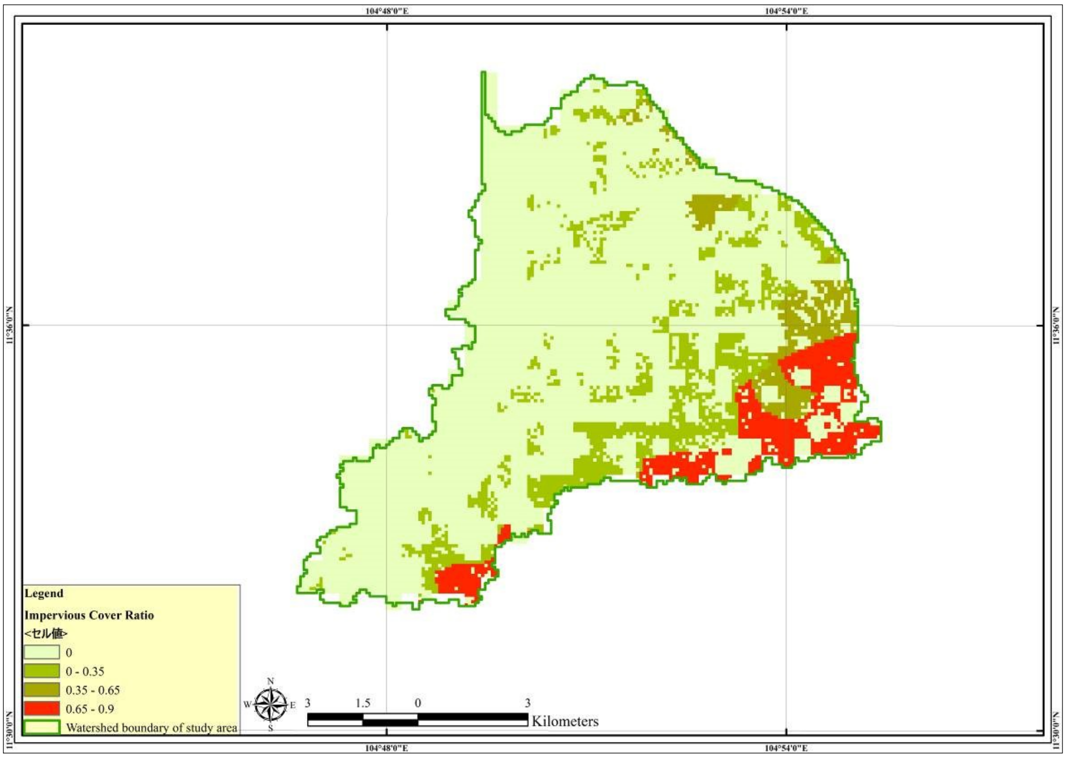


Fig.6.10 Impervious cover ratios.

6.2.4 Result of Topographical Index

Completion of **a)**, **b)** and **c)** of **section 6.2.3** enables the computation of depth to restrictive layer accounted for impervious surface area ratios based on Eq. (4) and Topographical Index based on Eq. (1) as expressed in **Fig. 6.11** and **Fig.6.12**, respectively.

In terms of considering the soil water storage, compared to wetness index concerning only topography condition, the value of TI is found decreasing with the interval of [3.82; 16.83], whereas wetness index is determined as [7.36; 20.13]. The higher value of TI implies that certain places in one's area are a source of runoff, saturation excess, which is considered as the areas able to contribute the increasing of flood risk in the urban area like PPC.

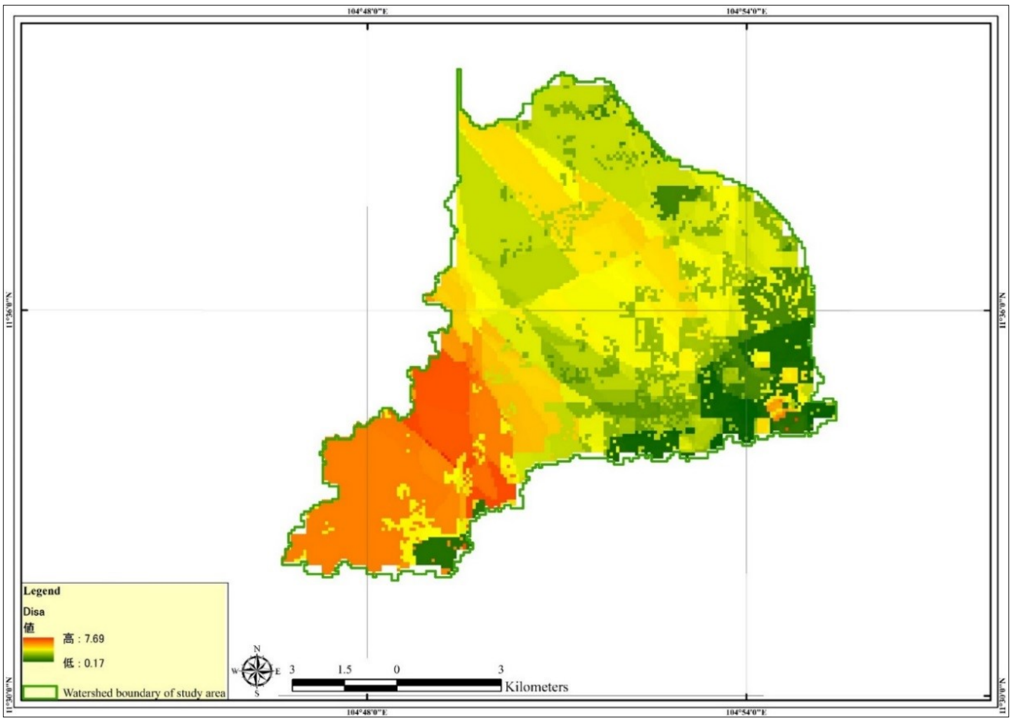


Fig.6.11 Depth to restrictive layer accounted for ISA of each grid.

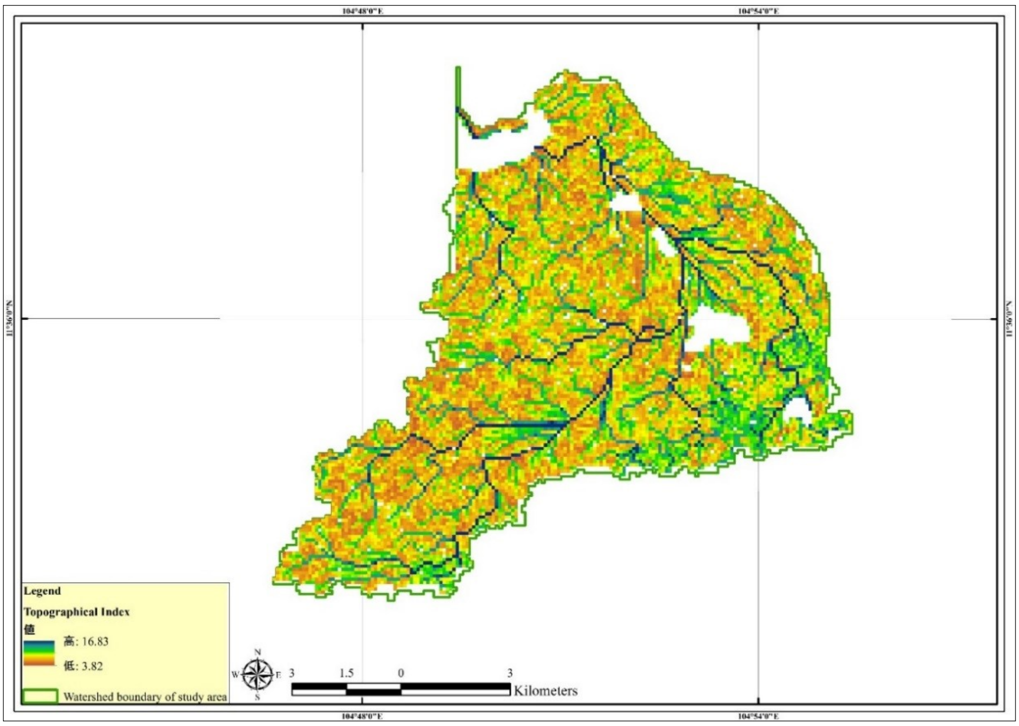


Fig.6.12 Topographical Index.

6.2.5 Result of Hydrological Sensitive Areas (HSAs)

With different threshold values, several sets of HSAs can be defined[5)]. Based on the result of flood simulation obtained from existing study[18)] as shown in **Fig.6.13**, existing threshold value from previous researches cannot reflect on the actual condition of HSAs for PPC; it's essential to define threshold value of HSAs for PPC.

In this respect, identifying matching level between the simulated result of flooding and trialing threshold values of HSAs is needed. The formula of matching level can be expressed as follows:

$$M_i(\text{Matching level}_{\%}) = \frac{S(TI_i \cap P_{ref})}{S(TI_i)} \text{x } 100 \quad (6)$$

Where $\begin{cases} S\ (Ti)\ \text{is total area of polygons obtained from each trialed threshold values} \\ S\ (P_{ref})\ \text{is total area of polygons created based on flood simulated results} \end{cases}$

With the aid of ArcGIS 10.2 platform, **Fig.6.14** shows the polygons in the common area of flood simulated results and one part of watershed at macro scale known as reference polygons. Before trialing threshold values of HSAs, a total of 13236 Topographical Index points is created based on **Fig.6.12** and calculated for its mean value and standard deviation. On the basis of existing researches, threshold values of n=3, 2, 1.9...1, 0.001,-0.1,-0.3,-1.5 of standard deviation above mean value of Topographical Index are trialed. Some results are provided in **Fig.6.15**.

Areas of each trialed threshold values of HSAs are intersected with reference polygons. Based on the Eq. (6), matching level is identified by taking account into the highest matching level among those trialed threshold values of HSAs as summarized in **Fig.6.16**.

HSAs with 1.8 standard deviation above mean value of TI (11.21) is defined as HSAs for PPC as expressed in **Fig.6.17**. The Topographical Index value equal to or greater than 11.21 are HSAs for PPC. Based on the **Fig.6.17**, light green color is not considered as a source of runoff or saturation area, it's relative safe area; red areas are classified as the critical area sensitive to the flood events from the watershed-based land use planning perspective. Any development areas full of impervious cover taken place in HSAs can accelerate the flood risk to its surrounding areas.

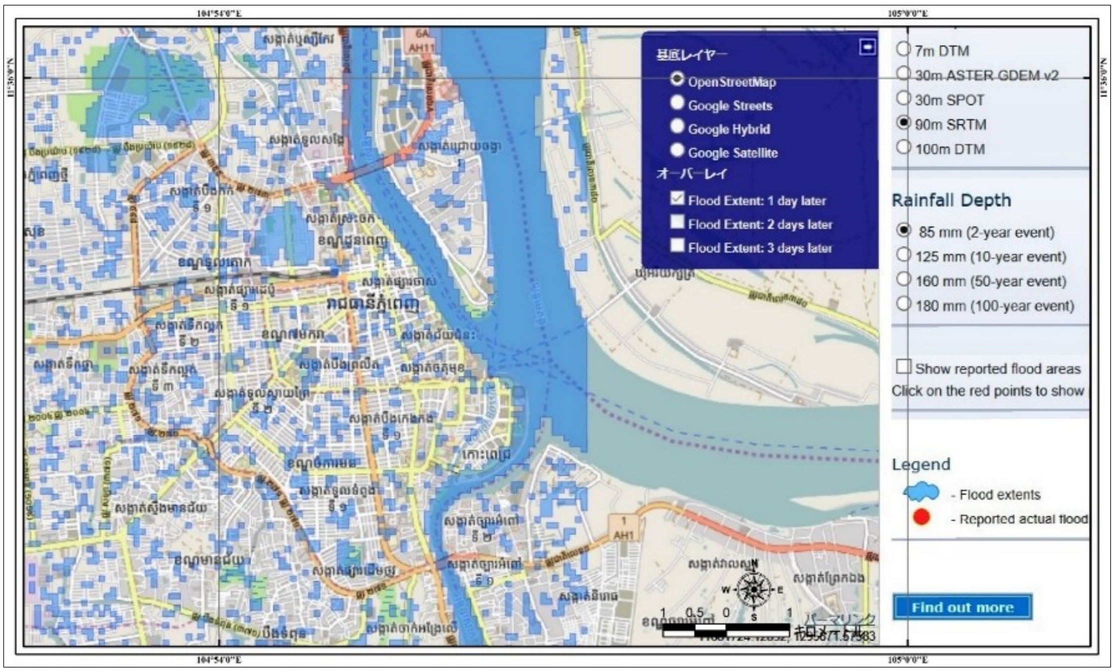


Fig.6.13 Result of flood simulation in PPC[16].

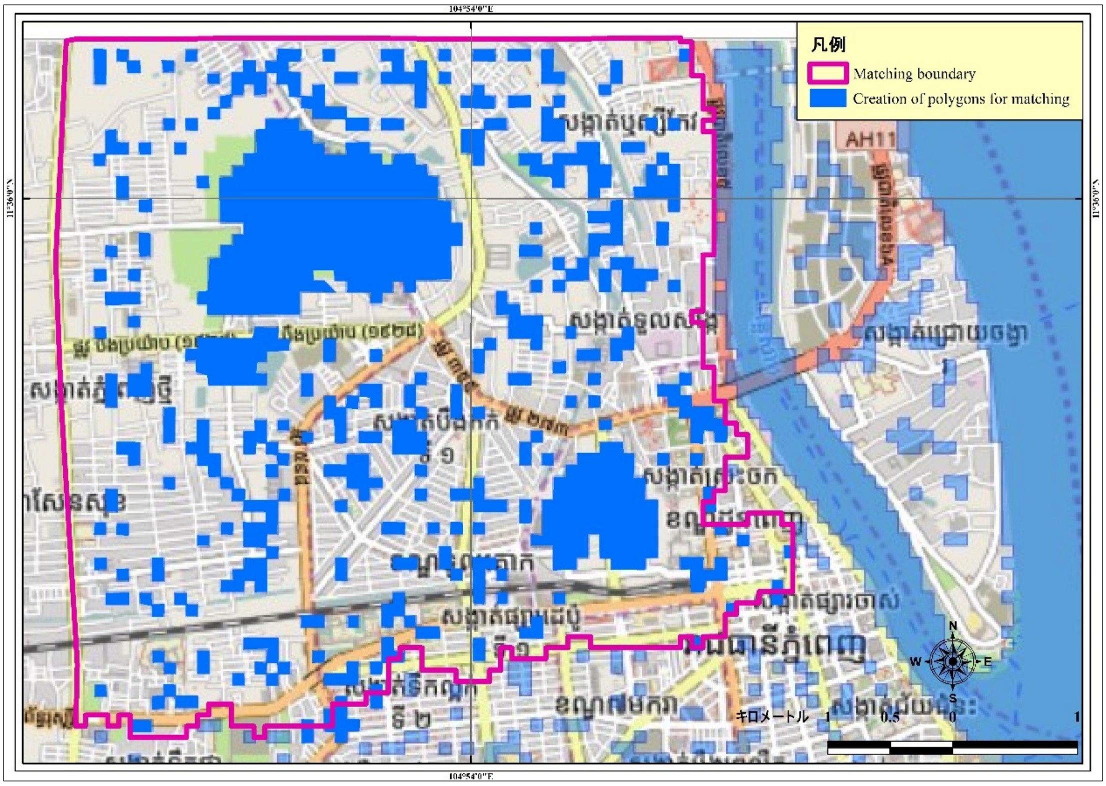


Fig.6.14 Polygon reference.

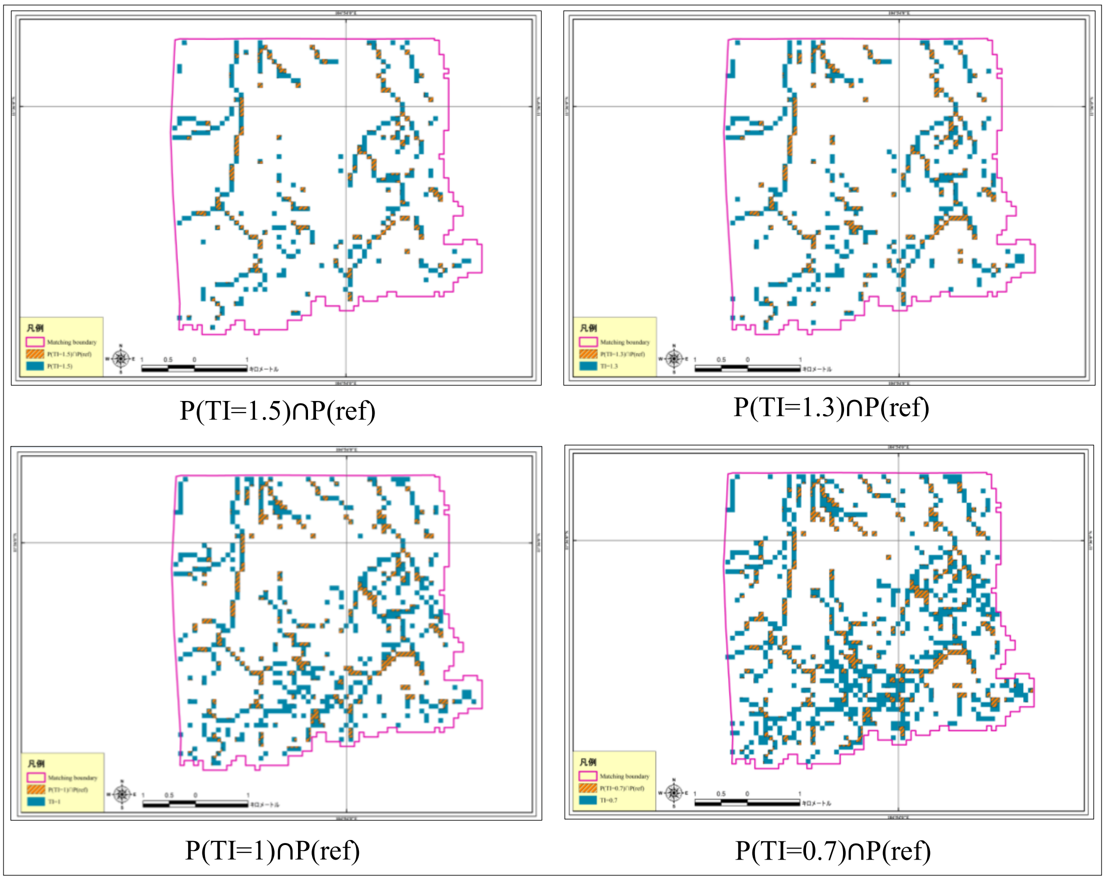


Fig.6.15 Examples of intersection between trialed threshold values of TI and Polygons reference.

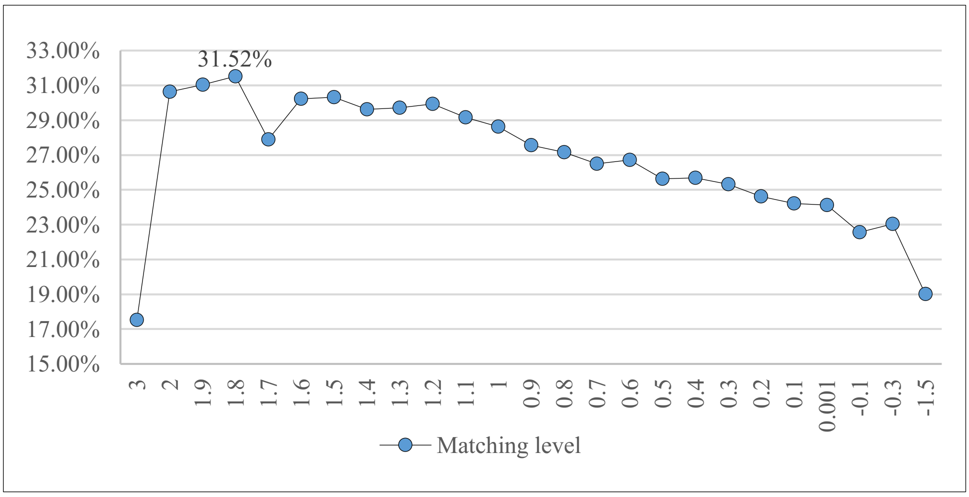


Fig.6.16 Results of matching level.

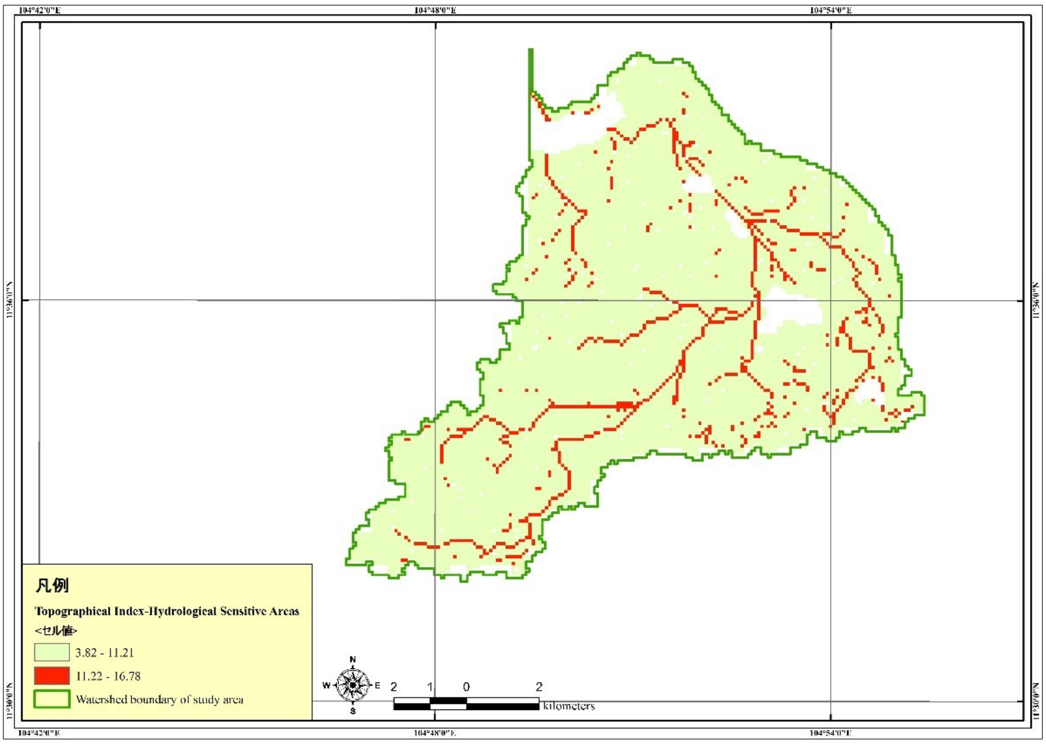


Fig.6.17 Hydrological Sensitive Areas (HSAs) for PPC.

6.3 Case study at middle scale

In this case study, PPC's development trends for each development stage occurred in HSAs are discussed based on the actual condition of land use obtained from site survey and master plan in 2020. In this respect, overlaying maps of HSAs, master plan in 2020, and middle scale watershed units are necessary for the study area.

Selection of the study area is on the basis of a watershed unit discussed at macro scale as shown in **Fig.6.18**. With watershed scale discussed at Sangkat level known as middle scale, one middle scale watershed unit is selected as a study area, as shown in **Fig.6.19**. Approximately one-third of study area belongs to the center area of PPC, where the development is rapidly increasing in recent year. **Fig.6.20** demonstrates the overlaying maps of HSAs and master plan in 2020 of PPC in the study area.

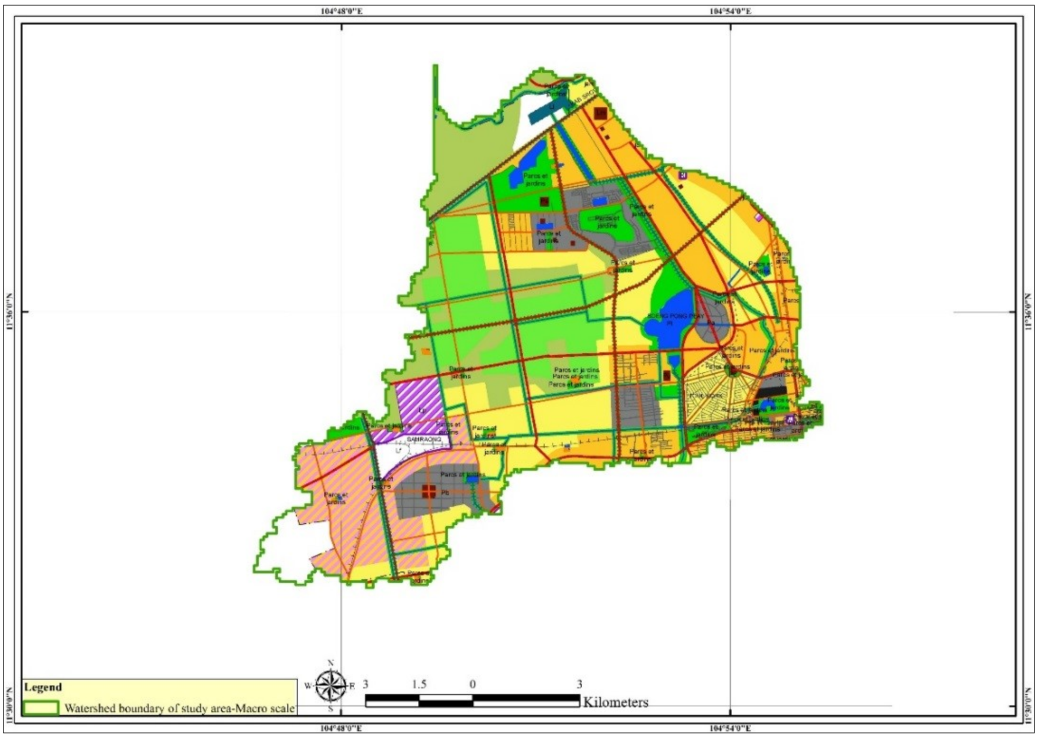


Fig. 6.18 Overlaying maps of a watershed unit at macro scale and master plan in 2020.

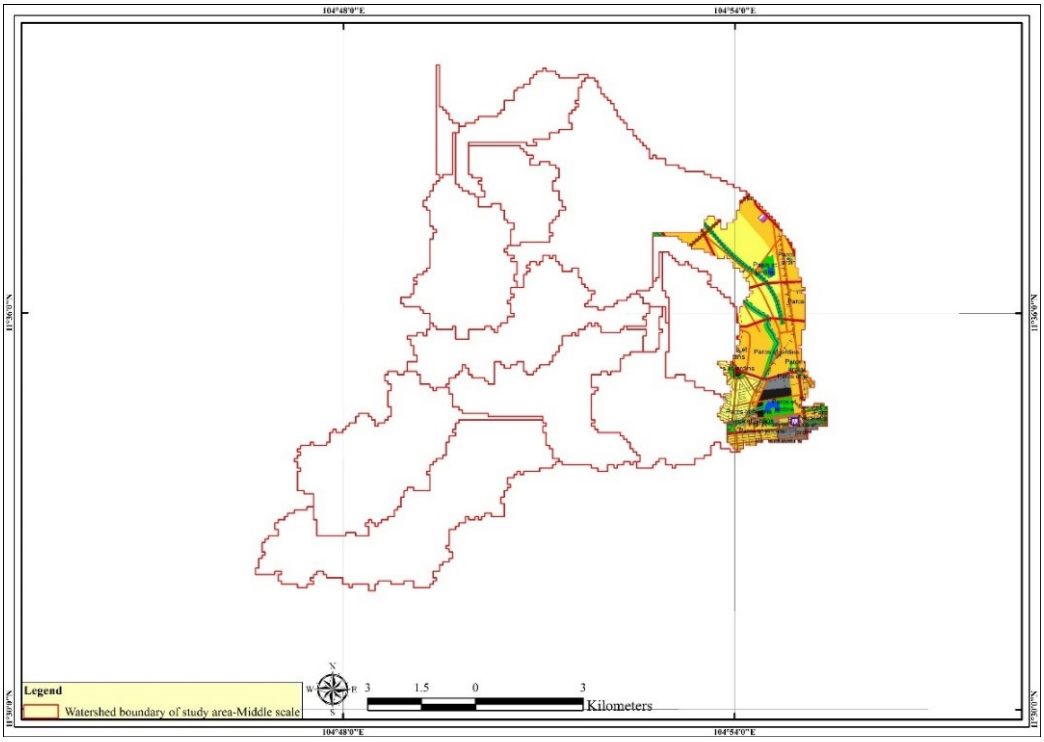


Fig.6.19 Study area at middle scale with a master plan in 2020.

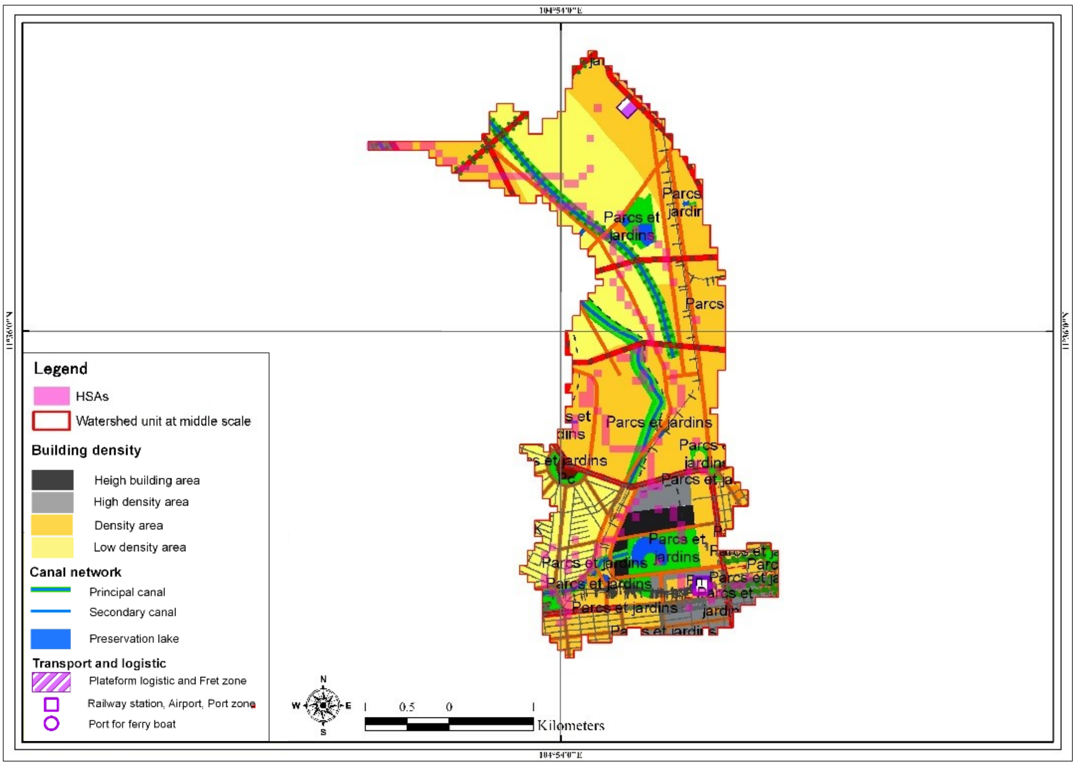


Fig.6.20 Overlaying of HSAs and PPC's 2020 master plan in the study area.

From the overlaying maps expressed in **Fig.6.20**, a development taken place in PPC regarding to HSAs are grasped with 4 important development stages: development area, ongoing development area, redevelopment area, and new development area. Development, ongoing, and redevelopment areas are mostly found in the center area of PPC. Southern and western part of the landfilled lake are densely by the development area. Whereas surrounding lake reclamation area are mostly ongoing development area.

Fig.6.21 shows some cases concerning about the development, ongoing, and redevelopment areas taken place on HSAs with white triangles show the locations and directions of observations.

Based on overlaying maps between master plan in 2020 and HSAs as shown in **Fig.6.21**, HSAs located in the southern part are high density and density area with its current situation of land use from bottom to top is shown in **Fig.6.22** and **6.23**, respectively. In the western part, HSAs are located along the main roads, density, and low-density areas. Current situation of land use in HSAs from bottom to top and left to right directions with corresponding locations as noted in **Fig.6.21** are illustrated as **Fig.6.24**, **Fig.6.25,** and **Fig.6.26**, respectively. While inside the landfilled lake area, with a small portion of the garden and preservation lake areas overlaid, the HSAs are frequently found in the height building and high-density areas, where mostly ongoing projects and under being constructed are shown in **Fig.6.27**.

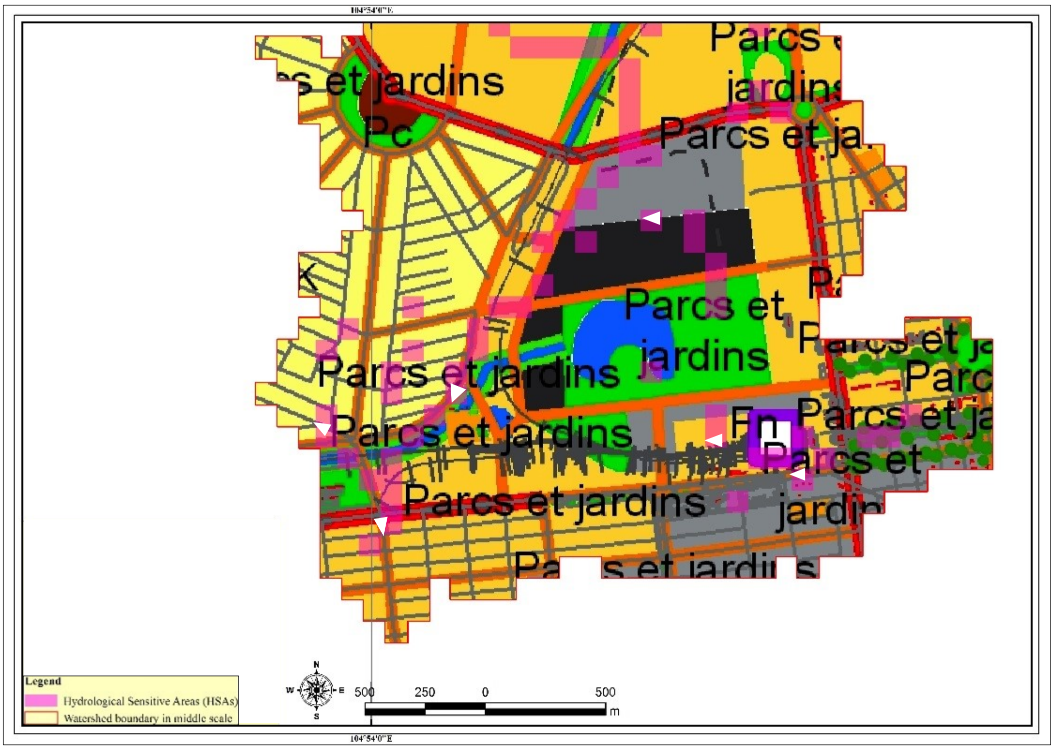


Fig.6.21 Core zone of PPC in the case study.

Fig.6.22 HSAs (buildings at the right side) in high-density area.

Fig.6.23 HSAs (land on the rail and land both sides of the rail) in density area.

Fig.6.24 HSAs (vacant land lot at the right side) in density area

Fig. 6.25 HSAs (roads and both sides of the buildings) in low-density area.

Fig.6.26 HSAs (road and both sides of the buildings) in low-density area

Fig.6.27 HSAs (ongoing development area both sides along the road) in height building & high-density areas.

In brief, from both the future development and current trends in HSAs, development situation of all HSAs in the center area of PPC can be classified into three categories: developed area, ongoing development area, and redevelopment area.

In terms of developed area, as shown in **Fig.6.22** and **Fig.6.25**, it's not practical to stop or reverse the development in the HSAs; however, improvement of the areas by retrofitting can be taken into consideration. Measures can be in the form of increasing green space such as rooftop gardens, trees, and gardens, etc. Unlike developed area, for the ongoing development area as expressed in **Fig.6.23**, **6.24** and **6.27**, redefining or readjustment of the early planning stages incorporated with the measures of reducing runoff can be pondered. Whereas in the redevelopment areas, as shown in **Fig.6.26**, particularly for the buildings on the right side of the road, seem to have a high tendency of redevelopment due to the disorder of construction and the constantly demand for development in the future. New land use zoning and design from the watershed-based planning perspective seeking for future sustainable development should be determined by not only concern about the economic aspect, but also the environment aspect for future sustainable development.

Secondly, for new development area situated in the upper part of the center area of PPC as shown in **Fig.6.21**, it can be confirmed that tendency of the development of the center area to the northern part of this case study is composed of both density and low-density areas. Besides, a small part of the HSAs overlaid with certain preservation lakes, parks, gardens, and canals, while a great portion of HSAs is situated in both of density and low-density areas are identified in the northern part.

Not differently from the development classification in development in the center area of PPC in terms of HSAs, situations of development in the new development area can be categorized into two classifications of development stages including ongoing development area and new development area, where similar suggestions proposed for redevelopment area in the center area of PPC can be considered. Prior to the redevelopment area, new development area can be selected and planned properly based on watershed-based planning perspective. It implies that as long as the development is not yet carried out, planners are able to perform primary screening assessment to define critical area for development; not only the future urban flooding can be controlled in the new development area, but also the appropriate area for development can be chosen at macro scale as discussed in **Chapter 5**. Whereas in this chapter, discussion on the development area at macro scale is zoomed in. At the middle scale planning, avoiding the development of area having a high potential of increasing flood risk can be identified using zoning indicator known as HSAs. Finally, the design measures within these HSAs are suggested in the next chapter.

6.4 Conclusions of chapter

First, this chapter shows the creation of soil databases using sub-soil data and impervious cover ratios for PPC by employing land use detection, impervious cover ratios index, and calculation methods of imperviousness following existing studies, typical residential density index, and population density for computation of Soil Water Storage.

Second, 1.8 standard deviation above the mean value of Topographical Index is defined as zoning indicator known as HSAs for PPC. By knowing the zoning indicator, the suggestion of development area having the potential of flood risk is identified.

Thirdly, based on the actual condition obtained from site survey and master plan in 2020 on zoning indicators, HSAs, 4 development stages including developed area, ongoing development area, redevelopment area, and new development area were defined. Suggestions for each development stage are proposed.

References

1. Walter, M. T., Walter, M. F., Brooks, E. S., Steenhuis, T. S., Boll, J. and Weiler, K.: Hydrologically sensitive areas: variable source area hydrology implications for water quality risk assessment, *Soil and Water Conservation*, Vol.3, pp. 277-284, 2000.
2. Agnew, L. J., Lyon, S., Gérard-Marchant, P., Collins, V. B., J. Lembo, A., Steenhuis, T.S., Walter, T. M.: Identifying hydrologically sensitive areas: Bridging the gap between science and application, *Environmental Management*, Vol.78, pp. 63-76, 2006.
3. Qiu, Z., Hall, C., Drewes, D., Messinger, G., Prato, T., Hale, K. and Abs, D. V.: Hydrologically sensitive areas, land use controls, and protection of healthy watersheds, *Water Resource Planning Management*, Vol. 140, Issue 7, pp.-1--1,2014.
4. Martin-Mikle, C. J., de Beurs, K. M., Julian, J. P. and Mayer, P. M.: Identifying priority sites for low impact development (LID) in a mixed-use watershed, *Landscape and Urban Planning*, Vol. 140, pp. 29-41, 2015.
5. Qiu, Z.: Assessing critical source areas in watersheds for conservation buffer planning and riparian restoration, *Environmental Management,* Vol.44, Issue 5, pp. 968-980, 2009.
6. Lim, L. and Sasaki, Y.: Review of research trends in watershed-based land use analysis, *J. Infrastructure Planning and Management,* JSCE, Vol.4, 227-242, 2016.
7. Qiu, Z.: Validation of a locally revised topographic index in central New Jersey, USA. *Water,* pp. 6616-6633, 2015
8. Manfreda, S., Di Leo, M. and Sole, A.: Detection of flood-prone areas using digital elevation

models, *Hydrologic Engineering*, Vol.16, Issue 10, pp. 781-790, 2011.

9. GIS 4 Geomorphology, *Topographic Wetness Index (TWI),* viewed 02 February 2016, from http://gis4geomorphology.com/topographic-index-model/.
10. *Hydraulic Conductivity,* viewed 02 February 2016, from http://web.ead.anl.gov/resrad/datacoll /conuct.html
11. terra GIS, *Saturated water flow*, viewed 05 May 2016, from http://www.terragis.bees.unsw. edu.au/terraGIS_soil/sp_water-saturated_water_flow.html.
12. Touch, S., Likitlersuan, S. and Pipatpongsa, T. 3D geological modelling and geotechnical characterisitcs of Phnom Penh subsoils in Cambodia. *J. Engineering Geology.,* Vol. 178, pp.58-69, 2014.
13. Esri, *Interpolating Surfaces in ArcGIS Spatial Analyst*, viewed 03 May 2016, from https://w ww.esri.com/news/arcuser/0704/files/interpolating.pdf.
14. Open Development Cambodia, *Base Map*, viewed 01 October 2014, from http: //archive.opendevelopmentcambodia.net/maps/downloads/? map=base&submit=Search.
15. JICA: *Overview of urban development in Phnom Penh Capital City*, 2011.
16. City of Anderson, *City of Anderson general plan*, viewed 06 July 2016, from http://www.ci .anderson.ca.us/andersonca/departments/kristen_development_services_and_building_departments/uploads/General_Plan_2007.pdf
17. Yang, B. and Li, M. H.: Assessing planning approaches by watershed stream flow modeling: Case study of the Woodland, Texas, *Landscape and Urban Planning*., Vol. 99, pp. 9-22, 2011.
18. Demonstrator of interactive flash flood mapping for Phnom Penh, *flood simulation,* viewed 02 February 2017, from http://flooddemo.jennylestil.com/.

CHAPTER 7
Concept of watershed-based land use planning at micro scale

7.0 Summary of chapter

Facing current trends of land use development and seeking for the sustainable development in the future, this chapter proposes preventive and controllable measures known as Low Impact Development-Best Management Practices, cost-effective measures, to mitigate water quantity impact of urban runoff to the cities sensitive to urban flooding as Phnom Penh City (PPC).

Basically, this chapter is composed of three sections. Firstly, reviews of Low Impact Development (LID) and Best Management Practices (BMPs) are performed where concepts and techniques of LID-BMPs measures are explained. Secondly, explanation of the criteria in LID-BMPs and calculation of weights for suitability analysis used for GIS-based multi-criteria assessment modeling are conducted. Thirdly, suitability matrix of HSAs based on LID-BMPs suggesting in terms of current situation obtained from site survey is illustrated. The maps of HSAs and suitability of design measures for the study area are finalized with the flowchart of watershed-based land use planning proposed to PPC.

7.1 The idea of Low Impact Development-Best Management Practices (LID-BMPs) prospects and its importance

The world widely constant increasing of the urbanization process has made the management of the urban drainage become more and more important.

As primarily focusing on the conveyance of water away from the urban area, many terms including Low Impact Development (LID) and Best Management Practices (BMPs) are originated from the approaches used to solve the issues related to the urban stormwater management, which is also known as urban drainage management[1)], as shown in **Table 7.1**. With the primary problem of urban flooding, which is mainly due to the excessive runoff generated in every storm event during the rainy season in PPC, this conveyance of runoff from the urban area has posed many problems to the social and environmental aspect in this city. In this respect, the combination of both terms LID-BMPs measures not only enable the designs full of greenery but also help to control and reduce the urban flooding extent are used for developing a watershed-based methodology for land use planning in PPC.

Table 7.1 Urban drainage management terms.

Low Impact Development (LID)	Primary focused on conveyance of water away from urban area
Water Sensitive Urban Design (WSUD)	
Integrated Urban Water Management (IUWM)	
Sustainable Urban Drainage Systems (SUDS) or Sustainable Drainage System (SuDs)	
Best Management Practices (BMPs)	
Stormwater Control Measures (SCMs)	
Alternative techniques (ATs) or Compensatory techniques (CTs)	
Source Control	
Green Infrastructure	
Stormwater Quality Improvement Devices (SQIDs)	

7.1.1 Evolution and concepts of Low Impact Development (LID)

a) Evolution of Low Impact Development (LID)

As the city grows, the high demand of land is required not only within the city, but also its surrounding areas for the purposes of development. This process is known as urbanization, which has brought about not only increase of surface areas covered by parking lots, roads, and rooftops called impervious cover but also altering the hydrologic function of the natural water cycle[2)], as shown in **Fig.7.1**. Instead of rainfall infiltrating into these hard surfaces, the flow velocity of excessive runoff is increasing. In the contrast, both times of concentration and water quality are decreasing. These processes have been causing many negatives effects to the social and environmental aspects. Water pollution and urban flash flooding are the most common negative backsets. In this research, the backsets focusing on urban flash flooding is essential to discuss about land use planning in PPC.

With increasing concerns over the impact on the land development, Low Impact Development approach was introduced with its evolution[1)] as shown in **Table 7.2**. LID has been commonly used in North America (USA and Canada) and New Zealand. It’s interesting to note that a land use planning, as well as engineering approach known as LID, began to increase its popularity as one of many strategies and techniques applied to counteract the impact of development in the early 1990s[3)].

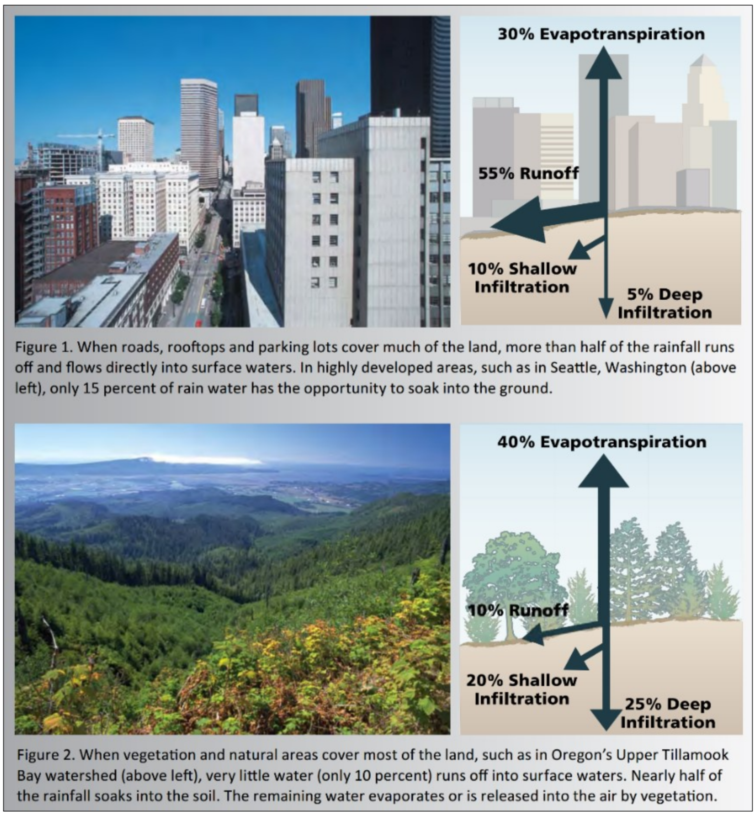


Figure 1. When roads, rooftops and parking lots cover much of the land, more than half of the rainfall runs off and flows directly into surface waters. In highly developed areas, such as in Seattle, Washington (above left), only 15 percent of rain water has the opportunity to soak into the ground.

Figure 2. When vegetation and natural areas cover most of the land, such as in Oregon's Upper Tillamook Bay watershed (above left), very little water (only 10 percent) runs off into surface waters. Nearly half of the rainfall soaks into the soil. The remaining water evaporates or is released into the air by vegetation.

Fig.7.1 Comparison of land covered by impervious cover and vegetation[2)]

Table 7.2 Evolution of Low Impact Development Approach[1)].

Year	Purposes of using Low Impact Development & its evolution	Countries
1977	Minimizing of cost for stormwater management considering the concept of "design with nature approach"	Vermont, USA
1984	New focusing on urban stormwater runoff and water quality	USA
1990	Distinguishing of the site-design and catchment-wide approach from the common stormwater management approach	Prince George's County, USA
1998	Low Impact Development Design Manual	
2000	Low Impact Development Design Manual	New Zealand
2003	Site design to avoid pollution	
2005	Evaluating the LID practices' effects on ground water quality, runoff volume, and quality	USA
2009	Reestablishing of hydrologic targets for both retrofitting and new urban development	NC State University, USA
2010	Codification of LID in legislation throughout North America	USA, Canada
2011	Focusing on ecosystem health	New Zealand

b) Concepts of Low Impact Development (LID)

By managing runoff as close to its source as possible, Low Impact Development (LID) is considered as a management approach and practices' sets enable the reduction of runoff and pollutant loadings, and it is also an approach to land development (or re-development) that works with nature[4), 5)].

In terms of managing stormwater, a variety of LID's practices is used for preservation of natural drainage process. Practically, rainwater is retained and encouraged to infiltrate into the ground rather than allowing the excessive runoff to flow into the ditches and storm drains[2)]; the overcapacity of these collectors help to generate urban flooding and pollution problems in the city.

LID practices are bioretention, vegetated swales, green roof, porous pavers, infiltration box planters, naturalized drainage way, rainwater harvesting, etc.

Generally, the application of LID techniques can be utilized at any development stages including developed and undeveloped areas[2)]. In undeveloped areas, protection of open spaces and natural areas, and pavement amount reduction can be conducted incorporated of early planning stages with holistic LID design[2)]. While in developed areas, in terms of providing benefits and solving problems, adding of LID practices can be performed. These practices are composed of features used to capture and soak water, which is limited from directing roof drainage to rain garden then to the retrofitting of streets.

In respect of environmental and economic benefits, LID practices provide many advantages as following[2)]:

- Reducing of costly flood events
- Improvement of water quality
- Restoration of aquatic habitat
- Improvement of groundwater recharge
- Enhancement of neighborhood beauty

7.1.2 Evolution and concepts of Best Management Practices

Dramatically increasing of impervious cover by the urbanization processes have caused excessive runoff in the urban areas, which brought about the generation of urban flooding and also harmful to the water quality in the receiving water bodies such as a stream, lake, river, or ocean.

With the increasing emphasis on the deleterious impact as the results of urbanization, Best Management Practices (BMPs) is introduced as the means to mitigate the excessive runoff.

In the most cost-effective manner, Best Management Practices (BMPs) for stormwater control is considered as a technique, measure or structural control employed for management and improvement of quantity and quality of stormwater runoff under a given set of conditions[6]. These conditions include drainage area, drainage slope, imperviousness, hydrological soil group, road buffer, stream buffer, and building buffer, etc.

In the North America (USA and Canada) context, BMPs are used for describing a type of practice or structured approach to prevent pollution[1]. Trends of researches and evolution of BMPs in North America are shown in **Table 7.3**.

Table 7.3 Research and evolution trends of BMPs in North America.

Year	Purposes of BMPs and its evolution
1949	• Restoration of more favorable plant cover and soil structure • Maintenance of land stream condition • Serving present and future needs for usable water
1972	As part of the Clean Water Act (CWA) (never explicitly defined)
1979-1983	Treat urban storm water from the Clean Water Act enacted in 1972
1990	• Stormwater design manual • Implement of BMPs ranged practices across North America
2011	Satisfying the wastewater permit applications (under the regulation of phase II: National Pollution Discharge Elimination System (NPDES))

7.1.3 Concepts and Techniques of Low Impact Development-Best Management Practices (LID-BMPs)

a) Concepts of LID-BMPs

The effective of Low Impact Development (LID) utilizes both of nonstructural and structural stormwater management measures, and a subset of a larger group of practices, and facilities known as Best Management Practices (BMPs). All the BMPs in stormwater runoff control used in LID approach hereafters presented as LID-BMPs, which are cost effective measures for mitigating the deleterious impact of excess runoff in terms of water quantity and quality[7].

With the basic principle of managing rainfall at the source using uniformly distributed decentralized micro-scale controls, LID-BMPs design is employed to mimic a site's pre-development hydrology. This versatile approach can be applied at any development stages including new development, urban retrofits, and redevelopment or revitalization projects; it's widely accepted and used in United State, Europe, Japan, and Australia[2), 6)].

b) Techniques of LID-BMPs

With the nature of depending on the natural process, techniques in LID-BMPs are used for managing both water quantity and quality including:

- Absorption
- Infiltration
- Evaporation
- Evapotranspiration
- Filtration using both of standing plant material and soil layers
- Potential pollutant being absorbed by select vegetation
- Biodegradation of pollutants using soil microbial communities

Basically, LID-BMPs techniques include both nonstructural and structural measures[6), 7)] as shown in **Table 7.4**. Regarding to the reduction of pollution levels like either reducing the generation of stormwater runoff or pollutants amount contained in the runoff, nonstructural LID-BMPs are stormwater runoff management techniques using natural measures which do not require extensive construction efforts. It seeks to decrease disturbance in the site, keep and maintain site features, minimize and disconnect of impervious cover, take advantage of native vegetation, and preserve both the natural drainage features and characteristics etc[7)].

In terms of removing the pollutant, structural LID-BMPs as expressed in **Table 7.4**, which are engineering system and designing methods, are utilized to provide temporary storage and treatment of stormwater runoff. The structural BMPs used for controlling and treating runoff close to runoff's source are considered as LID-BMPs[7)].

Table 7.4 Nonstructural and structural of LID-BMPs.

LID-BMPs Techniques

Nonstructural LID-BMPs	Structural LID-BMPs
<u>Vegetation and Landscaping</u>	<u>Detection/Retention</u>
• Preservation of Natural Area	• Dry ponds
• Native Ground Control	• Extended ponds
• Vegetative filters and Buffer	• Wet ponds
<u>Minimizing land disturbance</u>	<u>Infiltration</u>
<u>Impervious Area Management</u>	• Infiltration trenches
• Street and Sidewalks	• Infiltration basin
• Parking and Driveway Areas	• Porous pavement
• Pervious Paving Material	<u>Filtration</u>
• Unconnected Impervious Areas	• Surface sand filters
• Vegetated Roofs	• Media filters
<u>Time of Concentration Modification</u>	• Underground vault filters
• Surface Roughness Changes	<u>Vegetation</u>
• Slope Reduction	• Grass swales
• Vegetated Conveyance	• Filter strip/buffers
	• Bioretention cells
	• Stormwater Wetland
	<u>Green Building</u>
	• Green roofs
	• Rain barrels
	• Cisterns

7.2 GIS-based multi-criteria assessment modeling for suitability analysis of Low Impact Development-Best Management Practices (LID-BMPs)

Unlike other existing researches, suitability maps of LID-BMPs are obtained from GIS-based multi-criteria assessment modeling, in which the multi-criteria assessment is based on a decision support tool known as Analytical Hierarchy Process (AHP) with the integration of Grey Rational Analysis (GRA) method used for assisting and determining the most cost-effective implementation of LID-BMPs practices.

Three main issues are discussed including the decision of criteria for each design measures of LID-BMPs, concepts of AHP and GRA, each weight of factor in LID-BMPs is numerically calculated using AHP-GRA method with the modification of reference sequence, and the suitability maps for design measures of LID-BMPs is identified by suitability analysis with the aid of Weight Overlay in GIS.

7.2.1 Criteria of LID-BMPs

Based on **Table 7.5**, a site suitability criteria matrix for Best Management Practices (BMPs) supported by Environmental Protection Agency (EPA) [8)] is adapted. In accordance with the concept of LID-BMPs, application of these criteria applied to the Hydrological Sensitive Areas (HSAs) known as a source of runoff is hereafters appropriate and utilized for suitability analysis of LID-BMPs in this research.

7 types of structural LID-BMPs are used including the categories of green building (green roof and rain barrels), vegetation (grass swale and bioretention), infiltration (porous pavement), and detection/retention (dry pond and wet pond) with usages and usefulness of these measures as shown in **Table 7.6**. These 7 types of measures are developed mainly in North America, in which some of the measures (green roof and porous pavement) might not effective for PPC where the rainfall condition is quite different. However, this research is developed following the concept and methodology for LID-BMPs.

Table 7.5 Default criteria for BMPs suitable locations used in BMP Setting Tool[8)].

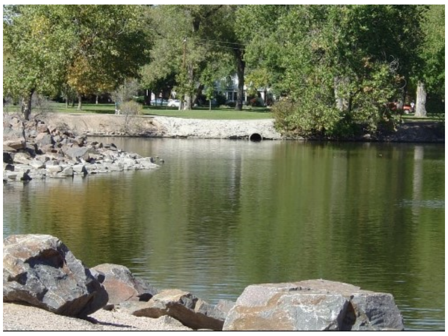
Types	Drainage area (acre)	Drainage Slope (%)	Impervious (%)	Hydrological Soil Group	Road Buffer (ft)	Stream Buffer (ft)	Building Buffer (ft)
Bioretention	<2	<5%	>0%	A-D	<100	>100	-
Grass Swales	<5	<4%	>0%	A-D	<100	-	-
Dry pond	>10	<15%	>0%	A-D	-	>100	-
Wet pond	>25	<15%	>0%	A-D	-	>100	-
Porous Pavement	<3	<1%	>0%	A-B	-	-	-
Rain Berrels	-	-	-	-	-	-	<30
Green Roofs	-	-	-	-	-	-	-

Table 7.6 Usage and usefulness of LID-BMPs.

LID-BMPs	Measures	Usage and Usefulness
Green building	 Green roof[9)]	● Rooftops being spread with top soil and planted with vegetation. ● Using in large urban areas for reducing runoff quantity from rooftops. ● Using natural sediment to filter pollutants.

	 Rain barrel[10]	● Preventing runoff from entering to storm drain system. ● Able to be used by home owner. ● Providing water for garden, lawns etc.
Vegetation	 Grass swale[11]	● A vegetated channel receiving direct flow and conveying storm water.
	 Bioretention[9]	● Enhancing the quality of downstream water bodies through providing the storm water treatment. ● Providing shade, wind break, absorb noise, and improving the landscape of the site.

<table>
<tr>
<td>Porous pavement</td>
<td>

Porous pavement[9]</td>
<td>● Capturing water volume and retaining, then allowing it to infiltrate into the ground.
● The high potential of disposal runoff at the local site level.
● Minimizing the concentration of pollutants to the receiving water bodies.
● Increasing the base flow levels of the nearby stream, underlying aquifers ‘recharge and treatment of water quality.
● Infiltration may not good for the areas where underground is a primary source of drinking water.
● Limitation of performance infiltration in poorly permeable soils areas.</td>
</tr>
<tr>
<td rowspan="2">Detention(Dry pond)/Retention(Wet pond)</td>
<td>
Wet pond[12]</td>
<td>● Capturing runoff volume, retaining until the following storm events.
● Keeping as a permanent pool of water throughout the year.</td>
</tr>
<tr>
<td>
Dry pond[9]</td>
<td>● Capturing runoff volume, temporally retaining, and subsequently being released.</td>
</tr>
</table>

7.2.2 Calculation of weight using Analytical Hierarchy Process (AHP)-Grey Rational Analysis (GRA) method

a) Concepts of Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), a decomposition multi-attribute decision-making method (MADM), is a powerful tool to assist decision makers to solve complex problems with multi-complicating and subjective criteria, and widely used among the scholars [13) 14)]. After all decision problems are structured hierarchy at a different level, the AHP is applied with the comparison scale introduced by Thomas L.Saaty[15)]. A fundamental 9 points scale measurements are used to express individual preferences or judgments by creating a matrix of pairwise comparison as shown in **Table 7.7**.

Table 7.7 The comparison scale in AHP[15)]

Intensity of importance	Definition	Explanation
1	Equal importance of i and j	Two activities contribute equally to the objective
3	Weak importance of i over j	Experience and judgment slightly favor one activity over another
5	Strong importance of i over j	Experience and judgment strongly favor one activity over another
7	Demonstrated importance of i over j	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance of i over j	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values of the two adjacent judgments	When compromise is need
Reciprocals of above nonzero	If activity i has one the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	

Using pairwise comparison, weights of factors are calculated by comparing two weights at a time. The weights for each criterion (w_i) by taking eigenvector corresponding to the largest eigenvalue of the matrix are calculated by AHP[16), 17), 18), 19)] as following steps:

1. Formation of pairwise comparison matrix

$$X = (x_{ij}) = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & & \vdots\vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{pmatrix}$$

Where x is the important degree of the i^{th} factor compared to the j^{th} factor

2. Normalization of the element of X

$$x_{ij}^{norm} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{kj}} \text{ Where i, j=1, 2,…, n}$$

3. Aggregation of the element of the same line/row of normalization matrix

$$w_i^{norm} = \sum_{j=1}^{n} X_{ij}{}^{norm} \text{ where i= 1, 2,…, n}$$

4. Identification of weights vector

$$w_i = \frac{w_i^{norm}}{\sum_{k=1}^{n} w_k{}^{norm}} \text{ where i=1, 2, …,n}$$

5. The maximum value λ_{max}

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{XW}{w_i}$$ is the largest or principal eigenvalue of the matrix

where n is the dimension of the comparison matrix

6. Computation of consistency ratio (CR) for consistency check

$$CR = \frac{CI}{RI} \text{ where } \begin{cases} CI = \frac{\lambda_{max} - n}{n-1} \\ \text{RI is the random index, as } \textbf{Table 7.8} \end{cases}$$

Table 7.8 Random Index[20]

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

$$\text{If } \begin{cases} CR \leq 0.1 \text{ pairwise comparision matrix has acceptable consistency} \\ CR \geq 0.1 \text{ pairwise comparision matrix has indequate consistency} \end{cases}$$

b) Concepts of Grey Rational Analysis method (GRA)

A systematic analysis tool for handling multi-criteria decision-making process known as AHP enables the consideration of many important aspects including social, economic objectives, ecological as well as environmental, is found very useful; however, this tool excessively relies on the subjective weight of each performance indicator coming from the experience and the interrelationship among multi indicators are generally ignored[13]. In this respect, the Grey Rational Analysis (GRA) method, which has been proved as an effective tool dealing with incomplete and uncertain information, with the integration of AHP used to solve several inexact issues containing multiple criteria and objectives involved in the typical evaluation process is introduced in this research.

Basically, the integrated evaluation value of all related factors in AHP can be defined and expressed as:

$$S_i = \sum_{j=1}^{n} w_j \times x_i(j) \text{ where } \begin{cases} S_i \text{ integrated evaluation value of grid i} \\ w_j \text{ weight for factor j of grid i} \\ x_i(j) \text{ the value of factor j of grid i} \end{cases}$$

With the modification of AHP using GRA, the integrated land use suitability evaluation model can be written as follows:

$$S_i = \sum_{j=1}^{n} w_j \times \xi_j(j) \text{ where } \begin{cases} S_i \text{ integrated evaluation value of grid i} \\ w_j \text{ weight for factor j of grid i} \\ S_i \in [0,1] \end{cases}$$

To tackle the uncertainties for integrated land use suitability evaluation model, GRA method is used to modify the model in AHP as following[21), 22), 23), 24)]:

1. Define reference sequence

Generally, reference sequence is identified after the performance of normalization procedure $x_{0j} = \left(x_{01}(1), x_{02}(2), \ldots, x_{0n}(n)\right) = (1, 1, 1, \ldots, 1)$. However, this sequence doesn't exist in the reality[25)]. Therefore, the reference sequence can be expressed as:

$$x_{0j} = \max_{i}\{x_{ij}\}$$

With the expectancy of the larger the better, normalization of the original attribute performance can be defined as follow:

$$x_{ij} = \frac{\left\|\ln(x_{ij})\right\|}{\left\|\ln\left(\ln(\prod_{j=1}^{m} x_{ij}\right)\right\|}$$

For i= 1, 2, 3,….n and j=1, 2, 3,…m

2. Denote the m sequence to be compared as

$x_i = (x_i(1), x_i(2), \ldots, x_i(n))$, i=1, 2… m

3. Normalize the sequences to ensure for the same order of all sequences then normalized sequences can be denoted as

$x_i^* = (x_i^*(1), x_i^*(2), \ldots, x_i^*(n))$, i=1, 2… m

4. The Grey Rational Coefficient between the compared sequences, x_i and the reference sequence,

x_0, for the *j*th factor (j= 1, 2, …n) is defined as

$$\xi_j(j) = \frac{\min_i \min_j |x_0(j) - x_i^*(j)| + \sigma \max_i \max_j |x_0(j) - x_i^*(j)|}{|x_0(j) - x_i^*(j)| + \sigma \max_i \max_j |x_0(j) - x_i^*(j)|}$$

$$\text{Where} \begin{cases} \xi_j(j) \in [0, 1] \\ x_i^*(j) \text{ the value of factor j of grid i} \\ \sigma \in [0, 1],\ \text{typically } \sigma = 0.5 \text{ the distinguishing coefficient} \end{cases}$$

c) Numerical calculation of LID-BMPs based on AHP and GRA method

A total of 7 types of LID-BMPs are used for defining the integrated land use suitability evaluation models following the steps in **a)** and **b)** in **section 7.2.2** by author as expressed in **Table 7.9**, **Table 7.10**, **Table 7.11**, **Table 7.12**, **Table 7.13**, **Table 7.14**, and **Table 7.15** with the denotations including drainage area as DA, drainage slope as DS, hydrological soil group as HSG, road buffer as RB, stream buffer as SB, building buffer as BB, and impervious surface as IS.

In this research, judgment of the importance of i factor (DA, DS, HSG, RB, SB, BB and IS) over j factor (DA, DS, HSG, RB, SB, BB and IS) of each design measures is based on **Table 7.5** and **Table 7.7**. Each pairwise comparison shown in the tables below reflects on the importance of i factor over j factor subjectively judged by the author as a trial to develop the methodology in this research. However, in the case of real application, discussion with stakeholders and professionals are required.

Table 7.9 Weights for Green roof based on AHP-GRA

Pairwise Comparison							
Factors	DA (acre)	DS (%)	HSG	RB (ft)	SB (ft)	BB (ft)	IS (ft)
DA (acre)	1.00	3.00	3.00	3.00	3.00	3.00	3.00
DS (%)	0.33	1.00	3.00	3.00	3.00	3.00	3.00
HSG	0.33	0.33	1.00	3.00	3.00	3.00	3.00
RB (ft)	0.33	0.33	0.33	1.00	3.00	3.00	3.00
SB (ft)	0.33	0.33	0.33	0.33	1.00	3.00	3.00
BB (ft)	0.33	0.33	0.33	0.33	0.33	1.00	3.00
IS (%)	0.33	0.33	0.33	0.33	0.33	0.33	1.00
Total	3.00	5.67	8.33	11.00	13.67	16.33	19.00
Normalization							
DA	0.33	0.53	0.36	0.27	0.22	0.18	0.16
DS	0.11	0.18	0.36	0.27	0.22	0.18	0.16
HSG	0.11	0.06	0.12	0.27	0.22	0.18	0.16
RB	0.11	0.06	0.04	0.09	0.22	0.18	0.16
SB	0.11	0.06	0.04	0.03	0.07	0.18	0.16

BB	0.11	0.06	0.04	0.03	0.02	0.06	0.16
IS	0.11	0.06	0.04	0.03	0.02	0.02	0.05
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CR=-0.87<0.1 (pairwise comparison is acceptable)							
Reference sequence							
DA	0.00	0.17	0.17	0.17	0.17	0.17	0.17
DS	0.25	0.00	0.25	0.25	0.25	0.25	0.25
HSG	0.50	0.50	0.00	0.50	0.50	0.50	0.50
RB	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SB	0.50	0.50	0.50	0.50	0.00	0.50	0.50
BB	0.25	0.25	0.25	0.25	0.25	0.00	0.25
IS	0.17	0.17	0.17	0.17	0.17	0.17	0.00
Total	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Grey Rational Coefficient							
DA	0.66	1.00	0.71	0.58	0.52	0.48	0.46
DS	0.43	0.48	0.71	0.58	0.52	0.48	0.46
HSG	0.43	0.40	0.43	0.58	0.52	0.48	0.46
RB	0.43	0.40	0.38	0.41	0.52	0.48	0.46
SB	0.43	0.40	0.38	0.38	0.40	0.48	0.46
BB	0.43	0.40	0.38	0.38	0.38	0.40	0.46
IS	0.43	0.40	0.38	0.38	0.38	0.37	0.39
Total	0.66	1.00	0.71	0.58	0.52	0.48	0.46
Integrated land use suitability evaluation value							
	S1	S2	S3	S4	S5	S6	S7
Weights	0.21	0.16	0.14	0.13	0.12	0.12	0.12

Table 7.10 Weights for Rain barrel based on AHP-GRA

Pairwise Comparison							
Factors	DA (acre)	DS (%)	HSG	RB (ft)	SB (ft)	BB (ft)	IS (ft)
DA (acre)	1.00	3.00	3.00	3.00	3.00	0.13	3.00
DS (%)	0.33	1.00	3.00	3.00	3.00	0.13	3.00
HSG	0.33	0.33	1.00	3.00	3.00	0.13	3.00
RB (ft)	0.33	0.33	0.33	1.00	3.00	0.13	3.00
SB (ft)	0.33	0.33	0.33	0.33	1.00	0.13	3.00
BB (ft)	8.00	8.00	8.00	8.00	8.00	1.00	8.00
IS (%)	0.33	0.33	0.33	0.33	0.33	0.13	1.00
Total	10.67	13.33	16.00	18.67	21.33	1.75	24.00
Normalization							
DA	0.09	0.23	0.19	0.16	0.14	0.07	0.13
DS	0.03	0.08	0.19	0.16	0.14	0.07	0.13
HSG	0.03	0.03	0.06	0.16	0.14	0.07	0.13
RB	0.03	0.03	0.02	0.05	0.14	0.07	0.13
SB	0.03	0.03	0.02	0.02	0.05	0.07	0.13
BB	0.75	0.60	0.50	0.43	0.38	0.57	0.33
IS	0.03	0.03	0.02	0.02	0.02	0.07	0.04
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CR=-0.87<0.1 (pairwise comparison is acceptable)							
Reference sequence							
DA	0.00	0.32	0.32	0.32	0.32	0.61	0.32
DS	0.90	0.00	0.90	0.90	0.90	1.71	0.90
HSG	1.12	1.12	0.00	1.12	1.12	2.12	1.12

RB	0.35	0.35	0.35	0.00	0.35	0.65	0.35
SB	0.20	0.20	0.20	0.20	0.00	0.39	0.20
BB	0.17	0.17	0.17	0.17	0.17	0.00	0.17
IS	0.15	0.15	0.15	0.15	0.15	0.27	0.00
Total	1.12	1.12	0.90	1.12	1.12	2.12	1.12
Grey Rational Coefficient							
DA	0.68	0.73	0.80	0.70	0.70	0.45	0.69
DS	0.66	0.67	0.80	0.70	0.70	0.45	0.69
HSG	0.66	0.66	0.75	0.70	0.70	0.45	0.69
RB	0.66	0.66	0.73	0.67	0.70	0.45	0.69
SB	0.66	0.66	0.73	0.66	0.66	0.45	0.69
BB	1.00	0.90	0.98	0.81	0.79	0.54	0.77
IS	0.66	0.66	0.73	0.66	0.66	0.45	0.66
Total	0.68	0.73	0.80	0.70	0.70	0.45	0.69
Integrated land use suitability evaluation value							
	S1	S2	S3	S4	S5	S6	S7
Weights	0.14	0.14	0.14	0.14	0.14	0.17	0.13

Table 7.11 Weights for Grass swale based on AHP-GRA

Pairwise Comparison							
Factors	DA (acre)	DS (%)	HSG	RB (ft)	SB (ft)	BB (ft)	IS (ft)
DA (acre)	1.00	3.00	5.00	7.00	8.00	8.00	3.00
DS (%)	0.33	1.00	5.00	5.00	8.00	8.00	0.20
HSG	0.20	0.20	1.00	5.00	8.00	8.00	0.14
RB (ft)	0.14	0.20	0.20	1.00	8.00	8.00	0.14
SB (ft)	0.13	0.13	0.13	0.13	1.00	3.00	0.20
BB (ft)	0.13	0.13	0.13	0.13	0.33	1.00	0.17
IS (%)	0.33	5.00	7.00	7.00	5.00	6.00	1.00
Total	2.26	9.65	18.45	25.25	38.33	42.00	4.85
Normalization							
DA	0.44	0.31	0.27	0.28	0.21	0.19	0.62
DS	0.15	0.10	0.27	0.20	0.21	0.19	0.04
HSG	0.09	0.02	0.05	0.20	0.21	0.19	0.03
RB	0.06	0.02	0.01	0.04	0.21	0.19	0.03
SB	0.06	0.01	0.01	0.00	0.03	0.07	0.04
BB	0.06	0.01	0.01	0.00	0.01	0.02	0.03
IS	0.15	0.52	0.38	0.28	0.13	0.14	0.21
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CR=-0.87<0.1 (pairwise comparison is acceptable)							
Reference sequence							
DA	0.00	0.11	0.16	0.20	0.21	0.21	0.11
DS	0.24	0.00	0.34	0.34	0.45	0.45	0.34
HSG	2.67	2.67	0.00	2.67	3.45	3.45	3.22
RB	0.66	0.55	0.55	0.00	0.70	0.70	0.66
SB	0.24	0.24	0.24	0.24	0.00	0.12	0.18
BB	0.19	0.19	0.19	0.19	0.10	0.00	0.16
IS	0.14	0.21	0.25	0.25	0.21	0.23	0.00
Total	2.67	2.67	0.55	2.67	3.45	3.45	3.22
Grey Rational Coefficient							
DA	0.48	0.46	0.95	0.46	0.38	0.38	0.44
DS	0.44	0.44	0.95	0.45	0.38	0.38	0.38

HSG	0.44	0.43	0.85	0.45	0.38	0.38	0.38
RB	0.44	0.43	0.84	0.43	0.38	0.38	0.38
SB	0.44	0.43	0.83	0.43	0.37	0.37	0.38
BB	0.44	0.43	0.83	0.43	0.37	0.37	0.38
IS	0.44	0.49	1.00	0.46	0.37	0.38	0.40
Total	0.48	0.46	0.95	0.46	0.38	0.38	0.44
Integrated land use suitability evaluation value							
	S1	S2	S3	S4	S5	S6	S7
Weights	0.15	0.14	0.14	0.14	0.14	0.14	0.15

Table 7.12 Weights for Biorentention based on AHP-GRA

Pairwise Comparison							
Factors	DA (acre)	DS (%)	HSG	RB (ft)	SB (ft)	BB (ft)	IS (ft)
DA (acre)	1.00	3.00	5.00	7.00	7.00	9.00	3.00
DS (%)	0.33	1.00	5.00	5.00	4.00	7.00	0.20
HSG	0.20	0.20	1.00	5.00	5.00	5.00	0.14
RB (ft)	0.14	0.20	0.20	1.00	0.17	5.00	0.14
SB (ft)	0.14	0.25	6.00	6.00	1.00	5.00	0.20
BB (ft)	0.11	0.14	0.20	0.20	0.20	1.00	0.17
IS (%)	0.33	5.00	7.00	7.00	5.00	6.00	1.00
Total	2.26	9.79	24.40	31.20	22.37	38.00	4.85
Normalization							
DA	0.44	0.31	0.20	0.22	0.31	0.24	0.62
DS	0.15	0.10	0.20	0.16	0.18	0.18	0.04
HSG	0.09	0.02	0.04	0.16	0.22	0.13	0.03
RB	0.06	0.02	0.01	0.03	0.01	0.13	0.03
SB	0.06	0.03	0.25	0.19	0.04	0.13	0.04
BB	0.05	0.01	0.01	0.01	0.01	0.03	0.03
IS	0.15	0.51	0.29	0.22	0.22	0.16	0.21
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CR=-0.87<0.1 (pairwise comparison is acceptable)							
Reference sequence							
DA	0.0	0.1	0.2	0.2	0.2	0.2	0.1
DS	0.3	0.0	0.4	0.4	0.4	0.5	0.4
HSG	4.8	4.8	0.0	4.8	4.8	4.8	5.8
RB	0.3	0.2	0.2	0.0	0.2	0.2	0.3
SB	7.7	5.5	7.1	7.1	0.0	6.4	6.4
BB	0.2	0.2	0.1	0.1	0.1	0.0	0.2
IS	0.1	0.2	0.2	0.2	0.2	0.2	0.0
Total	7.7	5.5	7.1	7.1	4.8	6.4	6.4
Grey Rational Coefficient							
DA	0.75	0.92	0.77	0.77	1.00	0.83	0.86
DS	0.73	0.90	0.77	0.77	0.98	0.83	0.81
HSG	0.72	0.89	0.76	0.77	0.99	0.82	0.81
RB	0.72	0.89	0.76	0.76	0.96	0.82	0.81
SB	0.72	0.89	0.78	0.77	0.97	0.82	0.81
BB	0.72	0.89	0.76	0.76	0.96	0.81	0.81
IS	0.73	0.94	0.78	0.77	0.99	0.82	0.83
Total	0.75	0.92	0.77	0.77	1.00	0.83	0.86
Integrated land use suitability evaluation value							
	S1	S2	S3	S4	S5	S6	S7

Weights	0.15	0.14	0.14	0.14	0.14	0.14	0.15

Table 7.13 Weights for Porous pavement based on AHP-GRA

Pairwise Comparison							
Factors	DA (acre)	DS (%)	HSG	RB (ft)	SB (ft)	BB (ft)	IS (ft)
DA (acre)	1.00	3.00	5.00	8.00	8.00	8.00	3.00
DS (%)	0.33	1.00	5.00	8.00	8.00	8.00	3.00
HSG	0.20	0.20	1.00	7.00	7.00	7.00	0.20
RB (ft)	0.13	0.13	0.14	1.00	3.00	3.00	0.20
SB (ft)	0.13	0.13	0.33	6.00	1.00	3.00	0.20
BB (ft)	0.13	0.13	0.33	0.33	0.33	1.00	0.20
IS (%)	0.33	0.33	5.00	5.00	5.00	5.00	1.00
Total	2.24	4.91	16.81	35.33	32.33	35.00	7.80
Normalization							
DA	0.45	0.61	0.30	0.23	0.25	0.23	0.38
DS	0.15	0.20	0.30	0.23	0.25	0.23	0.38
HSG	0.09	0.04	0.06	0.20	0.22	0.20	0.03
RB	0.06	0.03	0.01	0.03	0.09	0.09	0.03
SB	0.06	0.03	0.02	0.17	0.03	0.09	0.03
BB	0.06	0.03	0.02	0.01	0.01	0.03	0.03
IS	0.15	0.07	0.30	0.14	0.15	0.14	0.13
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CR=-0.87<0.1 (pairwise comparison is acceptable)							
Reference sequence							
DA	0.00	0.11	0.16	0.21	0.21	0.21	0.11
DS	0.14	0.00	0.21	0.26	0.26	0.26	0.14
HSG	1.59	1.59	0.00	1.93	1.93	1.93	1.59
RB	0.38	0.38	0.35	0.00	0.20	0.20	0.29
SB	0.52	0.52	0.28	0.45	0.00	0.28	0.40
BB	0.23	0.23	0.12	0.12	0.12	0.00	0.18
IS	0.26	0.26	0.38	0.38	0.38	0.38	0.00
Total	1.59	1.59	0.38	1.93	1.93	1.93	1.59
Grey Rational Coefficient							
DA	0.49	0.54	1.00	0.39	0.39	0.39	0.48
DS	0.43	0.44	1.00	0.39	0.39	0.39	0.48
HSG	0.42	0.41	0.81	0.39	0.39	0.39	0.41
RB	0.42	0.41	0.78	0.36	0.37	0.37	0.41
SB	0.42	0.41	0.79	0.38	0.36	0.37	0.41
BB	0.42	0.41	0.79	0.36	0.36	0.36	0.41
IS	0.43	0.42	1.00	0.38	0.38	0.38	0.43
Total	0.49	0.54	1.00	0.39	0.39	0.39	0.48
Integrated land use suitability evaluation value							
	S1	S2	S3	S4	S5	S6	S7
Weights	0.16	0.15	0.14	0.13	0.13	0.14	0.15

Table 7.14 Weights for Wet pond based on AHP-GRA

Pairwise Comparison							
Factors	DA (acre)	DS (%)	HSG	RB (ft)	SB (ft)	BB (ft)	IS (ft)
DA (acre)	1.00	3.00	5.00	8.00	7.00	8.00	3.00

DS (%)	0.33	1.00	5.00	8.00	0.20	8.00	0.20
HSG	0.20	0.20	1.00	8.00	0.14	8.00	0.14
RB (ft)	0.13	0.13	0.13	1.00	0.17	3.00	0.14
SB (ft)	0.14	5.00	7.00	6.00	1.00	8.00	0.20
BB (ft)	0.13	0.13	0.13	0.33	0.13	1.00	0.17
IS (%)	0.33	5.00	7.00	7.00	5.00	6.00	1.00
Total	2.26	14.45	25.25	38.33	13.63	42.00	4.85
Normalization							
DA	0.44	0.21	0.20	0.21	0.51	0.19	0.62
DS	0.15	0.07	0.20	0.21	0.01	0.19	0.04
HSG	0.09	0.01	0.04	0.21	0.01	0.19	0.03
RB	0.06	0.01	0.00	0.03	0.01	0.07	0.03
SB	0.06	0.35	0.28	0.16	0.07	0.19	0.04
BB	0.06	0.01	0.00	0.01	0.01	0.02	0.03
IS	0.15	0.35	0.28	0.18	0.37	0.14	0.21
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CR=-0.87<0.1 (pairwise comparison is acceptable)							
Reference sequence							
DA	0.00	0.11	0.16	0.21	0.20	0.21	0.11
DS	0.76	0.00	1.11	1.43	1.11	1.43	1.11
HSG	0.55	0.55	0.00	0.70	0.66	0.70	0.66
RB	0.23	0.23	0.23	0.00	0.20	0.12	0.22
SB	0.50	0.42	0.50	0.46	0.00	0.54	0.42
BB	0.19	0.19	0.19	0.10	0.19	0.00	0.16
IS	0.14	0.21	0.25	0.25	0.21	0.23	0.00
Total	0.76	0.55	1.11	1.43	1.11	1.43	1.11
Grey Rational Coefficient							
DA	0.89	0.87	0.56	0.47	0.70	0.47	0.76
DS	0.69	0.77	0.56	0.47	0.50	0.47	0.51
HSG	0.66	0.73	0.51	0.47	0.50	0.47	0.51
RB	0.64	0.73	0.50	0.43	0.50	0.44	0.51
SB	0.65	1.00	0.59	0.46	0.52	0.47	0.51
BB	0.64	0.73	0.50	0.43	0.50	0.43	0.51
IS	0.69	1.00	0.59	0.46	0.63	0.46	0.56
Total	0.89	0.87	0.56	0.47	0.70	0.47	0.76
Integrated land use suitability evaluation value							
	S1	S2	S3	S4	S5	S6	S7
Weights	0.18	0.14	0.13	0.13	0.14	0.13	0.15

Table 7.15 Weights for Dry pond based on AHP-GRA

Pairwise Comparison							
Factors	DA (acre)	DS (%)	HSG	RB (ft)	SB (ft)	BB (ft)	IS (ft)
DA (acre)	1.00	3.00	5.00	8.00	7.00	8.00	3.00
DS (%)	0.33	1.00	5.00	8.00	4.00	8.00	0.20
HSG	0.20	0.20	1.00	8.00	0.17	8.00	0.14
RB (ft)	0.13	0.13	0.13	1.00	0.17	3.00	0.14
SB (ft)	0.14	0.25	6.00	6.00	1.00	8.00	0.20
BB (ft)	0.13	0.13	0.33	0.33	0.13	1.00	0.17
IS (%)	0.33	5.00	7.00	7.00	5.00	6.00	1.00
Total	2.26	9.70	24.46	38.33	17.46	42.00	4.85
Normalization							

DA	0.44	0.31	0.20	0.21	0.40	0.19	0.62
DS	0.15	0.10	0.20	0.21	0.23	0.19	0.04
HSG	0.09	0.02	0.04	0.21	0.01	0.19	0.03
RB	0.06	0.01	0.01	0.03	0.01	0.07	0.03
SB	0.06	0.03	0.25	0.16	0.06	0.19	0.04
BB	0.06	0.01	0.01	0.01	0.01	0.02	0.03
IS	0.15	0.52	0.29	0.18	0.29	0.14	0.21
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CR=-0.87<0.1 (pairwise comparison is acceptable)							
Reference sequence							
DA	0.00	0.11	0.16	0.21	0.20	0.21	0.11
DS	0.25	0.00	0.36	0.47	0.31	0.47	0.36
HSG	0.58	0.58	0.00	0.74	0.64	0.74	0.70
RB	0.23	0.23	0.23	0.00	0.20	0.12	0.22
SB	2.70	1.92	2.48	2.48	0.00	2.88	2.23
BB	0.20	0.20	0.11	0.11	0.20	0.00	0.18
IS	0.14	0.21	0.25	0.25	0.21	0.23	0.00
Total	2.70	1.92	2.48	2.48	0.64	2.88	2.23
Grey Rational Coefficient							
DA	0.45	0.55	0.45	0.45	1.00	0.40	0.55
DS	0.42	0.51	0.45	0.45	0.91	0.40	0.46
HSG	0.41	0.50	0.43	0.45	0.81	0.40	0.46
RB	0.41	0.50	0.43	0.43	0.81	0.39	0.46
SB	0.41	0.50	0.45	0.44	0.83	0.40	0.46
BB	0.41	0.50	0.43	0.43	0.81	0.39	0.46
IS	0.42	0.59	0.46	0.45	0.94	0.40	0.48
Total	0.45	0.55	0.45	0.45	1.00	0.40	0.55
Integrated land use suitability evaluation value							
	S1	S2	S3	S4	S5	S6	S7
Weights	0.16	0.14	0.14	0.14	0.14	0.13	0.15

d) GIS-based suitability analysis using Weighted Overlay method

➢ **Data creation for each LID-BMPs**

Before performance the suitability analysis of LID-BMPs with the aid of Weighted Overlay in GIS, the creation of layers for each criterion in LID-BMPs at 1m resolution, which is high resolution for further analysis, is important for carrying out the suitability analysis in this research.

As shown in **Table 7.5**, the creation of the layers based on some criteria in LID-BMPs are created as follows:

- Drainage area, which refers to Hydrological Sensitive Areas (HSAs), a source of runoff, is created and expressed in **Fig.7.2**.
- Creation of drainage slope is conducted on a basis of mean slope in each HSAs as shown in **Fig.7.3**.

● In each HSAs, hydrological soil groups are made based on the mean saturated hydraulic conductivity of sub soil's first layer, as shown in **Fig.7.4**. Most of the hydrological soil groups in HSAs belongs to the soil texture class of sand.

● To reflect on the actual condition and accordance with the impervious cover ratios for PPC, Google Earth is used for defining roads, stream, as well as building buffers. Roads layers obtained from the open source, stream, and buildings on the HSAs with time slider to 2015 are manually traced. Each layer is determined as shown in **Fig.7.5, 7.6**, and **Fig.7.7**, respectively. Impervious cover is prepared based on the impervious cover ratios defined in **Chapter 6** as shown in **Fig.7.8**.

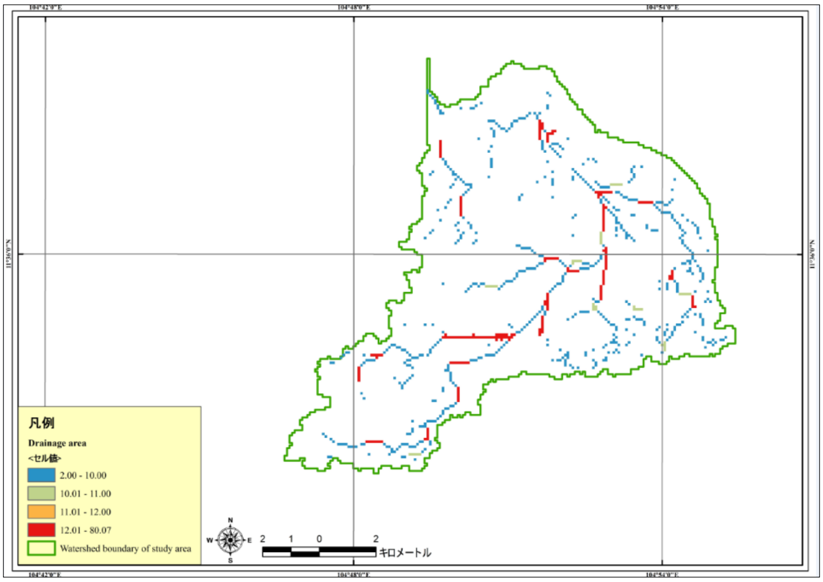


Fig.7.2 Drainage area

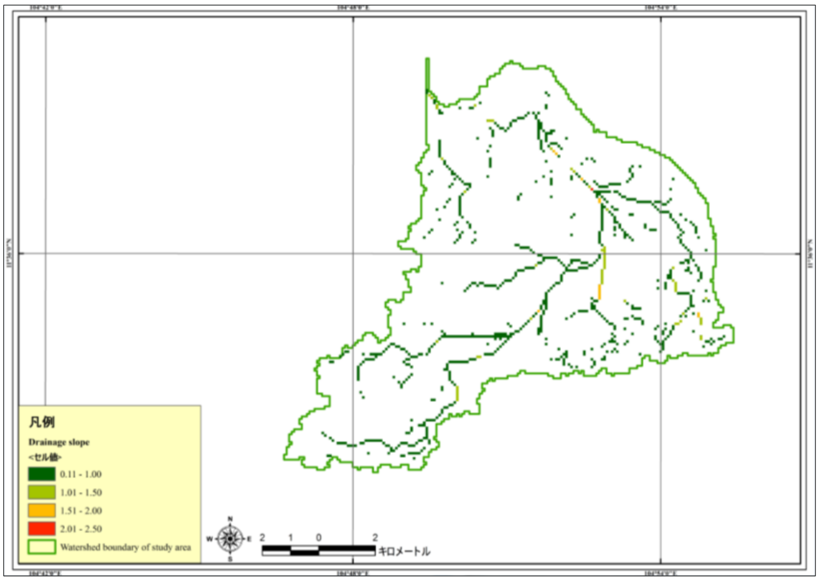


Fig.7.3 Drainage slope

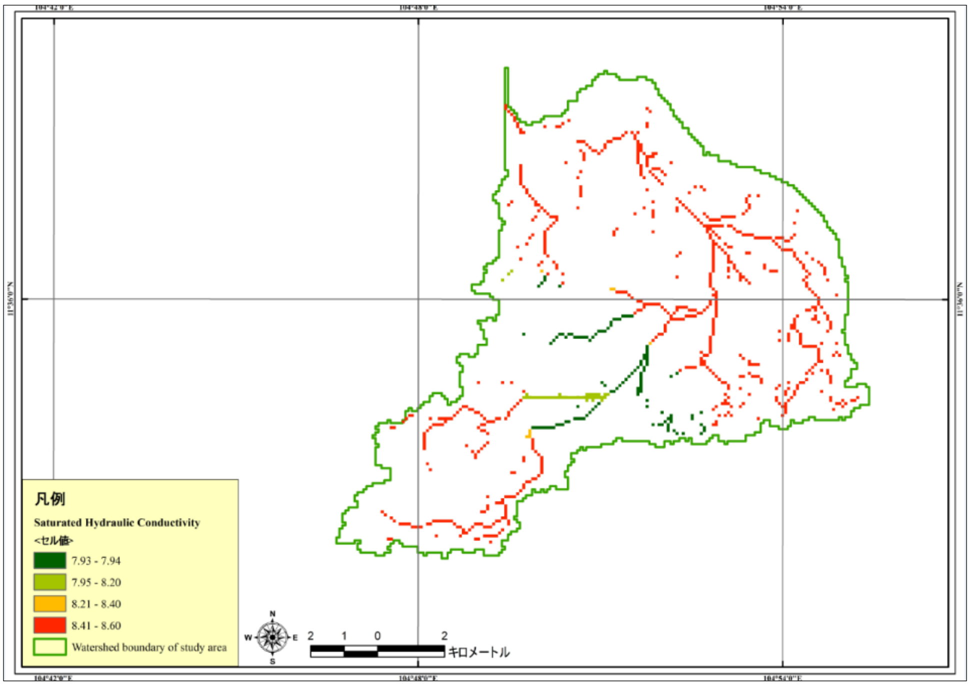


Fig.7.4 Hydrological soil groups

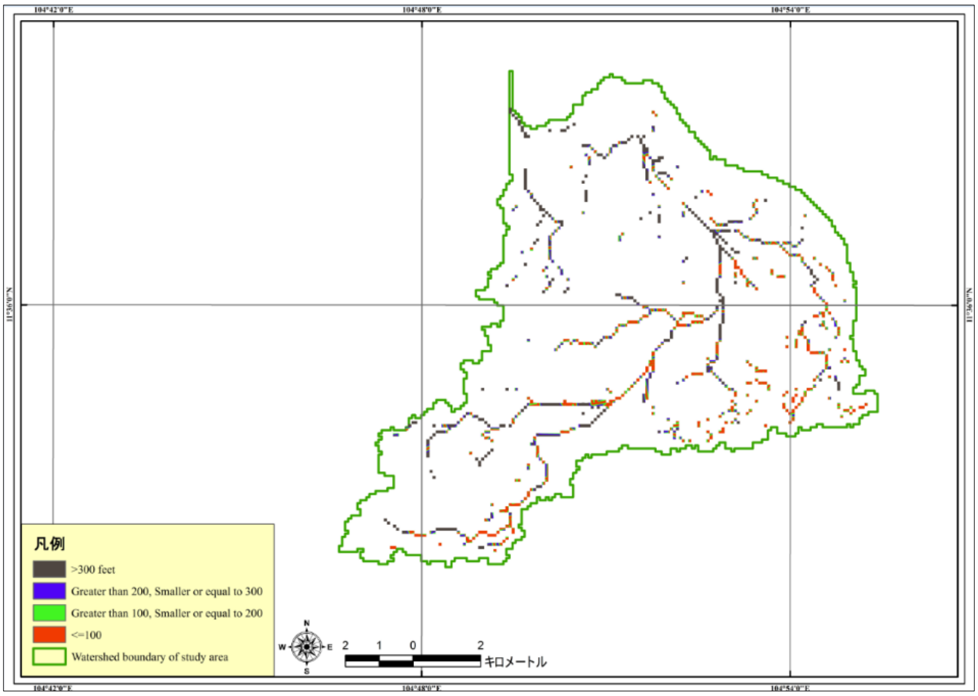


Fig.7.5 Road buffers

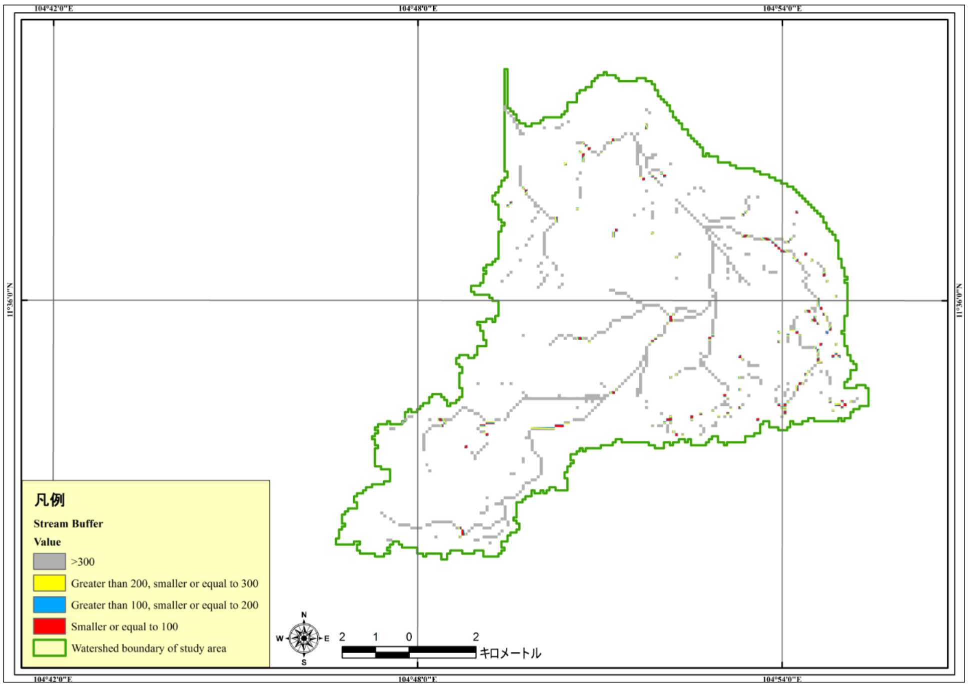


Fig.7.6 Stream buffers

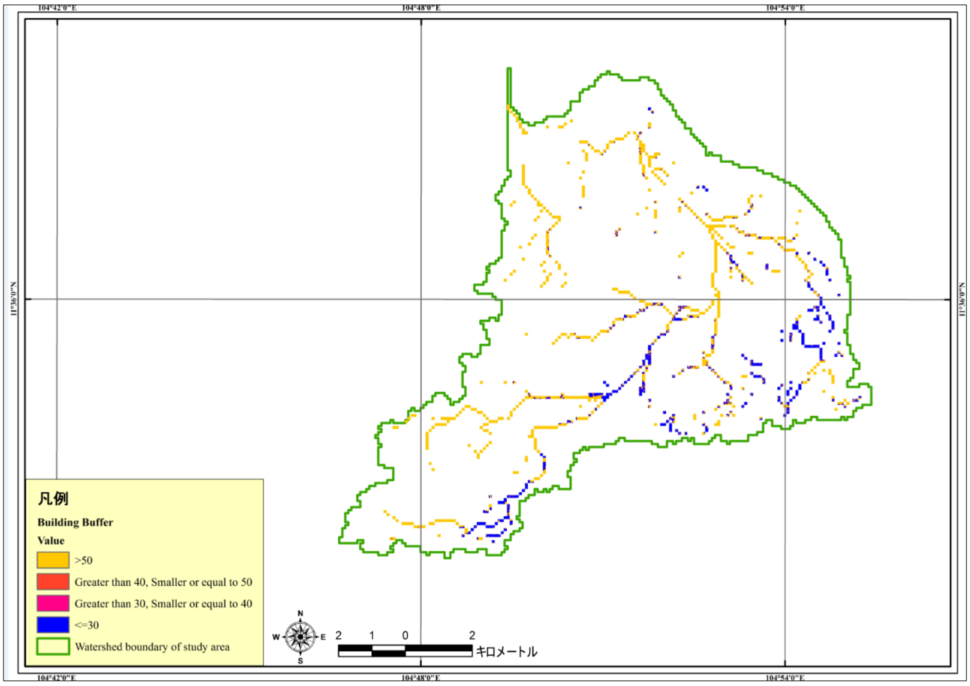


Fig.7.7 Building buffers

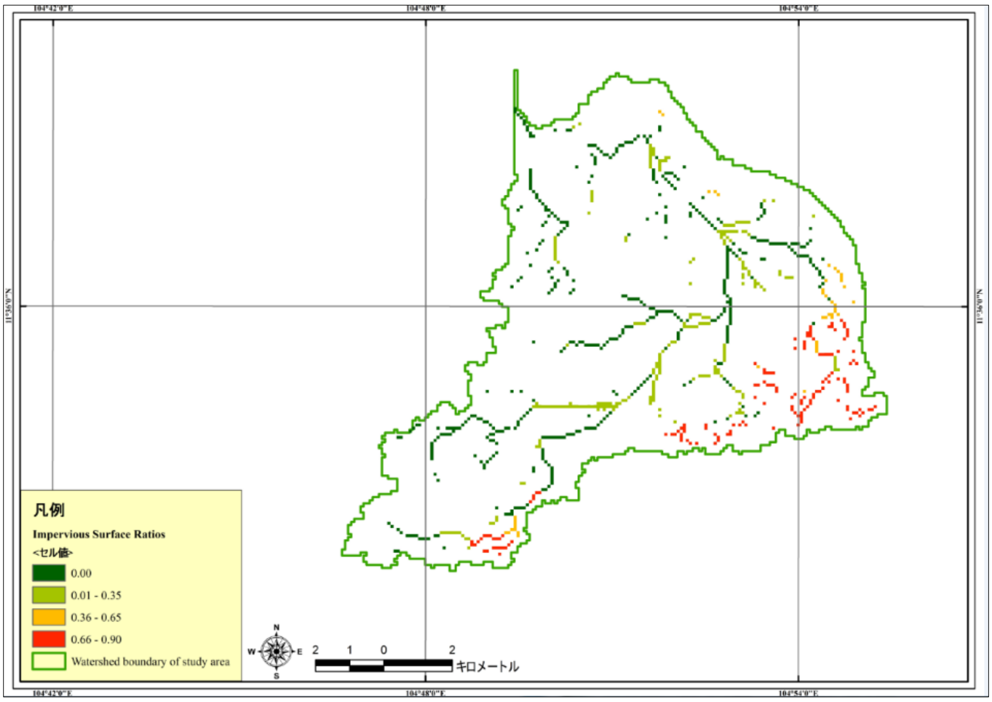


Fig.7.8 Impervious cover

- **Results of GIS-based suitability analysis using Weighted Overlay method**

Suitability analysis of this research is based on 4 conditions ranged from the worst condition to the best condition as 1=Not Suitable, 2=Moderate Suitable, 3=Suitable and 4=Highly Suitable.

By using the weights defined in **c)** and **d)** in **section 7.2.2** with the aid of Weighted Overlay analysis method in ArcGIS 10.2 platform, a so-called GIS-based multi-criteria assessment modeling using AHP-GRA method with the modification of reference sequence is performed in this research.

Suitability maps of LID-BMPs including a Green roof, Rain barrel, Grass swale, Bioretention, Porous pavement, Dry pond, and Wet pond can be identified as shown in **Fig.7.9**, **Fig.7.10**, **Fig.7.11**, **Fig.7.12**, **Fig.7.13**, **Fig.7.14**, and **Fig.7.15**, respectively**.**

According to the results of suitability maps defined in this research and the actual condition of land use in HSAs, planners can choose and allocate the appropriate design measure types of LID-BMPs to the areas where the developments have taken place.

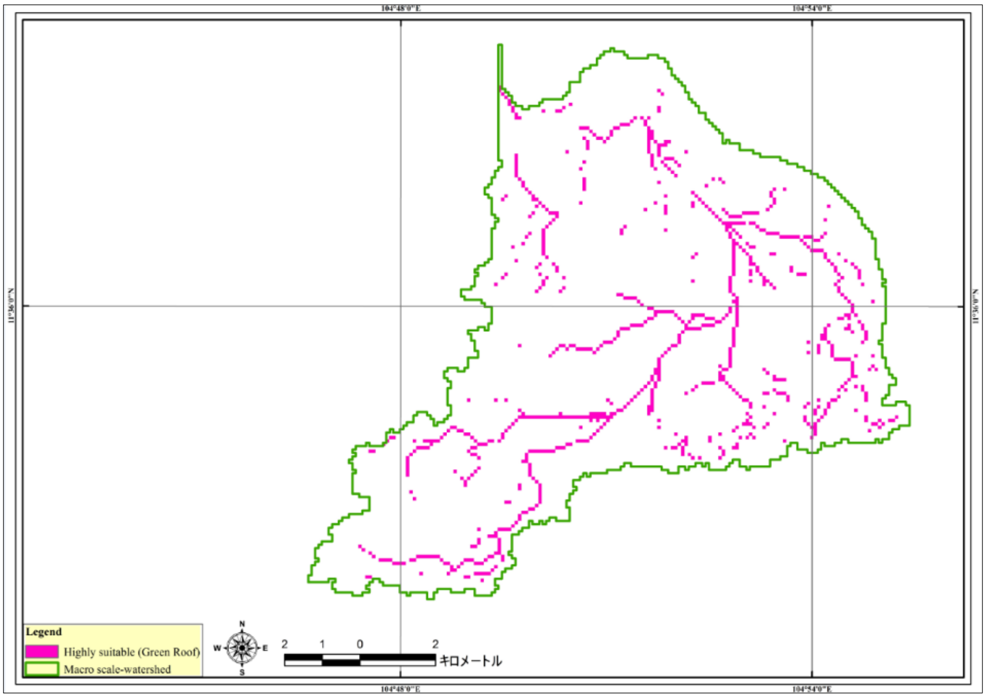


Fig.7.9 Suitability map of Green roof

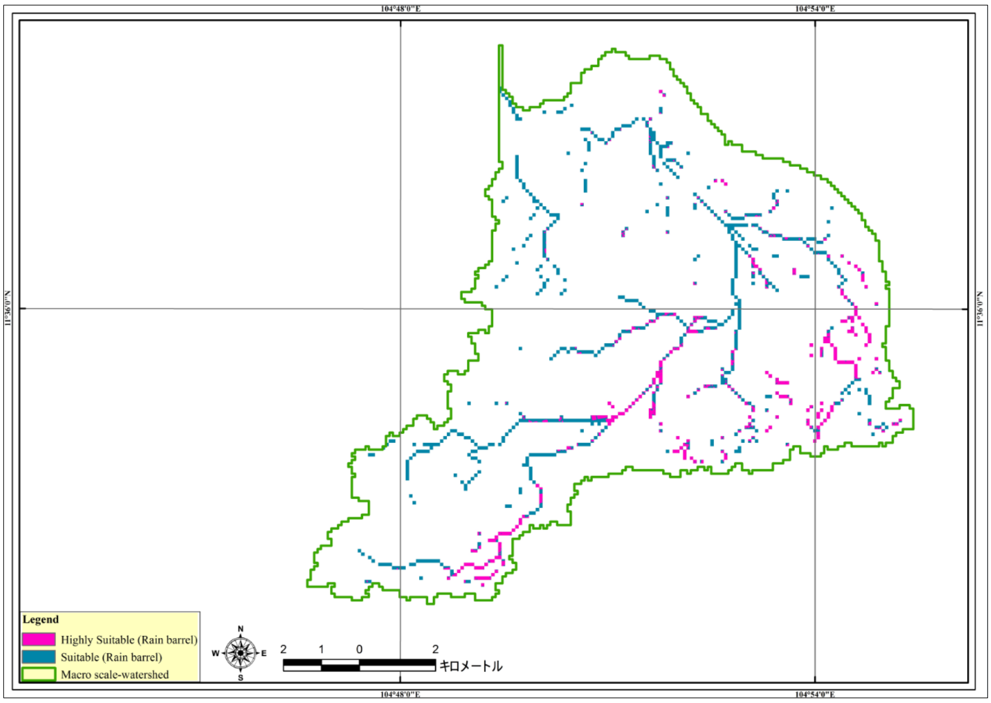


Fig.7.10 Suitability map of Rain barrel

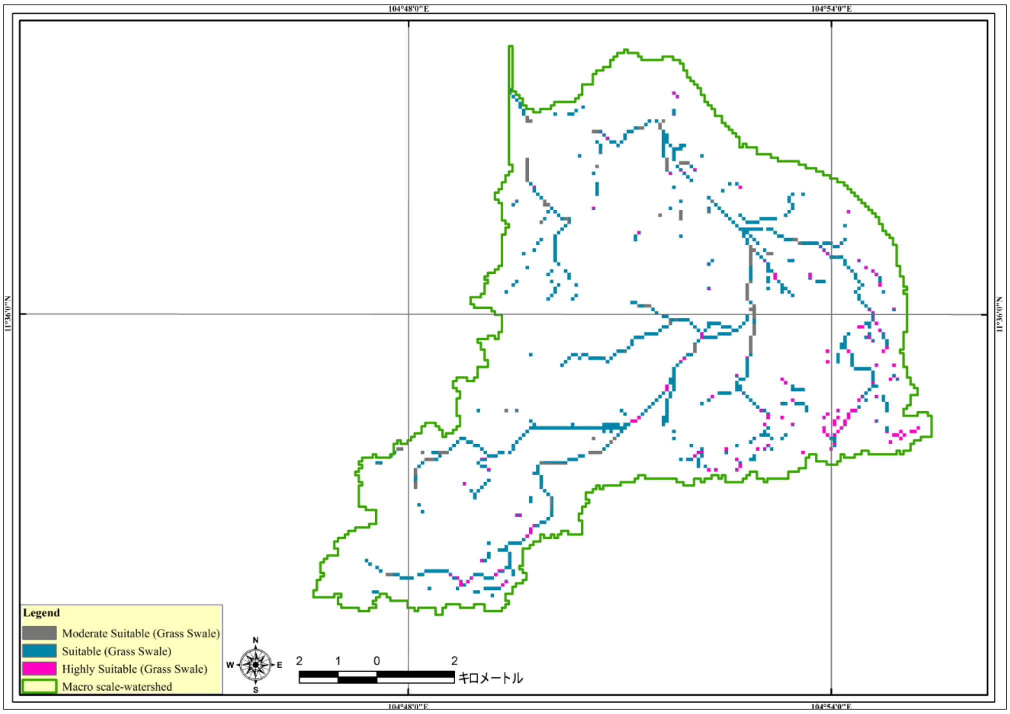


Fig.7.11 Suitability map of Grass swale

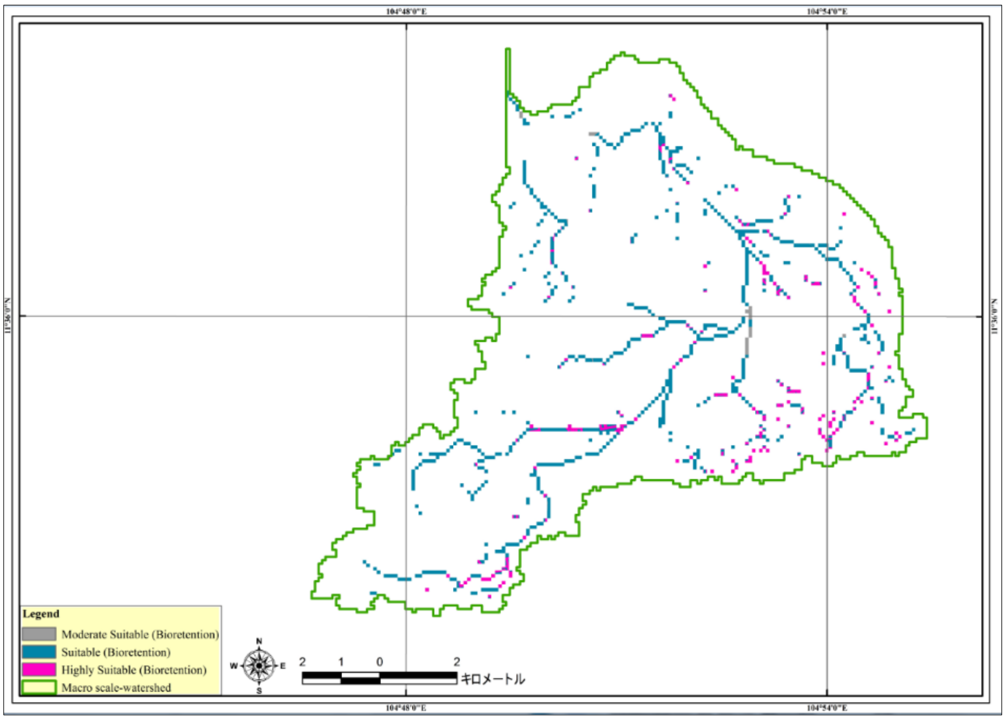


Fig.7.12 Suitability map of Bioretention

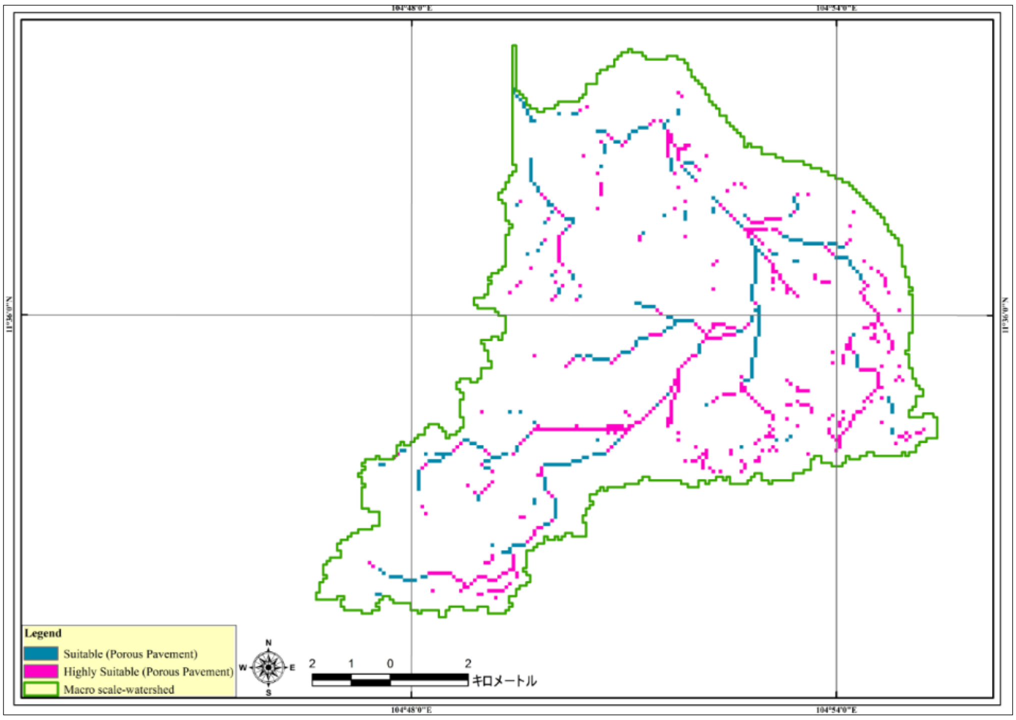


Fig.7.13 Suitability map of Porous pavement

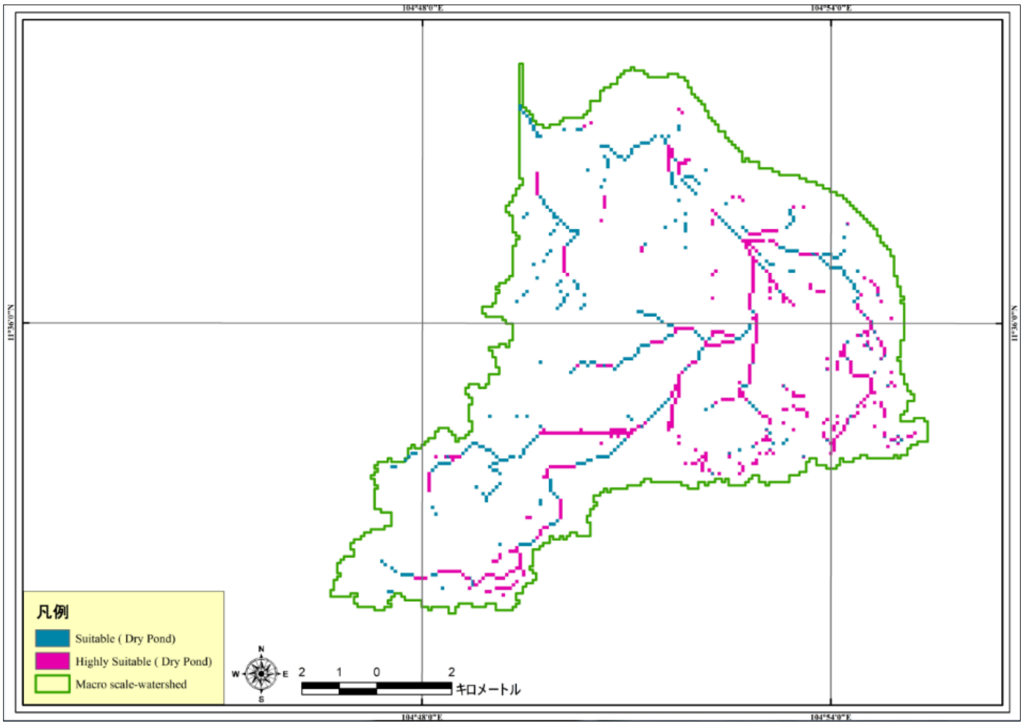


Fig.7.14 Suitability map of Dry pond

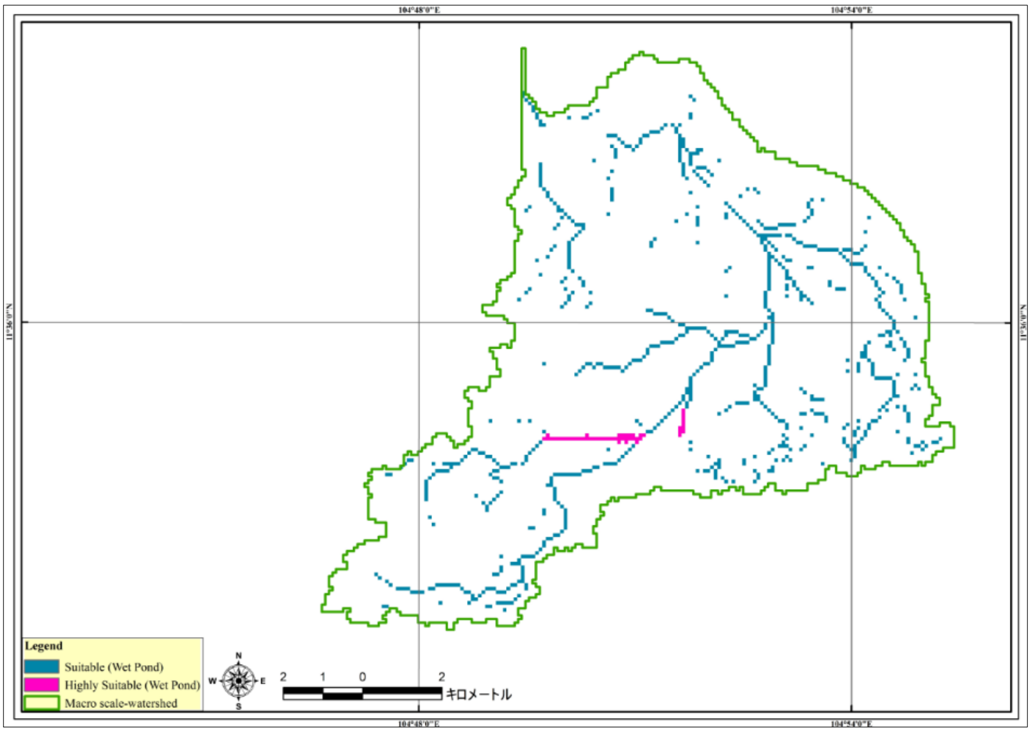


Fig.7.15 Suitability map of Wet pond

7.3 Case study at micro scale

7.3.1 Summary of case study

Firstly, research method concerning about the site survey including scale and condition of site selection, and the flowchart of the methodology used in the case area are explained. Secondly, suitability matrix of HSAs based on LID-BMPs suggesting in terms of the current situation is illustrated. Adjustment of zoning indicators, HSAs in the form of grids, based on existing conditions for finalizing suitability maps in the case study is performed.

7.3.2 Site survey

a) Flowchart of methodology

The flowchart of the methodology for the overall flow in this case study is presented in **Fig.7.16**.

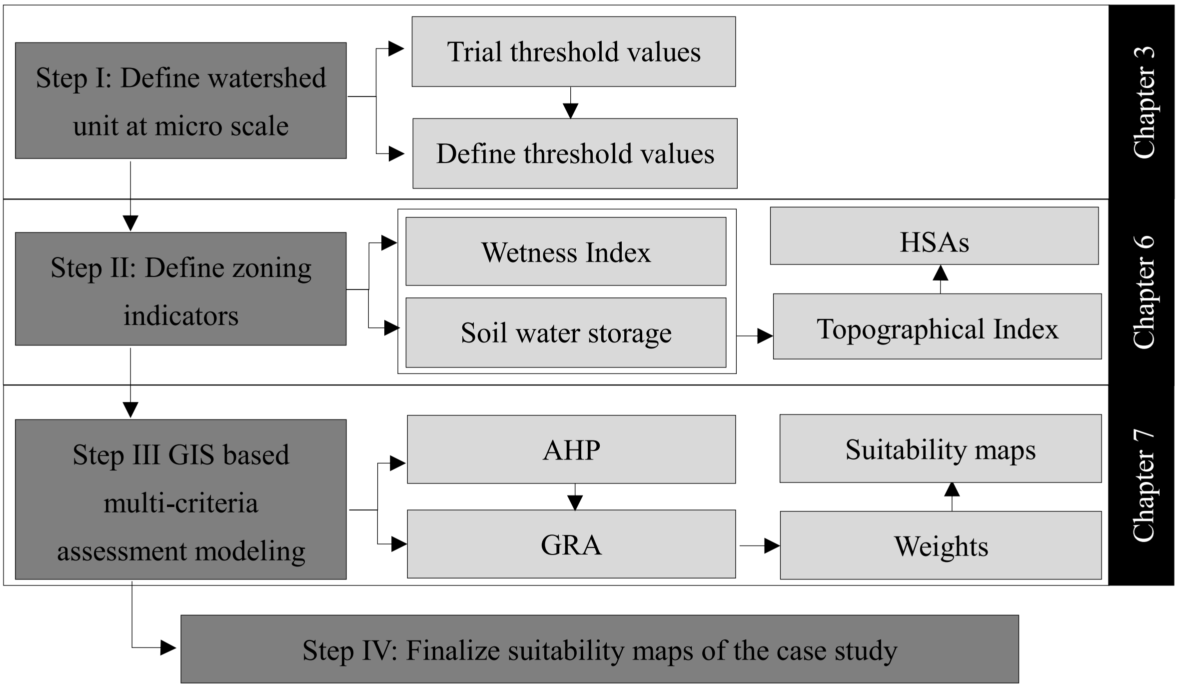


Fig.7.16 Flowchart of the methodology used in the case study

b) Site selection

Selection of site for the case study is focused on areas, where were used to suffer from flooding or the area sensitive to flood events based on a user-friendly interface showing the estimated flood events and flood records[26)].

As an area used to suffer from flooding events, as shown in **Fig.7.17**, it's selected as the study area in this case study. Subsequently, watershed analysis with threshold definition of 1 km^2 known as micro scale in this research is delineated for this case study. In general, the watershed boundary defined at micro scale is one catchment identified at middle scale as shown in **Fig.7.18**.

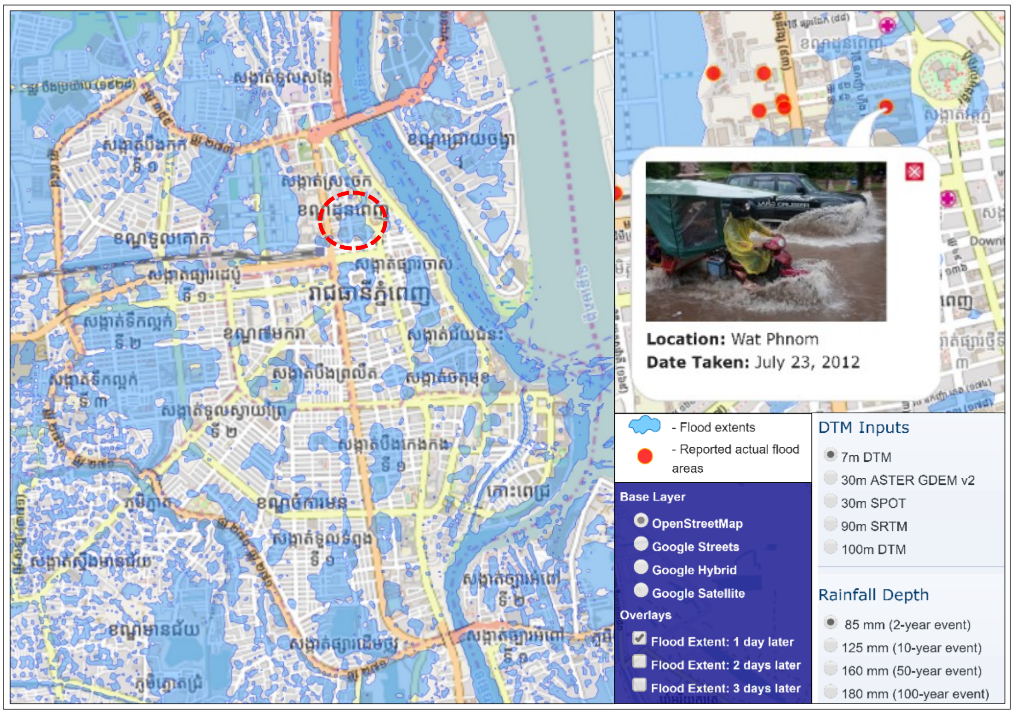


Fig.7.17 Flooding simulation in core zone of PPC[26)]

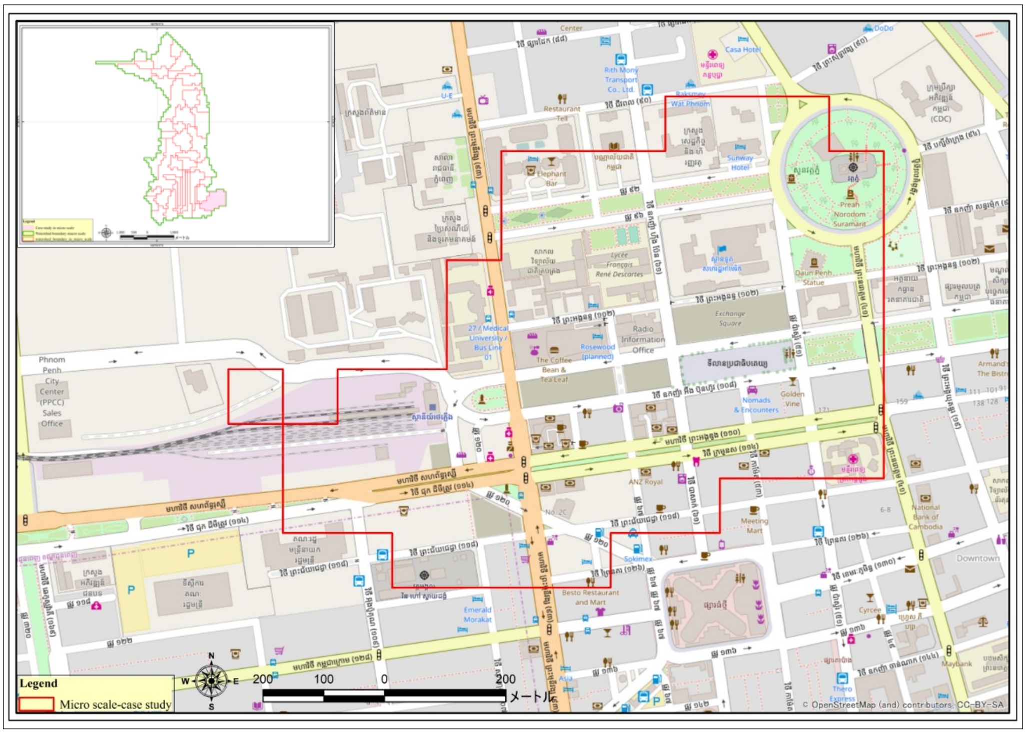


Fig.7.18 Study area

Northern of the study area, along with the main boulevards, is composed of many restaurants, embassy, hotels, public hospitals, which directs to the bridge across the river. The Southern part is close to the central market while the eastern part is along the riverside, and the western part is nearby the lake reclamation, Boeung Kak area, and governmental offices including City Hall of PPC, the Ministry of Posts and Telecommunications, the Ministry of Information, and Ministry of National defense, etc. In brief, both of some described areas and part of the areas in the study area had been created since the beginning of the formation of the city.

In addition, in recent year, a remarkable transformation of land use served as banks, department stores, hotels, and restaurants etc. are taken place everywhere surrounding and within the study area, these transformations are a symbol for the progressive development of the city. Under these circumstances, to achieve long-term vision of land use planning in the city, it's essential that zoning and design code should be considered in terms of the planning of urban flooding mitigation as well as prevention. By these reasons, a case study is selected to discuss about the better planning for current and future from a watershed-based planning perspective.

c) Land use characteristics in the study area

To discuss about planning in the case study, grasping characteristics of land use from the actual condition is very important. Overview of land use in the study area as shown in **Fig.7.19** is created manually based on the open street map and site survey conducted on 24th, 25th, and 28th January 2017 by the author. Whereas the details of building used in the commercial and service areas are extracted one by one based on the Google Earth with images based on the year of 2014. Characteristic of the most building use types mainly in the first floor is commercial and service areas, which are summarized and exported as shown in **Fig.7.20**.

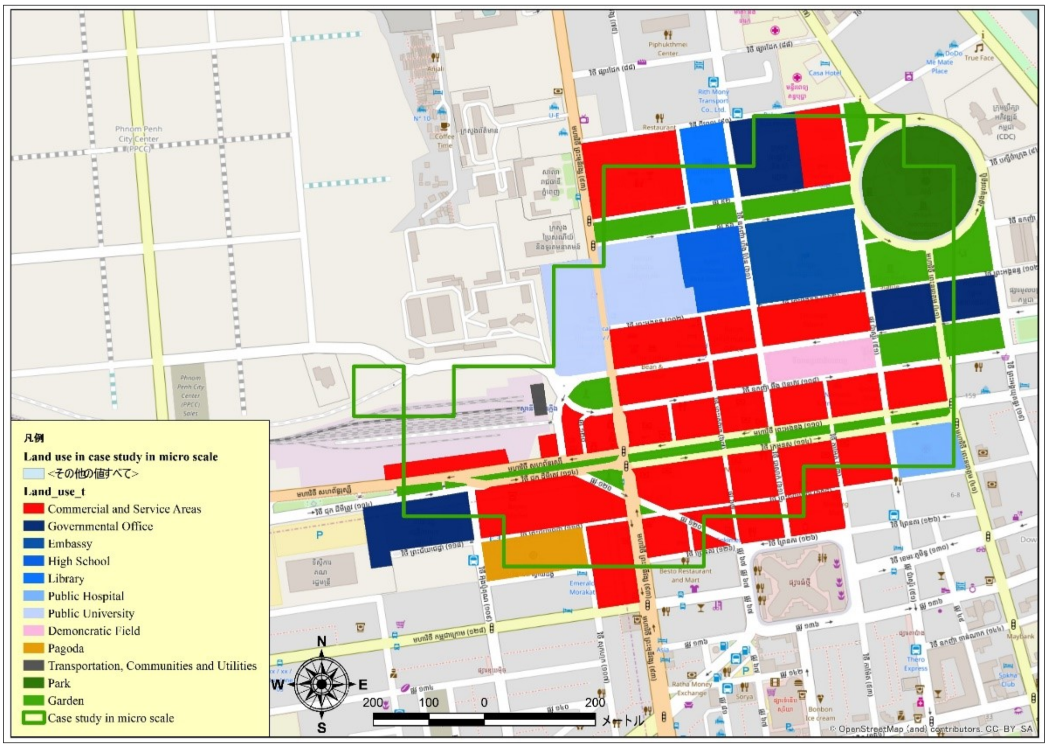


Fig.7.19 Land use in the study area

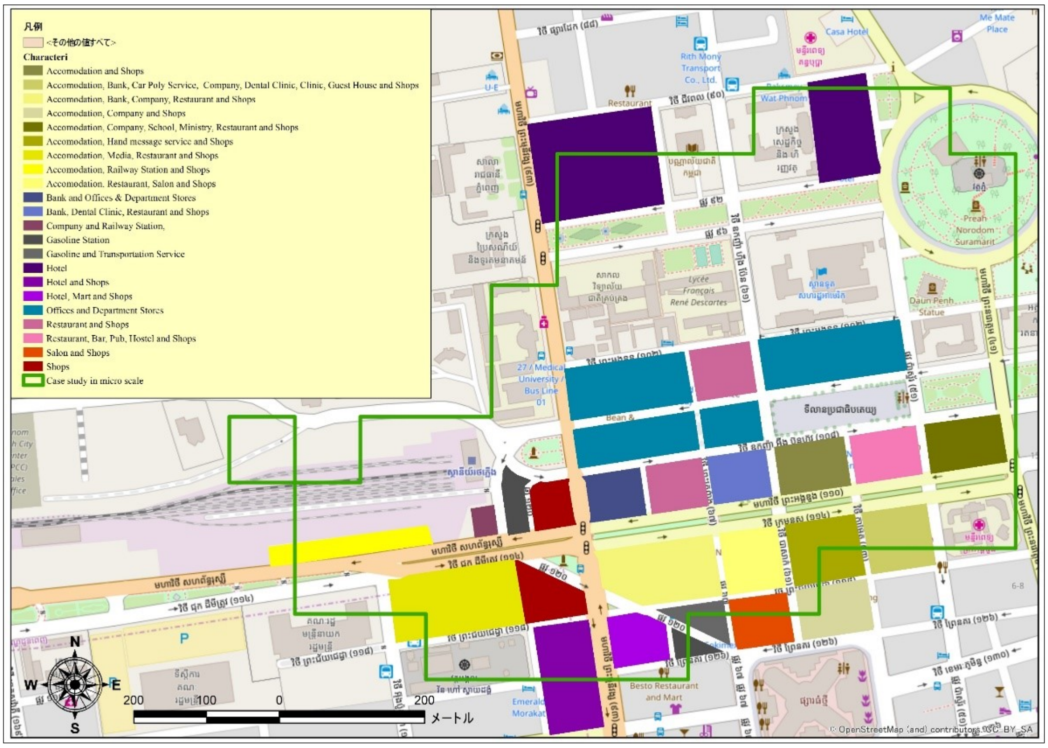


Fig.7.20 Characteristics of Land use in commercial and service area

7.3.3 Suitability maps for case study

a) Characteristic of land use based on HSAs

To propose adequate design measures for the current development, a site survey is essentially carried out to comprehend and reflect on the current situation of land use in the HSAs. While HSAs are defined following step II as presented in **Fig.7.16**, the result of HSAs is shown in **Fig.7.21**.

With locations and observed directions of some examples in HSAs are denoted as black triangles, demonstration of these examples is from the West, top to bottom, to the East of the study area as presented in **Fig.7.22**, **Fig.7.23**, **Fig.7.24**, **Fig.7.25**, **Fig.7.26**, and **Fig.7.27**, respectively.

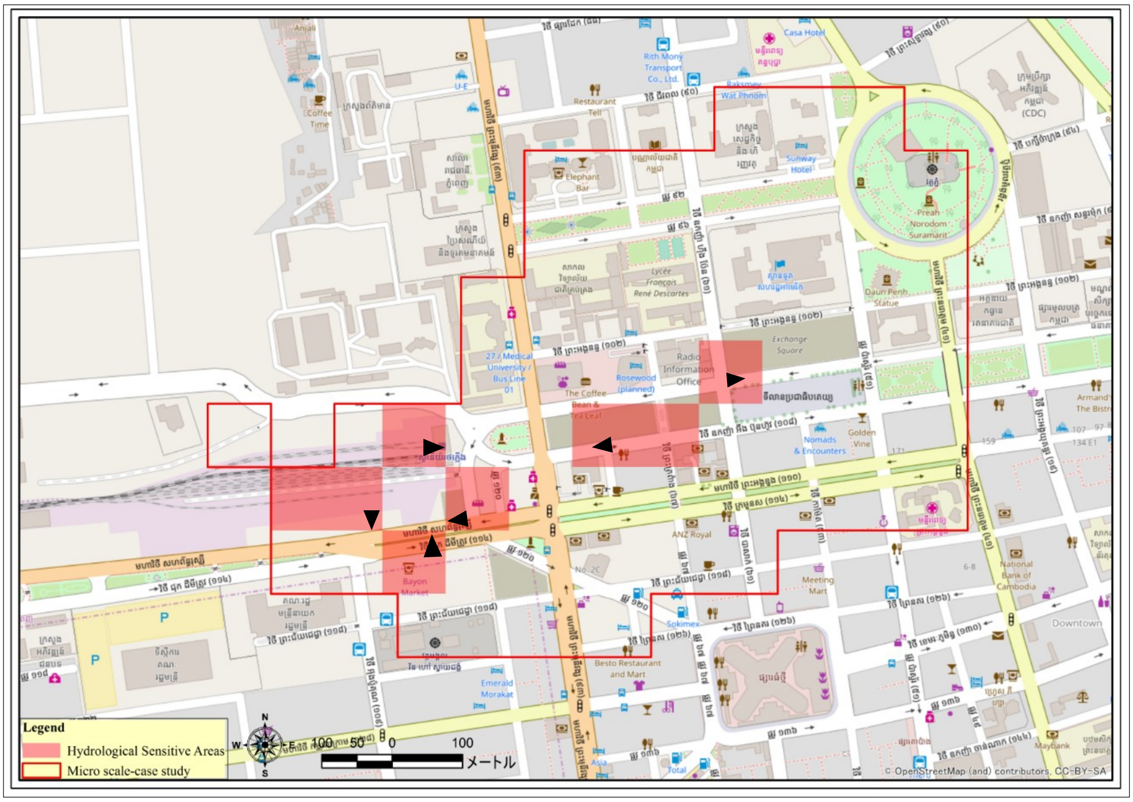


Fig.7.21 Hydrological Sensitive Areas (HSAs) of the study area

Fig.7.22 HSAs (land inside and outside of the railway station)

Fig.7.23 HSAs (land on the rail, right side)

Fig.7.24 HSAs (road and building)

Fig.7.25 HSAs (gasoline station and buildings in front of it, left side)

Fig.7.26 HSAs (road, construction site, and building along the road)

Fig.7.27 HSAs (road, under construction building, and the field along the road)

b) Design measures based on LID-BMPs

7 types of design measures in Low Impact Development-Best Management Practices (LID-BMPs) are used for better design measures applied to the Hydrological Sensitive Areas (HSAs). By following the step I to IV of the flowchart as presented in **Fig.7.16**, these 7 types of suitability maps based on LID-BMPs are expressed in **Fig.7.28**, **Fig.7.29**, **Fig.7.30**, **Fig.7.31**, **Fig.7.32**, **Fig.7.33**, and **Fig.7.34**.

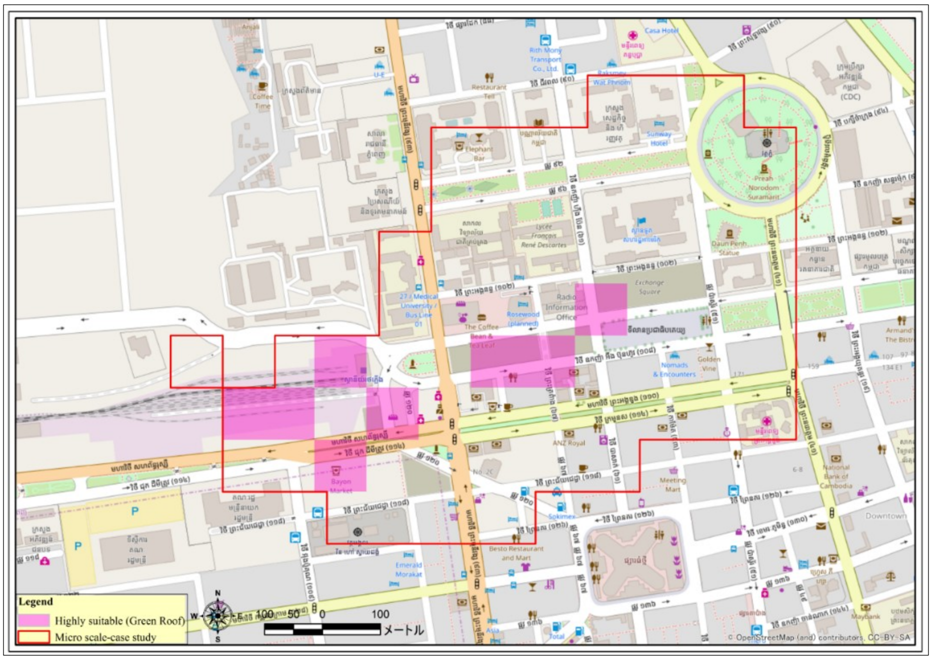


Fig.7.28 Suitability map of Green roof

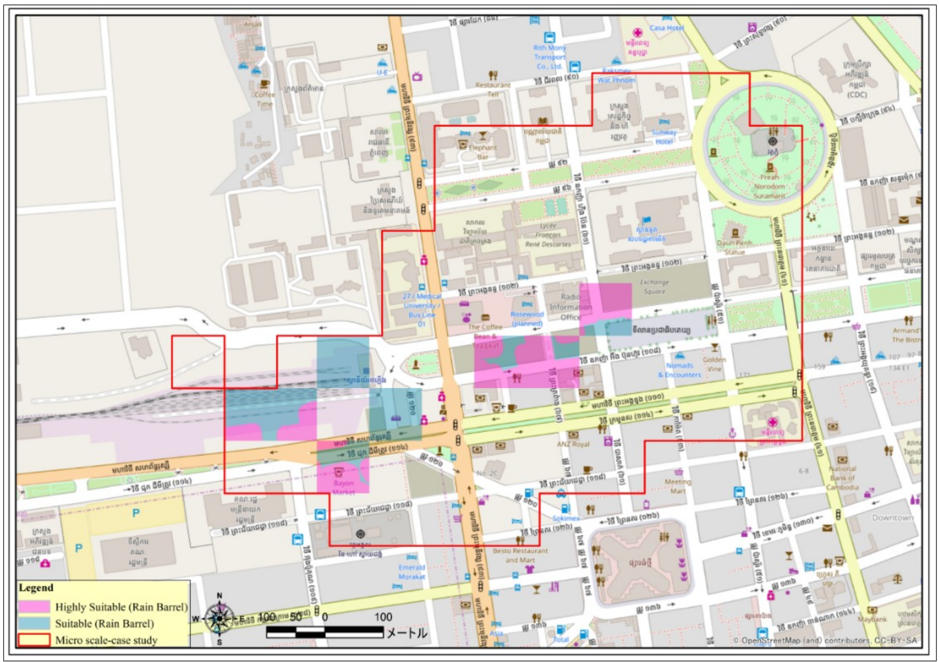


Fig.7.29 Suitability map of Rain barrel

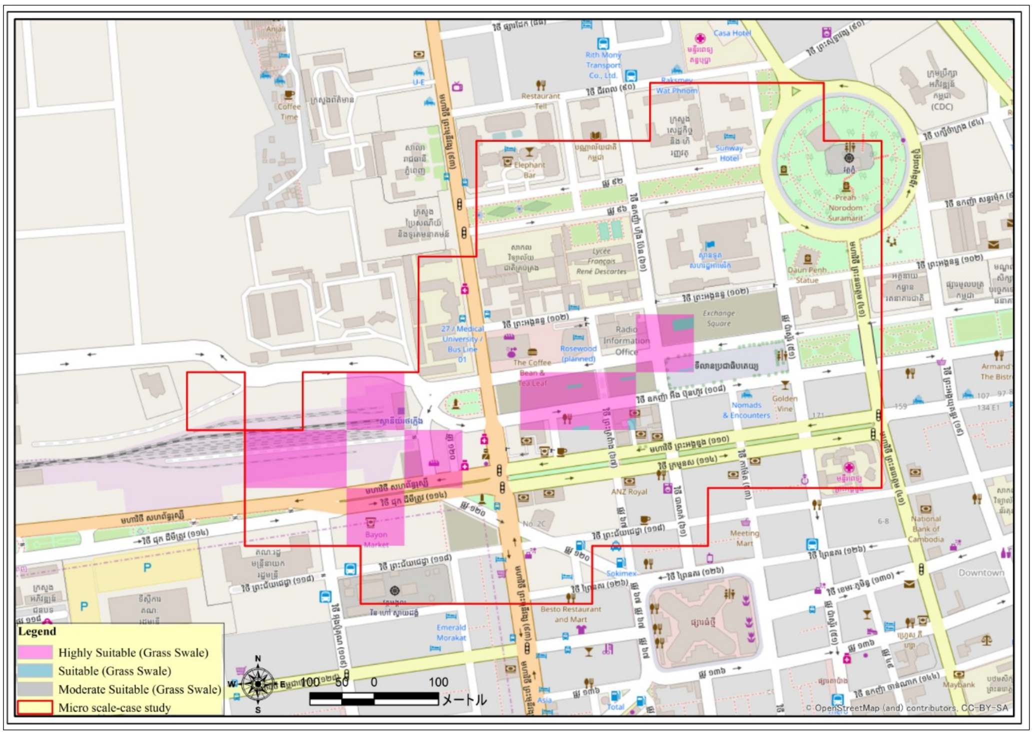


Fig.7.30 Suitability map of Grass swale

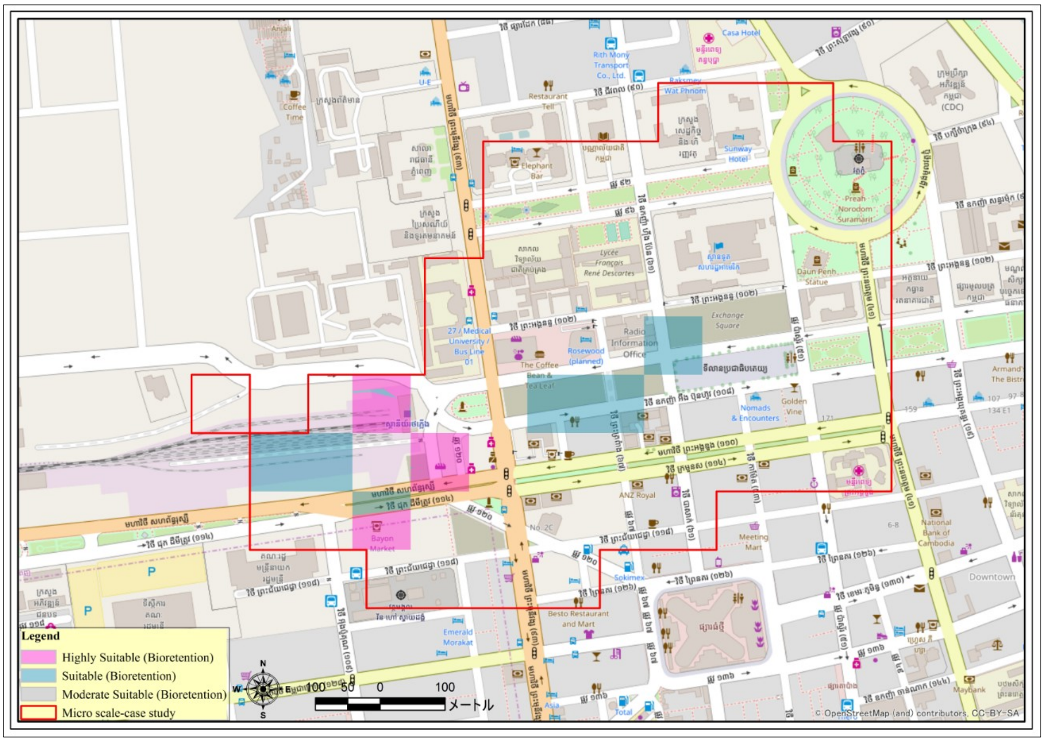


Fig.7.31 Suitability map of Bioretention

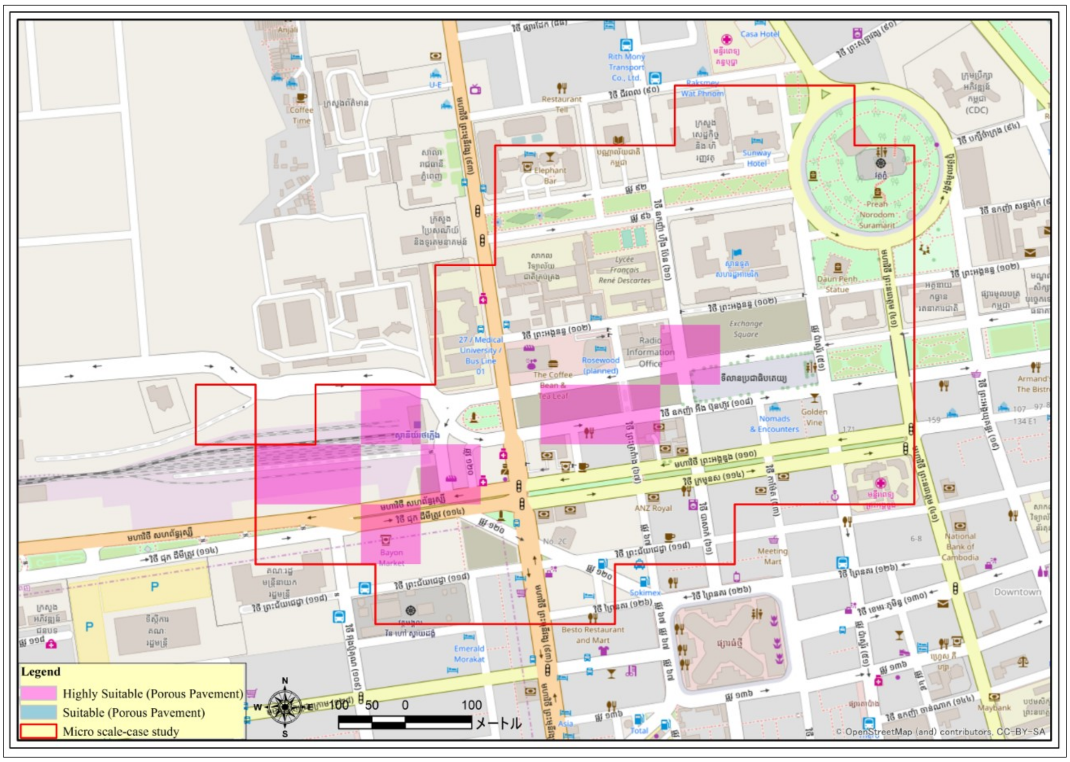


Fig.7.32 Suitability map of Porous pavement

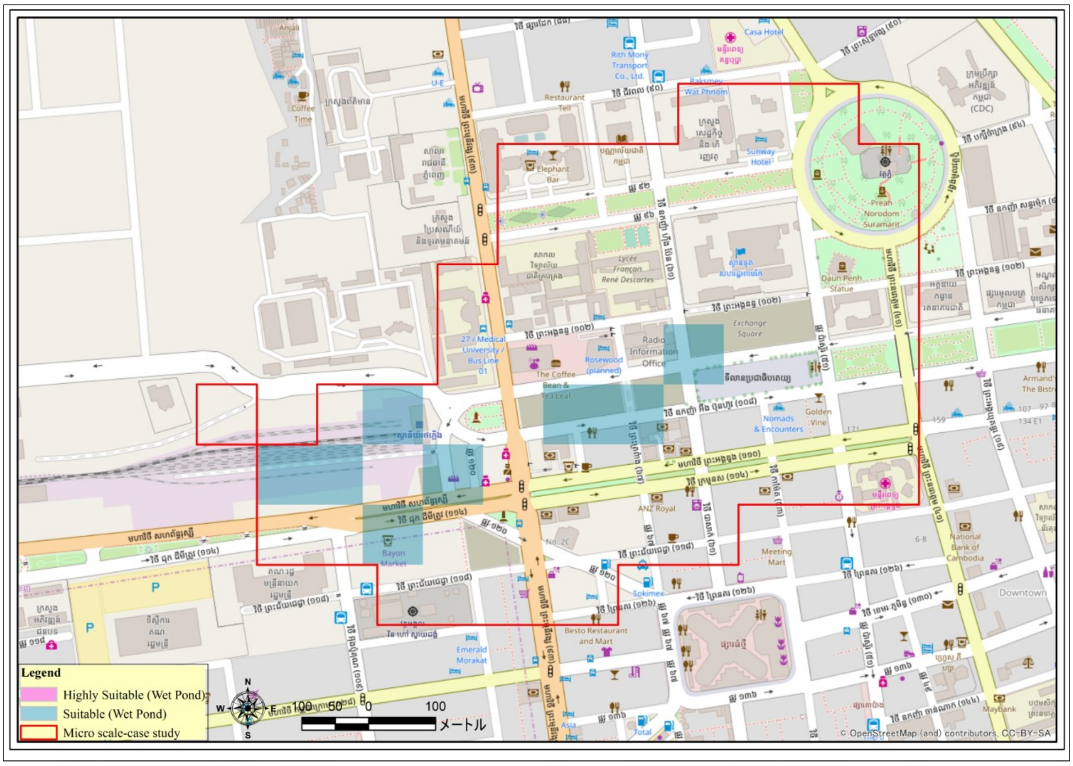


Fig.7.33 Suitability map of Wet pond

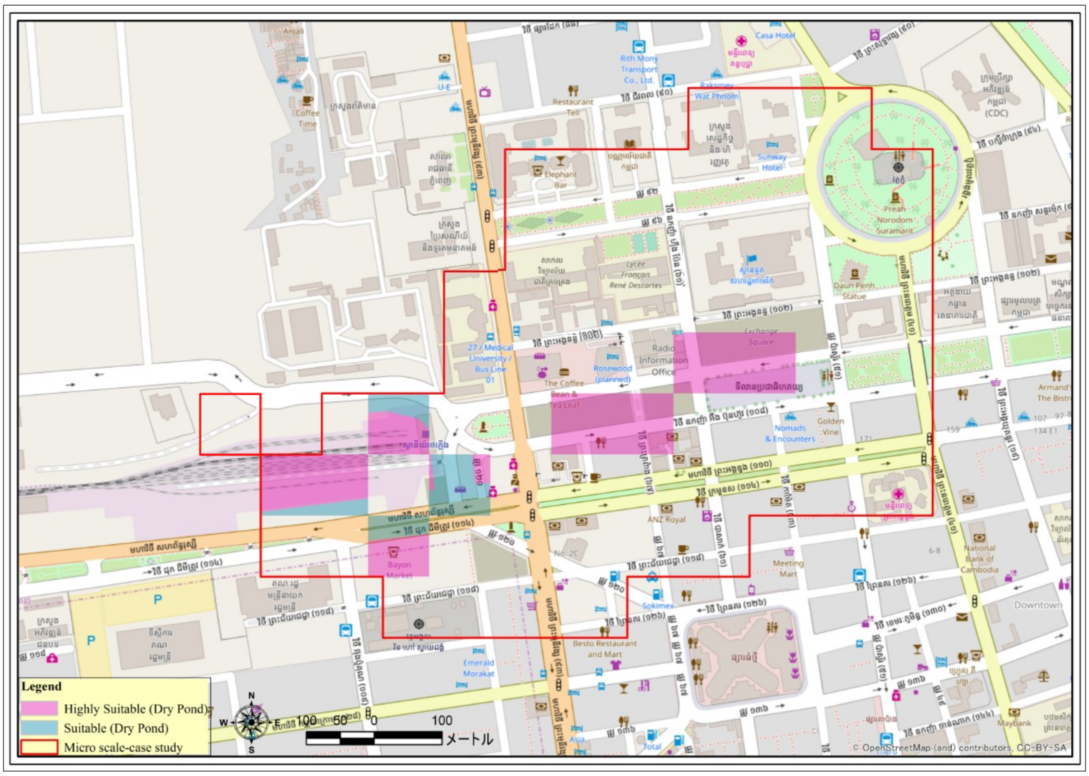


Fig.7.34 Suitability map of Dry pond

This case study considers the priority of suitability of LID-BMPs based on “highly suitable” and “suitable” conditions and applies these design measures to the study area. Based on the main structures of each HSA, suitability matrix of HSAs according to the suitability of LID-BMPs is created responding to the current situation as shown in **Table 7.16** with the circle symbol denoted as possible best design measures and the cross symbol as not appropriate design measures.

Within the study area, two of the most prominent development stages including developed area and ongoing development area exist. Taking account into the proposal of better development design measures, as shown in **Table 7.16**, in terms of any development stages, for example, categorized as developed stage like **Fig.7.24**, the planner can retrofit available spaces by considering installation of Rain barrel or Porous pavement for the improvement of the sidewalk. For retrofitting existing roads, Porous pavement is the only best design measures. In addition, for more variable and attractive site design measures, a combination of many measures proposed above can be well considered. Whereas in the stage categorized as an ongoing development area, as shown in **Fig.7.26**, Porous pavement is the best design measure to be considered for ameliorating the existing road, building, and its sidewalk.

Whereas for a construction site, many alternatives can be considered. Incorporation of Green roof , Rain barrel, Grass swale, Porous pavement, Wet pond, or Dry pond can be incorporated in the early stage of planning.

c) Adjustment of HSAs and finalization of suitability maps for the case study

For safety planning and design, the previously defined zoning indicators known as HSAs in the form of grids are enlarged and adjusted based on the same characteristics of blocks nearby these HSAs. On the basis of the previous HSAs, the finalized map of HSAs is defined and shown in **Fig.7.35**. All 7 types of previously defined suitability maps are finalized based on the actual existing condition as shown in **Fig.7.36**, **Fig.7.37**, **Fig.7.38**, **Fig.7.39**, **Fig.7.40**, **Fig.7.41**, and **Fig.7.42**.

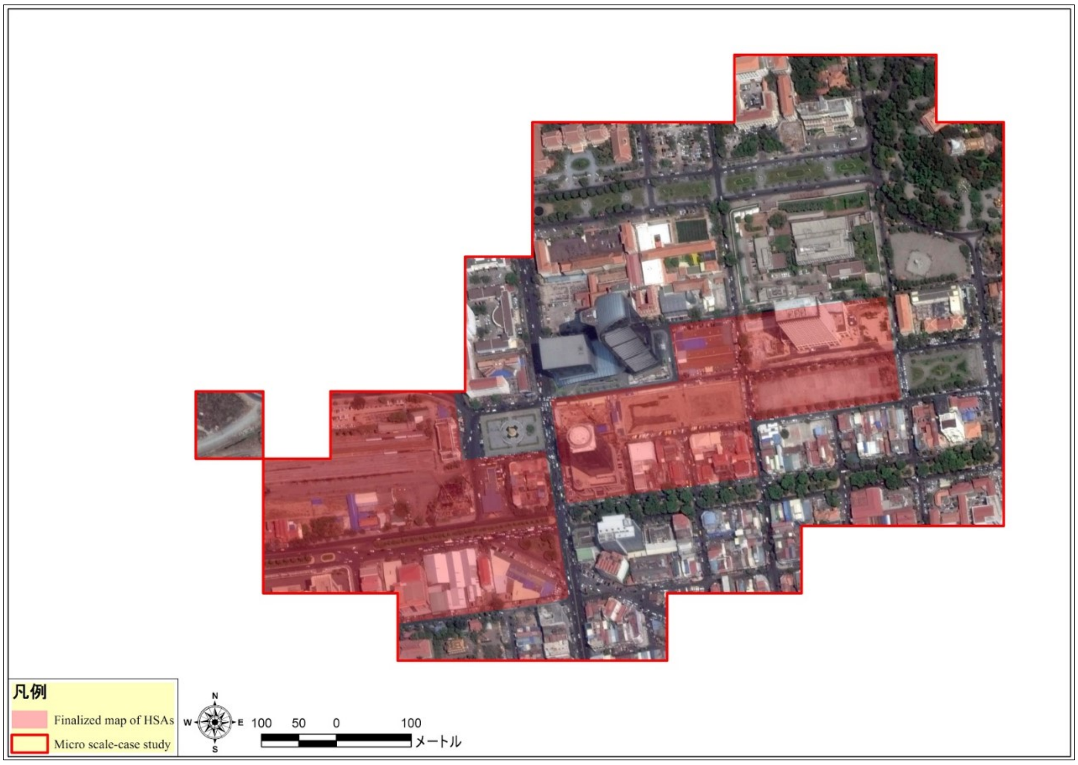


Fig.7.35 Finalized map of HSAs

Table 7.16 Suitability matrix of LID-BMPs based on HSAs suggesting in terms of current situation

HSAs/Measures		Green Building		Vegetation		Infiltration	Retention/Detention	
		Green roof	Rain barrel	Grass swale	Bioretention	Porous Pavement	Wet Pond	Dry Pond
Fig.7.22	Land on the rail	×	×	×	×	×	×	×
	Land beside the rail	×	○	×	×	×	×	○
Fig.7.23	Land on the rail	×	×	×	×	×	×	×
	Land beside the rail	×	×	×	×	×	×	○
Fig.7.24	Road	×	×	×	×	○	×	×
	Building and its sidewalk	×	○	×	×	○	×	×
Fig.7.25	Road	×	×	×	×	○	×	×
	Building and its sidewalk	×	○	×	×	○	×	×
Fig.7.26	Construction site	○	○	○	×	○	○	○
	Road	×	×	×	×	○	×	×
	Building and its sidewalk	×	×	×	×	○	×	×
Fig.7.27	Field	○	×	○	×	○	○	○
	Road	×	×	×	×	○	×	×
	Building and its sidewalk	×	×	○	×	○	×	×

Fig.7.36 Finalized suitability map of Green roof

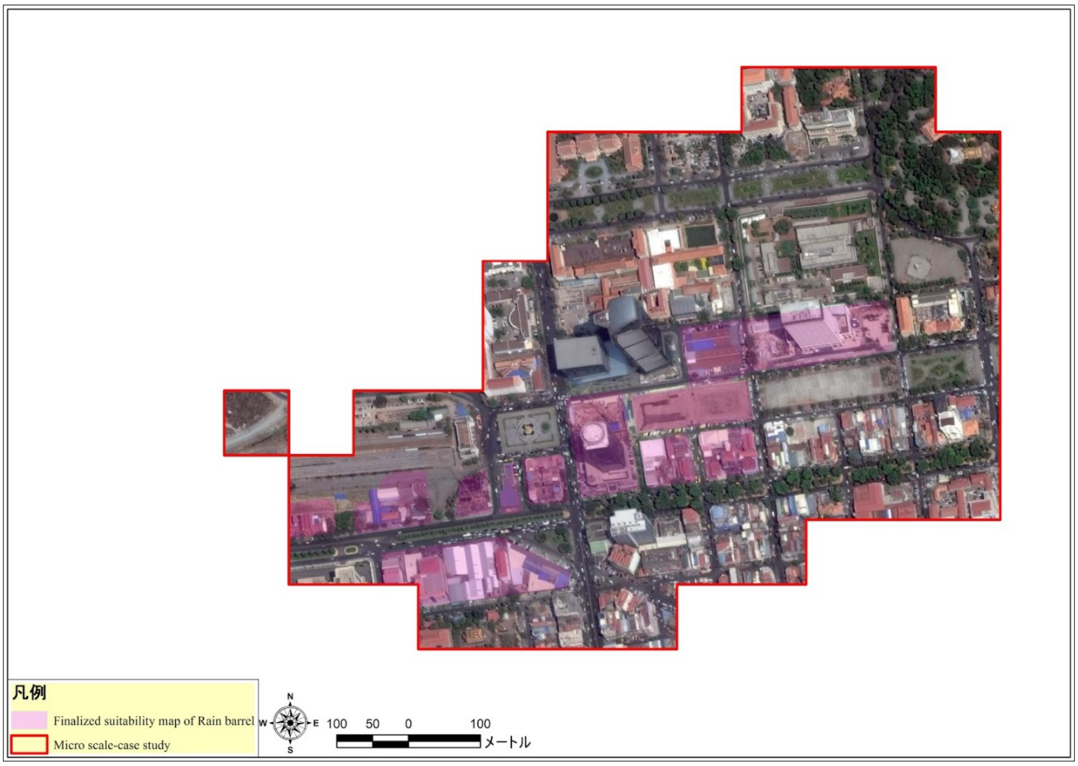


Fig.7.37 Finalized suitability map of Rain barrel

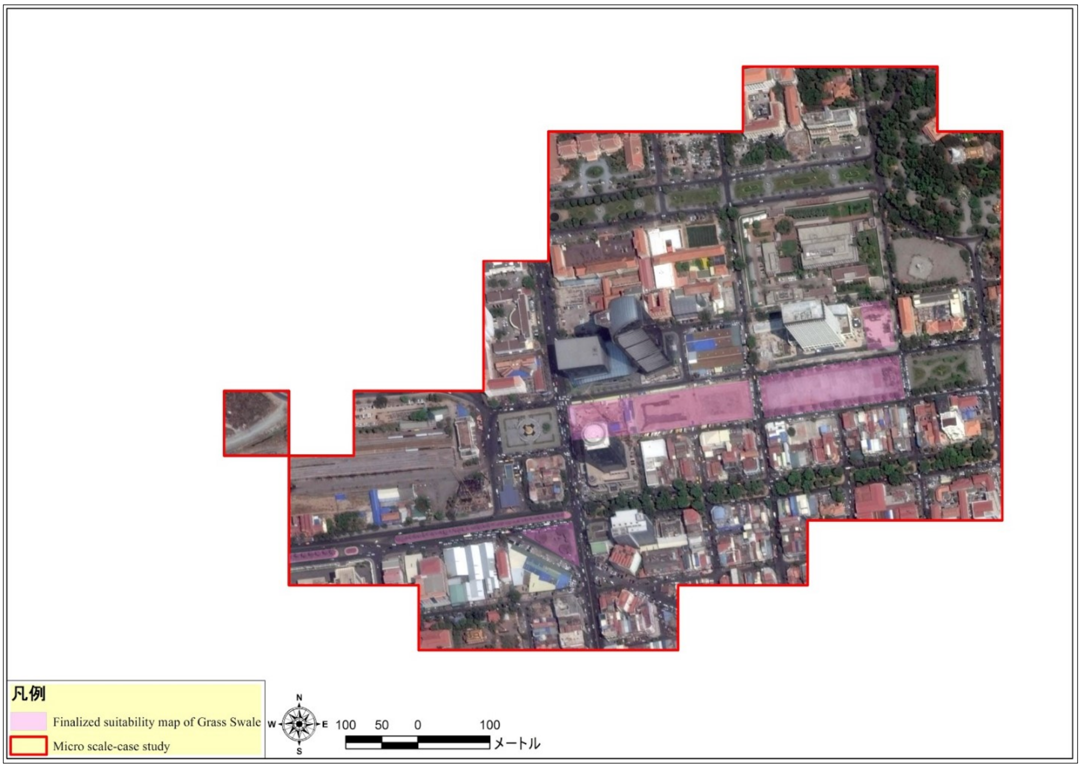


Fig.7.38 Finalized suitability map of Grass swale

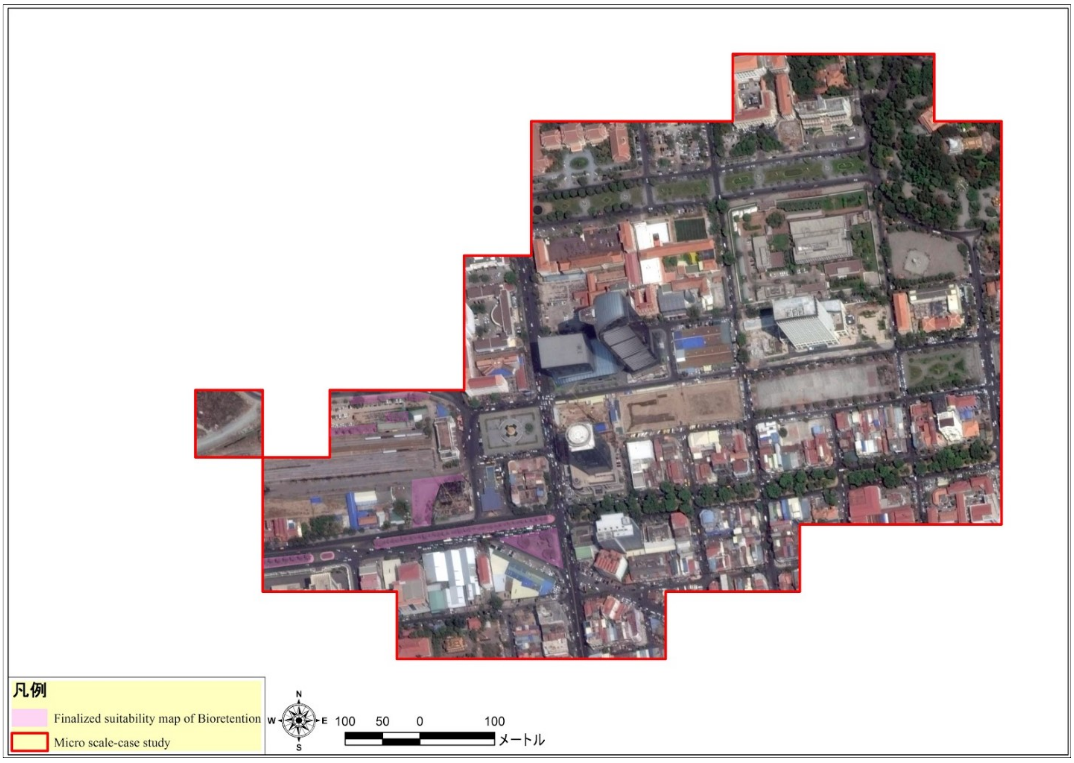


Fig.7.39 Finalized suitability map of Bioretention

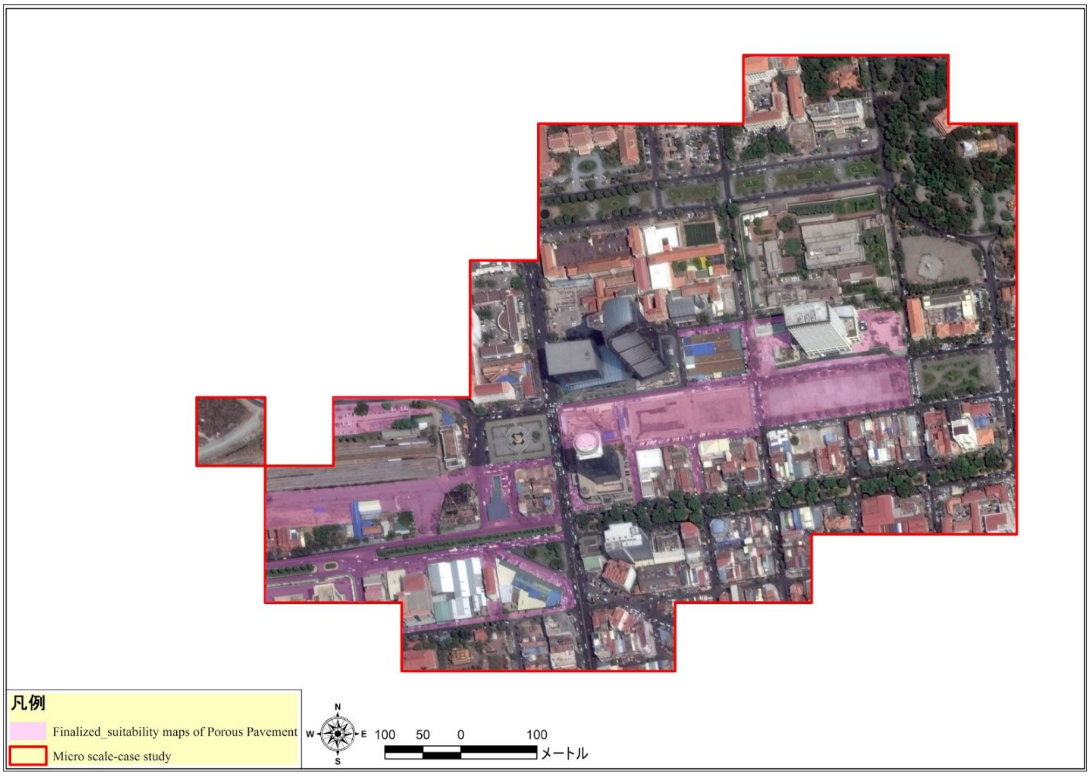


Fig.7.40 Finalized suitability map of Porous pavement

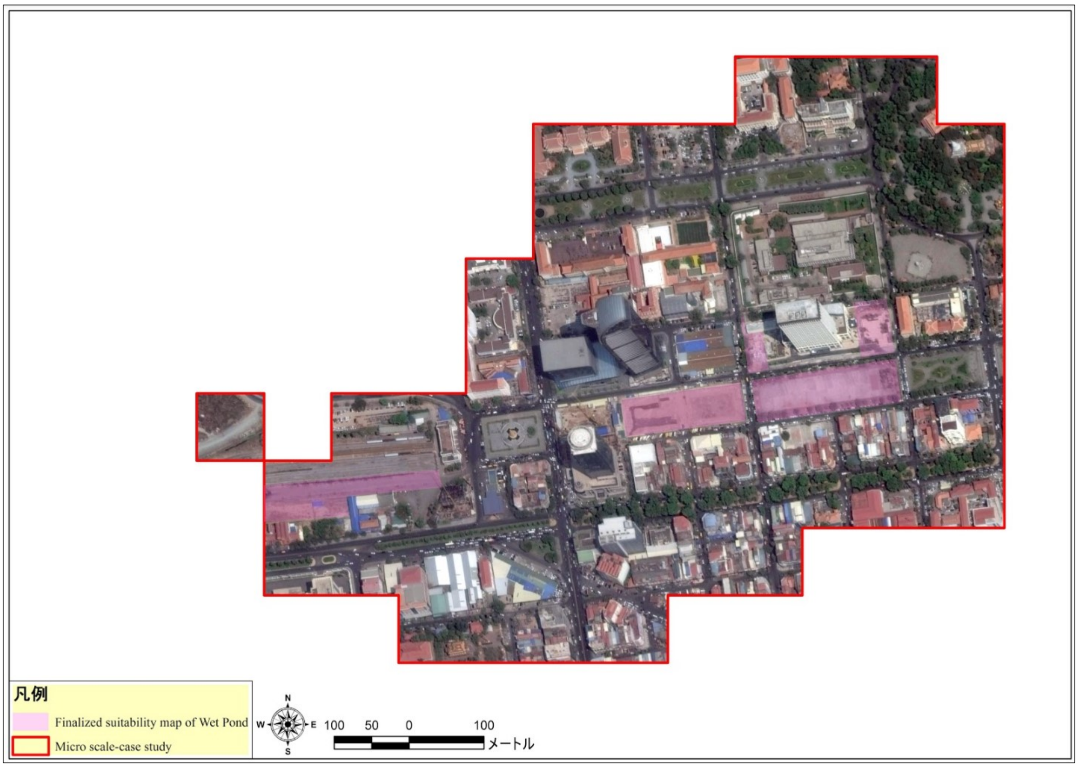


Fig.7.41 Finalized suitability map of Wet pond

Fig.7.42 Finalized suitability map of Dry pond

7.4 Conclusions of chapter

Fundamentally, this chapter shows the concept of design measures known as Low Impact Development-Best Management Practices (LID-BMPs), numerical calculation of weights with the aid of Analytical Hierarchy Process (AHP) integrated into Grey Rational Analysis (GRA) method with the modification of reference sequence for suitability analysis of 7 types' design measures: Green roof, Rain barrel, Grass swale, Bioretention, Porous pavement, Wet pond, and Dry pond for the case study in micro scale.

As the results, 7 types of design measures were firstly defined with zoning indicators named Hydrological Sensitive Areas (HSAs) in the form of grids while examples of suitability matrix for LID-BMPs are suggested based on the actual condition obtained from the site survey. For safety planning and design purpose, the zoning indicators, HSAs, were then adjusted and enlarged to adapt to the current situation. At last, finalized map of HSAs and 7 types of design measures were identified as a case study.

The finalized map of HSAs and suitability maps created by the methodology developed in this research can be used as an index for controlling the development so that high potential of increasing flood risk development area can be avoided or minimized.

References:

1. Fletcher, TD., Shuster, W., Hunt, WF., Ashley, R., Butler, D. and Arthur, S. SUDS, LID, BMPs, WSUD and more-The evolution and application of terminology surrounding urban drainage. *J. Urban Water*. Vol.12, pp. 525-542, 2014.
2. Environmental Protection Agency. *Benefits of low impact development*, viewed 05 May 2016, from https://www.epa.gov/sites/production/files/2015-09/documents /bbfs1bene-fits.pdf.
3. United State Geological Survey. *Effects of Low-Impact -Development (LID) Practices on Streamflow, Runoff Quantity, and Runoff Quality in the Ipswich River Basin, Massachusetts: A Summary of Field and Modeling Studies*, viewed 06 May 2016, from http://pub.usgs.gov/circ/1361/pdf/circ1361.pdf.
4. United States Environmental Protection Agency New England. *Incorporating low impact development into municipal stormwater programs* viewed 05 May 2016, from https://www3.epa.gov/region1/npdes/stormwater/assets/pdfs/IncorporatingLID.pdf.
5. The city of Edmonton. *Low impact development best management practices design guide edition 1.1,* viewed 05 May 2016, from https://www.edmonton.ca/city_government/docume- nts/PDF/LIDGuide.pdf.
6. Haifeng, J., Hairong, Y. and Shaw, LY. Advance in LID BMPs research and practice for urban runoff control in China. *J. Front. Environ. Sci. Eng.,* Vol.7, pp. 709-720, 2013.
7. New Jersey Stormwater Best Management Practices Manual. *Chapter 2 Low impact development techniques*, viewed 07 May 2016, from http://www.njstormwater.org /bmp _man- ual/NJ_SWBMP_2%20print.pdf.
8. United States Environmental Protection Agency, *Default criteria for BMPs suitable locations used in BMP Setting Tool*, viewed 07 August 2016, from https://www.epa.gov/water-research/best-management-practices-bmps-siting-tool
9. International Stormwater BMP Database, *Green roof*, viewed 02 February 2017, from http://www.bmpdatabase.org/.
10. GrowNYC, *Rain barrel,* viewed 02 February 2017, from http://www. grownyc.org /files/osg/RWH.how.to.pdf.

11. Ramsey-Washington Metro Watershed District, *Grass swales*, viewed 02 February 2017, from http://www.rwmwd.org/index.asp?Type=B_BASIC&SEC=%7BAAF12B9B-AF31-48C8-B303-86C8ECA92851%7D.

12. Best Management Practices for Stormwater runoff, *Retention vs. Detention*, viewed 02 February 2017, from http://www.lccdnet.org/wp-content/uploads/2011/04/Ponds.pdf.

13. Yang, F., Guangming, Z., Chunyan, D., Lin, T., Jianfei, Z. and Zhongwu, Li.: Spatial analyzing system for urban land use management based on GIS and multi-criteria assessment modeling, *J. Progress in Natural Science,* Vol.18,

14. Guangming, Z., Ru, J., Guohe, H., Min, X. and Jiangbing, L.: Optimization of wastewater treatment alternative selection by hierarchy grey rational analysis. *J. Environmental Management,* Vol.82, pp.250-259, 2007.

15. Saaty, T. L.: A scaling method for priorities in hierarchical structure. *J. mathematical psychology,* Vol. 4, No. 3, pp. 95-104, 2015.

16. Ayehu, G.T. and Besufekad, S.: Land suitability analysis for rice production: A GIS based-multi-criteria decision approach. *J. Geographic Information System,* Vol. 4, No. 3, pp. 95-104, 2015.

17. Nyeko, M.: GIS and multi-criteria decision analysis for land use resource planning. *J. Geographic Information System*, Vol. 4, pp. 341-348, 2012.

18. Sarucan, A., Baysal, M. E., Kahraman, C. and Engin, O.: A hierarchy grey rational analysis for selecting the renewable electricity generation technologies, *Proceedings of the World Congress on Engineering*, Vol. 2, 2011.

19. Bunruamkaew, K., 2012, *How to do AHP analysis in Excel*, viewed 07 August 2016, from http://giswin.geo.tsukuba.ac.jp/sis/tutorial/How%20to%20do%20AHP%20analysis%20in%20Excel.pdf .

20. Saaty, T. L.: The analytical hierarchy process. *McGraw Hill,* New York, 1976

21. Yu, Y. L., Wu, W. M., Chou, E. R. and Su, P. H.: Grey relational analysis for scholarship grants. 東海管理評論, 7:1, 頁 193-201, 民 94.07.

22. Lin, S. T., Horng, S. J. Lee, B. H., Fan, P., Pan, Y., Lai, J. L., Chen, R. J. and Khan, M. K.: Application

of grey-relational analysis to find the most suitable watermarking scheme. *J. Inovative Computing, Information and Control,* Vol. 7, No. 9, pp. 1349-4198, 2011.

23. Julong, D.: Introduction to grey system theory. *J. Grey System*, Vol. 1, pp. 1-24, 1989.
24. Zhang, J., Wu, D. and O, D. L.: The method of grey related analysis to multiple attribute decision making problems with interval number. *J. Mathematical and Computer Modelling,* Vol. 42, Issues 9-10, pp. 991-998, 2005.
25. Maniya, K. D. and Bhatt, M. G.: A multi-attribute selection of automated guided vehicle using the AHP/M-GRA technique. *J. Production Research,* Vol. 49, No. 20, pp. 6107-6124, 2011.
26. Demonstrator of interactive flash flood mapping for Phnom Penh*, flood simulation*, viewed 02 February 2017, from http://flooddemo.jennylestil.com/.

CHAPTER 8
Conclusions, future researches and limitations

8.1 Conclusions

8.1.1 Summary of findings

This dissertation addresses the importance of introducing the idea of watershed-based methodology in planning through the wide review of existing researches. Basic tools, factors, methodologies, study regions, scales, and areas in this research field are shown.

New concept and methodologies for land use planning highly respecting in mitigation of urban flooding and sustainable development in Phnom Penh City (PPC) based on the idea of the watershed-based planning are discussed at different scales of land use planning as follows:

a) At macro scale planning

It's essential that high attention on the area called outside of zoning area, which is defined as the area outside the intersection between master plan in 2020 and administrative boundary of PPC in each watershed unit in this research, was proved necessary due to the fact that the city is gradually being expanded so that aforementioned areas are going to be developed. In this concern, the appropriate way of choosing the right development area is demonstrated and treated as primarily screening assessment in terms of land use transition and its meanings in the context of influence for water stream and urban flooding in PPC as illustrated in **Chapter 5**. Comprehending the position (upstream or downstream) of the critical area in a watershed allows the planner to allocate and decide on the appropriate site and development strategy. This implies that if the critical area defined in the upstream while its downstream area is urbanized, instead of creating more pressures to downstream area, development of the critical area should take into consideration of creating more open spaces, greenery or any measures to reduce the flow of the water to the downstream area. In the contrast, for sustainable planning, controlling and retrofitting of land use development in the upstream area should be implemented before the development in the downstream area has taken place.

b) At middle scale planning

Hydrological Sensitive Areas (HSAs) considered as one of the key ideas in the environmental friendly planning was introduced and calculated for PPC even though with the limitation of several public databases as illustrated in **Chapter 6**. To respond with this limitation, the creation of soil databases and impervious cover ratios are illustrated. Based on the results, considering HSAs in the development plan enable the planner to avoid for the development of areas having a high potential of increasing flood risk. It also can be used as an indicator for controlling land use so that prevention or mitigation of urban flooding can be implemented right before it takes place.

Hints for both future and current development reflecting on the master plan in 2020 and actual condition of land use obtained from site survey are demonstrated. Understanding about these trends, on time measures based on the classified development stages: developed area, ongoing development area, redevelopment area, and new development area, are grasped.

c) At micro scale planning

Lastly, design measures of LID-BMPs, which are applicable to any development stages and widely utilized among developed countries, with the performance of GIS-based multi-criteria assessment modeling, AHP integrated into GRA method with the modification of reference sequence, for suitability analysis of LID-BMPs, is introduced. It was proved as useful solutions and tool applied for the HSAs in this research as demonstrated in **Chapter 7**. For the safety planning and design, HSAs in grids and suitability maps are finalized based on the same characteristics of existing conditions. Not account for any development stages in one target study area, by considering the finalized map of HSAs and suitability maps as conducted in this research, on time incorporation of best design solutions can be chosen and added in the planning process. These maps are treated as an index for directing the development and retrofitting of the development area.

8.1.2 Conceptual framework of research and flowchart of watershed-based methodology for land use planning in PPC

The overall conceptual framework of watershed-based methodology for urban flooding mitigation is expressed in **Fig.8.1**. Technical method of watershed-based methodology for land use planning in PPC is presented in **Fig.8.2**.

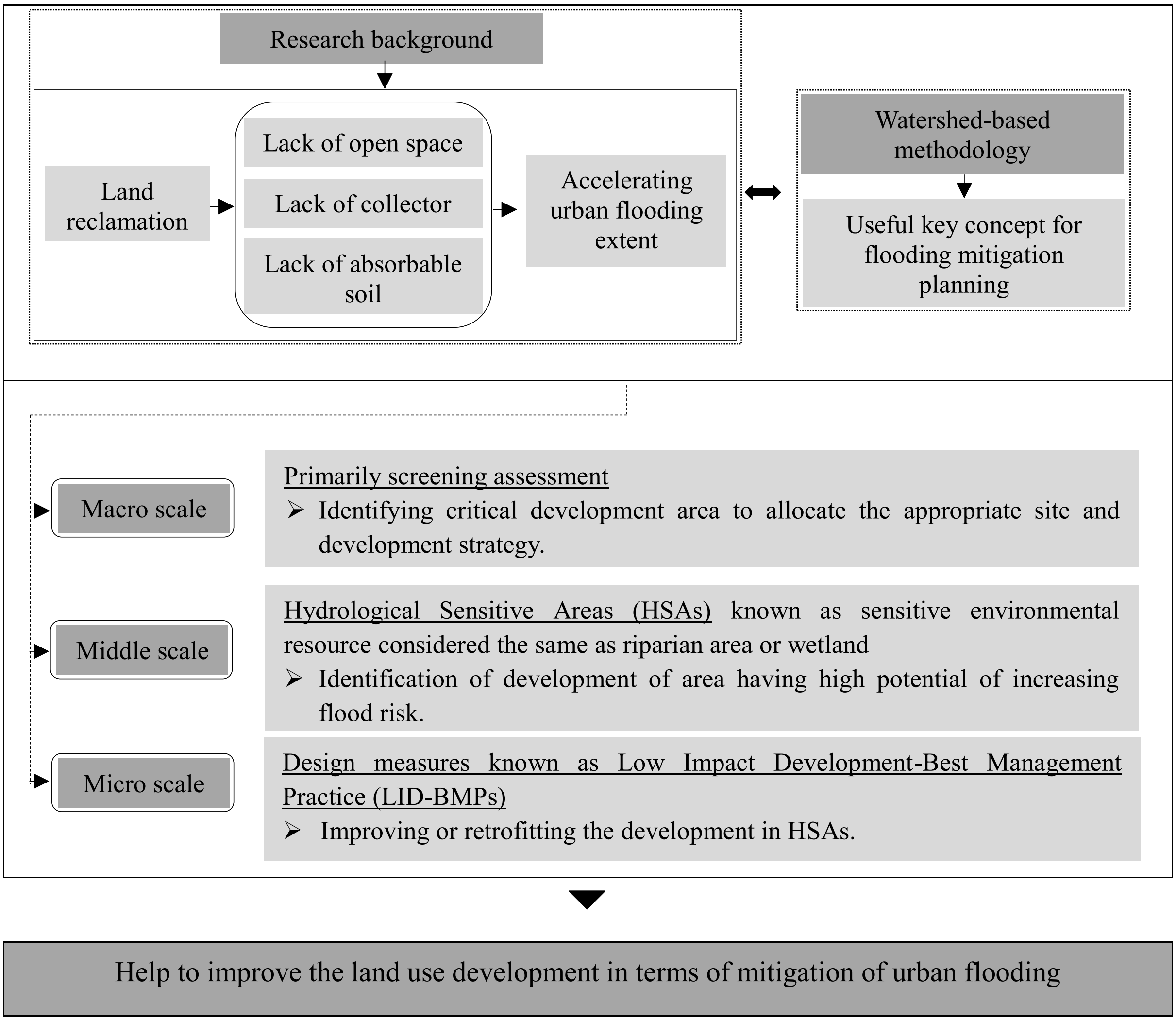


Fig. 8.1 Conceptual framework of watershed-based methodology for urban flooding mitigation

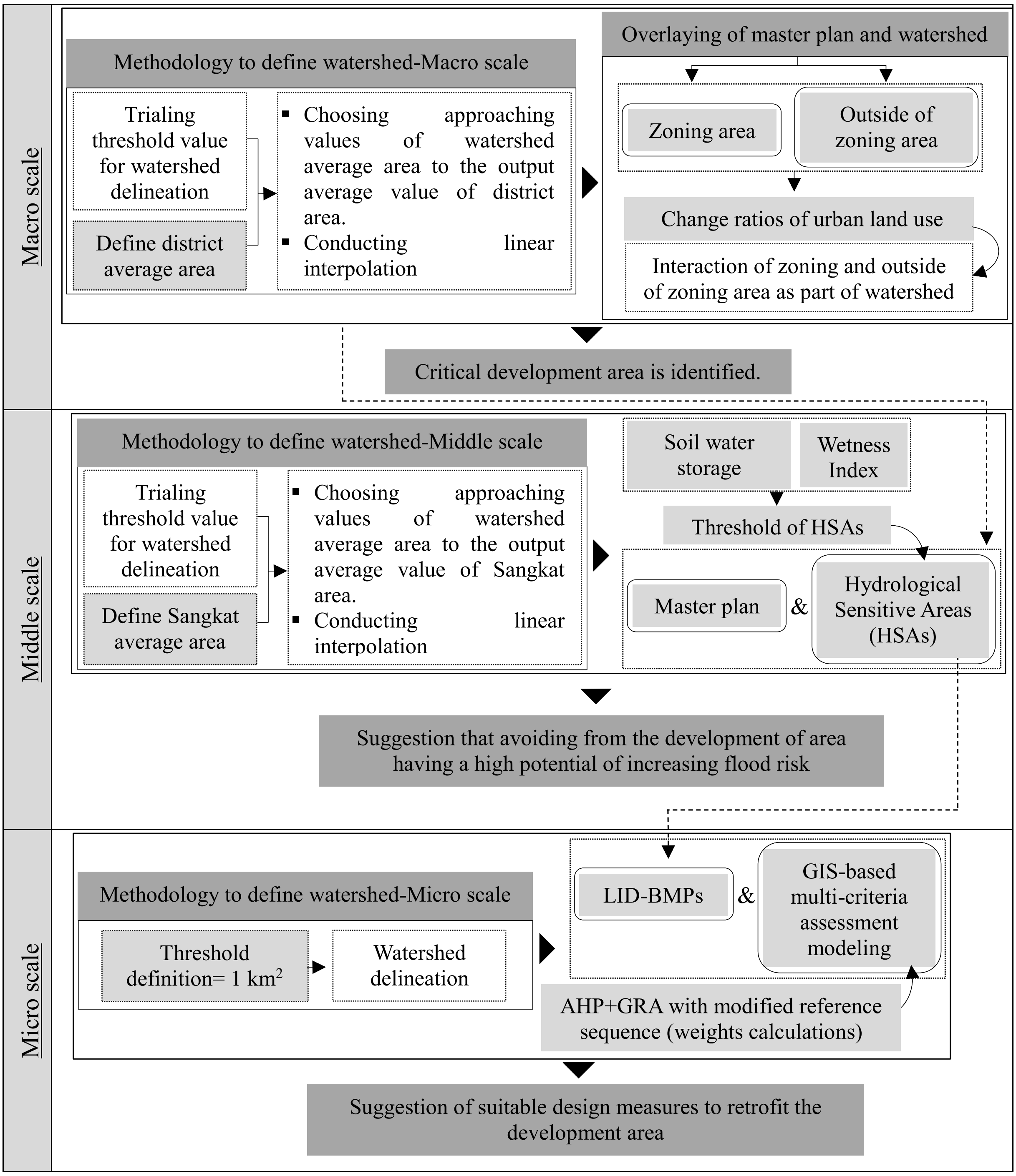


Fig. 8.2 Technical method of watershed-based methodology for land use planning in PPC

8.2 Future researches and limitations

Future researches and limitations of this research can be categorized into two aspects: (1) Requirement of more appropriate data, effective measures, and the suitable coefficient for weights calculation used for suitability analysis in the real application, and (2) Evaluation of the effects of developed methodology and design measures.

8.2.1 More appropriate data, effective measures, and suitable coefficient

a) More appropriate data and effective measures

Due to the lack of sufficient data in PPC, detection of land use is conducted on the medium spatial resolution and resulted in moderate accuracy using Image Classification in ArcGIS 10.2 platform as introduced in **Chapter 5**; however, to discuss planning at the macro scale, primarily screening assessment for critical area in terms of watershed-based land use planning, especially only one urban land use among five types of land use is used; this result is acceptable.

At the middle scale and micro scale planning as discussed in **Chapter 6** and **Chapter 7**, respectively, higher accuracy detection is required. Detection using medium spatial resolution is limited to one watershed boundary defined at the macro scale. This result can be used to discuss and illustrate the planning methodology proposed in this research; however, it's time-consuming process.

In brief, under the poor public databases, detection of land use used to discuss among three scales of planning is acceptable; however, high-resolution data and detection measures are needed for the higher reliable result.

b) Suitable coefficient for weights calculations used for suitability analysis of design measures

Coefficients of pairwise comparison for weight calculations used for suitability analysis in this research mainly based on the judgment by the author as a trial for the development of design method; however, for real application, more suitable coefficients in pairwise comparison matrix for weight calculations should be obtained from the discussion with stakeholders and professional. In addition, for certain design measures, Green roof and Porous pavement, might not effective to PPC due to the rainfall data is quite different from the North America; however, this research is following the measures as a case study to develop the methodology and concept for LID-BMPs.

8.2.2 Evaluation of the effects of developed methodology and design measures

In this research, optimum locations used for controlling the development of area having a high potential of increasing flood risk were identified. These locations with corresponding identified design measures were defined as not only paying high attention to the social and environmental aspects but also the economic aspect. By evaluating the effect of the developed methodology, improvement of this methodology can be achieved. For that purpose, by applying the appropriate design and land use based on developed methodology, reduction of urban flooding can be defined by taking account into the simulation. Furthermore, it’s also effective to compare the developed methodology with the current prominent aesthetic method in terms of ongoing development. In addition, it’s also a future task to think about the social system such as legal system and standard, which are necessary for the actual use of this developed methodology.

Research Publications and Presentations

Journal Publication	2016	Review of Research Trends in Watershed-Based Land Use Analysis. Journal of Infrastructure Planning and Management, JSCE. Vol.4, 227-242, 20th December 2016 Lim Luong, Sasaki Yoh.
Oral Presentation	2016	Transformation of Land Use Pattern in Phnom Penh City at A Watershed Scale. Proceeding of Civil Engineering Conference in The Asian Region CECAR 7, Hawaii, USA, 30th August-2nd September 2016. Lim Luong, Sasaki Yoh.
	2015	Methodology to Evaluate the Urban Spatial Characteristics of Traditional Cities by Watershed-Based Analysis. Proceeding of the 15th Science Council of Asia Conference and International Symposium, 15th-17th May 2015, Siem Reap, Cambodia. Lim Luong, Sasaki Yoh.
	2014	A Study on The Location of Castle and Urban Structure of Caste-Town by Watershed-Based Analysis. Proceedings of Infrastructure planning and Management, 7th-8th June 2014, Sendai, Japan. Lim Luong, Sasaki Yoh.
Poster Presentation	2017	Conceptual Idea of Land Use Zoning for Urban Flooding Mitigation in Developing Countries-Phnom Penh City as a case study. Proceeding of Infrastructure Planning and Management, 10th-11th June 2017, Matsuyama, Japan. Lim Luong, Sasaki Yoh.