การทำแผนที่แสดงความรุนแรงและความเปราะบางของการเกิดน้ำท่วมเมืองโดยใช้ MIKE 21: กรณีศึกษาเมืองนครราชสีมา ประเทศไทย

นางสาวปรินดา ภูคงเดือน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต

สาขาวิชาภูมิสารสนเทศ

มหาวิทยาลัยเทคโนโลยีสุรนารี

ปีการศึกษา 2557

MAPPING OF URBAN FLOOD SEVERITY AND VULNERABILITY USING MIKE 21: A CASE OF MUEANG NAKHON RATCHASIMA, THAILAND

Parinda Pukongduean

A Thesis Submitted in Partial Fulfillment of the Requirements for the

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MAPPING OF URBAN FLOOD SEVERITY AND VULNERABILITY USING MIKE 21: A CASE OF MUEANG NAKHON RATCHASIMA, THAILAND

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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ปรินดา ภูคงเดือน : การทำแผนที่แสดงความรุนแรงและความเปราะบางของการเกิดน้ำท่วมเมืองโดยใช้ MIKE 21: กรณีศึกษาเมืองนครราชสีมา ประเทศไทย (MAPPING OF URBAN FLOOD SEVERITY AND VULNERABILITY USING MIKE 21: A CASE OF MUEANG NAKHON RATCHASIMA, THAILAND) อาจารย์ที่ปรึกษา : รองศาสตราจารย์ ดร.สุวิทย์ อ๋องสมหวัง, 200 หน้า.

วิทยานิพนธ์ฉบับนี้เน้นเกี่ยวกับการจำลองสถานการณ์จากแบบจำลองทางอุทกพลศาสตร์แบบ 2 มิติ สำหรับการจัดทำแผนที่ความรุนแรงและความเปราะบางการเกิดน้ำท่วมเมืองและการลดผลกระทบจากน้ำท่วม วัตถุประสงค์หลักของการศึกษาคือ (1) เพื่ออธิบายคุณลักษณะความรุนแรงของน้ำท่วมเมือง (2) เพื่อพัฒนาและจัดทำแผนที่ดัชนีความเปราะบางการเกิดน้ำท่วมเมือง และ (3) เพื่อจำลองสถานการณ์สารสนเทศการเกิดน้ำท่วมเมืองสำหรับใช้บรรเทาผลกระทบและการป้องกันการเกิดน้ำท่วมเมือง ในการศึกษาลำดับแรก ใช้แบบจำลองอุทกพลศาสตร์ DHI MIKE 21 ที่ผ่านการสอบเทียบค่าสัมประสิทธิ์ความเสียดทาน Manning's M มาสร้างสารสนเทศการเกิดน้ำท่วมเมือง จากนั้น นำข้อมูลระดับความลึกและความเร็วของน้ำท่วมมารวมเข้าด้วยกันเพื่อสร้างแผนที่ความรุนแรงการเกิดน้ำท่วมเมือง ในขณะเดียวกัน นำปัจจัยทางกายภาพ สังคม เศรษฐกิจและสิ่งแวดล้อมมารวมเข้าด้วยกันด้วยวิธีการคูณภายใต้ระบบสารสนเทศภูมิศาสตร์เพื่อสร้างดัชนีความเปราะบางของการเกิดน้ำท่วมเมืองและแผนที่การจำแนกความเปราะบางของการเกิดน้ำท่วมเมือง นอกจากนี้ ทำการจำลองสถานการณ์การเกิดน้ำท่วมเมืองด้วยการปรับลดข้อมูลปริมาณน้ำเข้าเมืองจากเหตุการณ์น้ำท่วมปี พ.ศ. 2553 ณ ประตูน้ำกุดหินลงครั้งละ 10 เปอร์เซ็นต์ เพื่อจำลองสถานการณ์ขอบเขตน้ำท่วมและมูลค่าความเสียหายทางเศรษฐกิจในภาพเหตุการณ์ที่แตกต่างกัน สำหรับใช้กำหนดปริมาณน้ำเข้าเมืองเพื่อบรรเทาผลกระทบและการป้องกันน้ำท่วมให้เกิดขึ้นน้อยสุด

จากการสอบเทียบแบบจำลอง Mike 21 ระหว่างขอบเขตน้ำท่วมจากแบบจำลองและข้อมูลการเกิดน้ำท่วมจังหวัดนครราชสีมาในปี พ.ศ. 2553 ของสำนักงานพัฒนาเทคโนโลยีอวกาศและภูมิสารสนเทศ พบว่า ค่าสัมประสิทธิ์ความเสียดทาน Manning's M แบบเฉลี่ยเป็นพารามิเตอร์ที่มีความเหมาะมากสุดในการจำลองสถานการณ์การเกิดน้ำท่วม โดยพบว่า ขอบเขตน้ำท่วมสูงสุดเกิดขึ้นในวันที่ 24 ตุลาคม พ.ศ. 2553 ครอบคลุมพื้นที่ 88.36 ตารางกิโลเมตร โดยมีพื้นที่เกษตรกรรมได้รับผลกระทบสูงสุด คิดเป็นพื้นที่ 76.89 ตารางกิโลเมตร และรองลงมาเป็นพื้นที่ชุมชนและสิ่งปลูกสร้าง คิดเป็นพื้นที่ 7.74 ตารางกิโลเมตร ความลึกของน้ำท่วมทางกายภาพในระหว่างวันที่ 14-27 ตุลาคม พ.ศ. 2553 มีค่าอยู่ระหว่าง 0.10-3.91 เมตร ในขณะที่ความเร็วของน้ำท่วมทางกายภาพ มีค่าระหว่าง 0.00-2.06 เมตรต่อวินาที ในขณะเดียวกัน ระยะเวลาของน้ำท่วม 8 วันสร้างความเสียหายให้กับพื้นที่สูงสุด คิดเป็นพื้นที่ 18.48 ตารางกิโลเมตร สำหรับความรุนแรงการเกิดน้ำท่วมเมืองที่อาศัยค่าความ

ลึกและความเร็วของการเกิดน้ำท่วมที่ผ่านการปรับมาตรฐานและการจำแนกด้วยวิธีการความเบี่ยงเบนมาตรฐาน ประกอบด้วย 5 ระดับคือ ต่ำมาก ต่ำ ปานกลาง สูง และสูงมาก ครอบคลุมพื้นที่ 29.27 36.24 16.76 4.16 และ 2.31 ตารางกิโลเมตร ตามลำดับ ในขณะเดียวกัน ดัชนีความเปราะบางการเกิดน้ำท่วมเมืองซึ่งจำแนกด้วยวิธีการความเบี่ยงเบนมาตรฐาน ประกอบด้วย 5 ระดับคือ ต่ำมาก ต่ำ ปานกลาง สูง และสูงมาก ครอบคลุมพื้นที่ 83.70 2.17 1.11 0.66 และ 1.13 ตารางกิโลเมตร ตามลำดับ นอกจากนี้ ในการจำลองสถานการณ์การเกิดน้ำท่วมเมืองเพื่อการบรรเทาและการป้องกันน้ำท่วม พบว่า หากปริมาณน้ำท่าในอดีต ในปี พ.ศ. 2553 ณ ประตูน้ำกุดหินลดลง 60 เปอร์เซ็นต์ หรือคิดเป็นปริมาณน้ำท่าน้อยกว่า 17.82 ลูกบาศก์เมตรต่อวินาที จะสามารถบรรเทาผลกระทบจากน้ำท่วมเมืองได้ ในขณะเดียวกัน หากปริมาณน้ำท่าลดลง 67 เปอร์เซ็นต์ หรือคิดเป็นปริมาณน้ำท่าน้อยกว่า 14.70 ลูกบาศก์เมตรต่อวินาที จะสามารถป้องกันน้ำท่วมอำเภอเมืองนครราชสีมาได้

มหาวิทยาลัยเทคโนโลยีสุรนารี

สาขาวิชาการรับรู้จากระยะไกล ลายมือชื่อนักศึกษา__________

ปีการศึกษา 2557 ลายมือชื่ออาจารย์ที่ปรึกษา__________

ลายมือชื่ออาจารย์ที่ปรึกษาร่วม Somchai Ch.

PARINDA PUKONGDUEAN : MAPPING OF URBAN FLOOD SEVERITY AND VULNERABILITY USING MIKE 21: A CASE OF MUEANG NAKHON RATCHASIMA, THAILAND). THESIS ADVISOR : ASSOC. PROF. SUWIT ONGSOMWANG, Dr. rer. nat. Cycle. 200 PP.

DHI MIKE 2D HYDRODYNAMIC MODEL / FLOOD SIMULATION / URBAN FLOOD SEVERITY AND VULNERABILITY CLASSIFICATION / FLOOD MITIGATION AND PREVENTION / NAKHON RATCHASIMA PROVINCE.

This thesis focuses on the simulation of 2D hydrodynamic model for urban flood severity and vulnerability mapping and flood reduction. The main objectives of the study are (1) to characterize urban flood severity, (2) to develop urban flood vulnerability index and classification map, and (3) to simulate urban flood information for urban flood mitigation and prevention. DHI MIKE 21 hydrodynamic model was firstly here applied with Manning's M number calibration to extract urban flood information. Then, urban flood depth and velocity was combined to generate urban flood severity map. In addition, physical, social, economic, and environmental factors were integrated using the GIS-based multiplication to create urban flood vulnerability index and its classification map. Furthermore, the simulated urban flood of reducing historical discharge in 2010 at Kud Hin Watergate by 10% was applied to simulate flood extent and economic value loss in different scenarios to optimize minimal flood extent and economic value loss for flood mitigation and prevention.

Based on calibration process of DHI MIKE 21 between the derived flood extent by model and flood record of Nakhon Ratchasima province in 2010 by Geo-

Informatics and Space Technology Development Agency, it found that constant Manning's M is capable to give good comparable flood extent. Urban flood extent had represented the highest extent on 24 October 2010 with area of 88.36 sq. km. The agricultural land is the main land use that was affected from flood with area of 76.89 sq. km, followed by urban and built-up area with area of 7.74 sq. km. The simulated flood depth during 14-27 October 2010 ranged between 0.10 and 3.91 m while flood velocity varied from 0.00 to 2.06 m/s. Meanwhile, 8 days flood duration created the highest flooded area of 18.48 sq. km. For urban flood severity analysis, the combination of the normalized of flood depth and velocity was classified into 5 classes: very low, low, moderate, high, and very high using standard deviation classification method covered area of 29.27, 36.24, 16.76, 4.16, and 2.31 sq. km, respectively. Meanwhile, urban flood vulnerability index values were classified into 5 classes: very low, low, moderate, high, and very high using standard deviation classification covered area of 83.70, 2.17, 1.11, 0.66, and 1.13 sq. km, respectively. Furthermore, urban flood simulation for flood mitigation and prevention had illustrated that when historical discharge in 2010 at Kud Hin Watergate was reduced by 60 percent or less than 17.82 m^3/s, it can mitigate urban flood and when discharge was reduced by 67 percent or less than 14.70 m^3/s, it can prevent urban flood in Mueang Nakhon Ratchasima district.

School of Remote Sensing	Student's Signature_____________________
Academic Year 2014	Advisor's Signature_____________________
	Co-advisor's Signature__________________

ACKNOWLEDGEMENTS

It is my pleasure to express my gratitude to all people who have encouraged me to finish this work. First of all, I would like to express my deep appreciation and sincere gratitude to my advisor, Assoc. Prof. Dr. Suwit Ongsomwang for his valuable advice and moral support during the study periods at Suranaree University of Technology (SUT).

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Parinda Pukongduean

มหาวิทยาลัยเทคโนโลยีสุรนารี

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LIST OF ABBREVIATIONS

CBD	=	Central Business District
DEM	=	Digital elevation model
GISTDA	=	Geo-Informatics and Space Technology Development Agency
LDD	=	Land Development Department
LTOMP	=	Lam Takhong Operation and Maintenance Project
LU	=	Land Uses
MOAC	=	Ministry of Agriculture and Cooperatives
MDSS	=	Multi-Decision Support System
NRCT	=	National Research Council of Thailand
NRM	=	Nakhon Ratchasima Municipality
OIC	=	Office of Insurance Commission
PMO	=	Prime Minister Office
SAW	=	Simple Additive Weighting
TMD	=	Thai Meteorological Department
UFVI	=	Urban Flood Vulnerability Index
EVL	=	Economic Value Loss
UFV	=	Urban Flood Vulnerability
PAPF	=	Percentage of Affected Population by Flood

CHAPTER I

INTRODUCTION

1.1 Background problem and significance of the study

Flood is one of natural hazards that could cause great damages on physical, social, economic, and environmental effect in particular losses of properties and human lives. Commonly, floods can be divided into 4 types: river flood, coastal flood, flash flood, and urban flood (Ghosh, 2006).

River flood generally appears along rivers and it is an inevitable part of life. Some floods occur seasonally and some when winter or spring rains; coupled with melting snows, fill river basins with too much water, too quickly. Torrential rains from decaying hurricanes or tropical systems can also produce river flooding. Meanwhile, coastal flood can be produced by winds, tropical storms, and hurricanes or intense offshore low pressure systems which can drive ocean water inland and cause significant flooding. Also, it can be produced by tsunamis. Flash flood appears quite rapidly with little or no advance warning. It is not only caused by excessive rainfall of high intensity but also sudden release of high discharge of water from dams and by breaches or structural failures of dams and levees, gushing out large volumes of water in a short time. Urban flood is caused by land fields which lose their ability to absorb rainfall, and poor drainage system. Urbanization is a major cause to decrease the ability to absorb water on natural terrain. During periods of urban flooding, streets can become swift moving rivers, while basements can become death traps as they fill with water (Ghosh, 2006).

Urban flood generally can be defined as an overflowing of a great body of water over land in a built up area which is not usually submerged (Will, 2007). It is one of natural hazards that previously occur in many parts of South-East Asia including Thailand. Nakhon Ratchasima flood emerged on the 18th October 2010 which resulted in loss of life and affected to physical, social, economic, and environmental issues (Table 1.1). Figure 1.1 displays the extent of flooded areas visually extracted from RADATSAT-II image acquired on 23 October 2010 by GISTDA.

Table 1.1 Mueang Nakhon Ratchasima district flood damage in October 2010.

Mueang Nakhon Ratchasima flood damage			
Physical	**Social**	**Economic**	**Environmental**
16 Government Units	8 Deaths	Transport station	Landscape damaged
13 Hospitals	2 Injuries	Markets	
2 Reservoirs	24,785 Families	Industries and companies	
18 Temples		Real estates and accommodations	
23,535 Accommodations		Total 30,000 million baht	

Source**:** Mueang Nakhon Ratchasima District Office (2010).

In the history of human settlements, it often located along the riverside and developed into towns and urban due to the development of the country. Population number has been rising as well as demand on land, especially living and working area in the city. This can lead to the scarcity of suitable land in the urban area. Consequently, urban flood frequently occurs and results in many problems. Considering with the hydrological balance, the urban flood process could be resulted from unstable of the water balance as shown in Figure 1.2. Main causes of urban floods are include; the changes in precipitation attributed to climate change, changes in surface runoff influenced by urbanization, and features of urban areas suffering from flood damage (Toda, 2007).

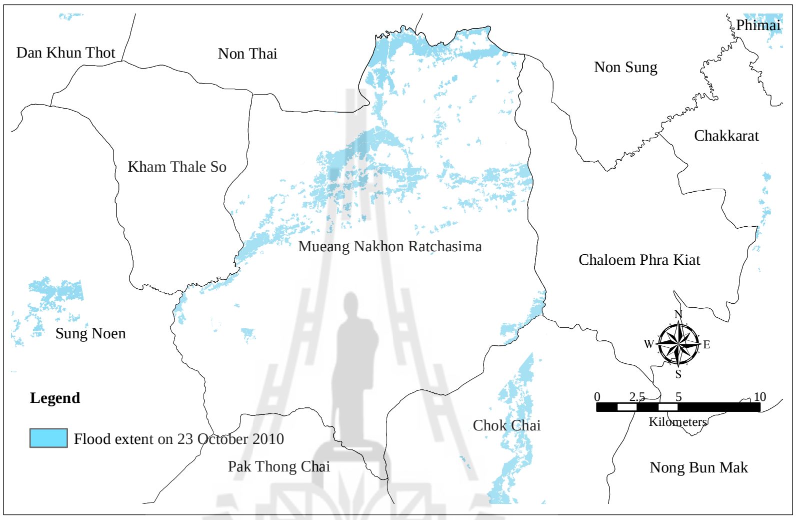

Figure 1.1 Nakhon Ratchasima flood on 23 October 2010 of GISTDA.

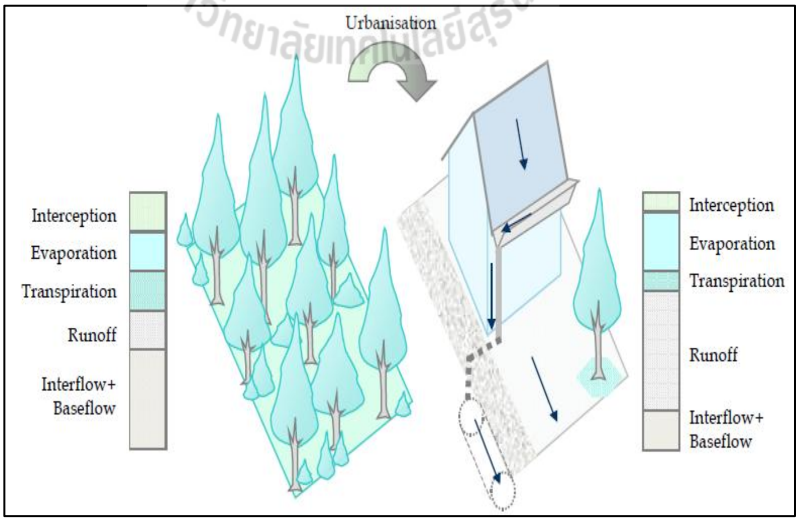

Figure 1.2 Picture of urbanization changes in the water balance.

Source: Miguez and Magalhaes (2010).

Miguez and Magalhes (2010) had illustrated that portion of the total precipitation can be divided into three parts: intercepted by vegetation canopy or retained at surface depression, infiltrates, and the rest of the rainfall volumes flows over the terrain and lower areas. The urbanization process is the main change to the water budget, resulted in increase of superficial runoff production and also physical flow obstruction as well as road networks construction. Although the city can influence runoff pattern changes within itself, it also changes the whole river system downstream, including surrounding areas. Although flood and vulnerability have been studied for decades, the urban flood vulnerability is mostly studied using 1 dimensional model such as DHI MIKE 11 or SOBEK and expressed results in term of economic value loss (Kelman, 2002). This study attempts to combine a new advance hydrodynamic model "DHI MIKE 21" for simulating flood flows in urban area with developed urban flood indicators based on literature reviews and actual conditions of the study area. The vulnerability study covers four sections include physical, social, economic, and environmental, using multiplication method to demonstrate the results, also contribute a suitable method of urban flood vulnerability classification.

Furthermore, historical flood event of Mueang Nakhon Ratchasima district in 2010 and simulated scenario in the future with varying of cut-off inflow volume (discharge) has reprocessed to evaluate economic value loss based on actual cash value (Office of Insurance Commission, 2010), compare land use (LU) damage, and minimize the effect of urban flood on LU. These results can be used as a baseline for urban flood prevention in the future. Consequently, 2D hydrodynamic model of DHI MIKE 21 was applied to urban flood vulnerability analysis in order to reduce economic value loss, loss of life and assets in the future.

1.2 Research objectives

The urban flood in Mueang Nakhon Ratchasima district described in the previous section has emphasized the important requirement to identify levels of urban flood severity and vulnerability, and simulate urban flooded area with economic value loss representation. In response to these matters, the principle objective of this research is to illustrate an urban flood severity, urban flood vulnerability index, and urban flood simulation. Potentially, this study can be used to map and locate the urban flood vulnerability and economic value loss. Thus, to achieve the key aim, the specific objectives of this work are as follows:

(1) To characterize urban flood severity from two sources of water: (1) precipitation downstream of Lam Taklong dam and (2) water inflow of Lam Takhong streams network to Mueang Nakhon Ratchasima district;

(2) To develop urban flood vulnerability index (UFVI) map of Mueang Nakhon Ratchasima district;

(3) To simulate urban flood information (cut off inflow volume) for urban flood impact mitigation and prevention.

1.3 Scope and limitations of the study

Scope and limitations of the study can be briefly explained as follows:

1) Hydrodynamic DHI MIKE 21 model is used to quantified flood extent, velocity and depth over Lam Takhong sub-watershed covering major part of Mueng Nakhon Ratchasima district (275.04 sq. km) and minor parts of Sung Noen (18.74 sq. km), Kham Thale So (90.62 sq. km), and Chaloem Phra Kiat districts (12.84 sq. km).

Herein, the study time for the urban flood simulation covers period of available inflow (discharge) data during 14 - 28 October 2010.

2) The derived flood velocity and depth are separately used to classify urban flood severity accordance with its property based on Chen's classification in 2007. Then, they are combined to classify physical urban flood with optimal classification method for urban flood vulnerability index.

3) Four factors include physical, social, economic, and environmental are used to analyzed the urban flood vulnerability index with index model (multiplication method).

4) For urban flood reduction, flood extent are reiterately simulated by systematic cutoff discharge at 10 percent of historical discharge without precipitation in 2010. The optimal cutoff inflow are indentified based on the minimized flood extent and economic loss.

1.4 Basic assumptions

Basic assumptions of the study are set up as follows:

1. Urban flood behavior based on Mueang Nakhon Ratchasima district flood in 2010 is considered as unsteady flow.

2. Main causes of Mueang Nakhon Ratchasima district flood in 2010 are considered as being large volume of water from Lam Takhong dam and high precipitation rate occurring over the study area.

3. Watergates in the study area are assumed all watergates open entirely to prevent damage that might occur to the structure.

4. The interpreted flood extent data in 2010 of GISTDA are reliable and can be accepted as refecence data for accuracy assessment.

1.5 Study area

1.5.1 Location and administrative boundary

The study area covers area of 397.24 sq. km (Figure 1.3) which over four districts including Sung Noen, Kham Thale So, Mueang Nakhon Ratchasima, and Chaloem Phra Kiat. This area is considered as the lowest part of Lam Takhong watershed. It is connected to Lam Choengkrai watershed at the North, and Upper Part of Lam Nam Mum watershed at the East. Mueang Nakhon Ratchasima district is the main part of study area. It includs an imporatnt Central Business District (CBD) of Nakhon Ratchasima province which locates at centre of the study area.

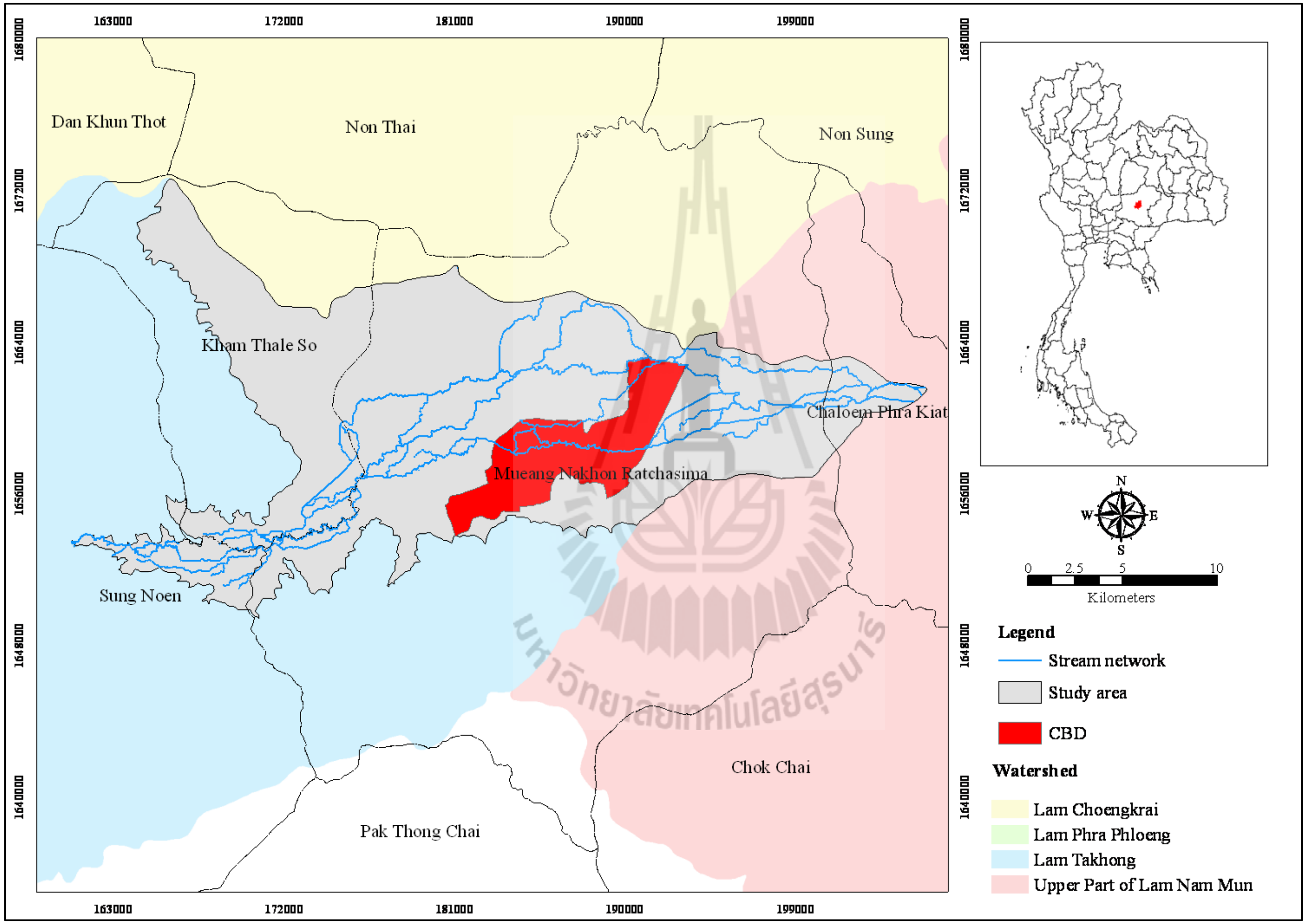

Figure 1.3 Study area and its administrative boundary.

1.5.2 Topography

The elevation of the study area ranges approximately from 162.27 m to 215.66 m above mean sea level (amsl). Most of higher elevation in the western part is undulating terrain while the lower elevation in central and eastern parts are flood plain (Figure 1.4). The central part represents urban and built-up areas. The agricultural lands widely spread over flood plain and along the main river (Lam Takhong) that flows from the West to the East of the area.

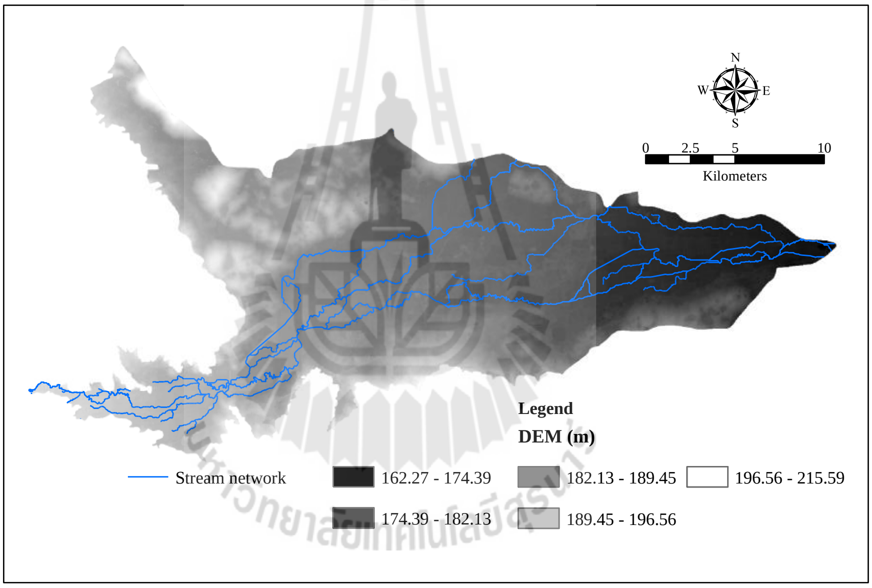

Figure 1.4 Topography.

1.5.3 Climate data

The climate of the region has separated to three seasons: hot season (mid February to mid May), rainy season (mid May to mid October) and cool dry season (mid October to mid February). Rainy season is under the influence of the southwest monsoons, while cool-dry season is influenced by the northeast monsoon carrying cold air from China (Saravisutra, 2010).

Temperature of the region normally has highly in April with average of 36.5 °C and the lowest in December with average of 18.3 °C (Thai Meteorological Department, 2010)

During Nakhon Ratchasima flood in 2010, the precipitation in the rainy season had highly in August to October. The maximum of precipitation had shown on 15 October 2010 was 116.3 mm/day with no evaporation and stop raining on 20 October 2010 with evaporation of 4.6 mm/day (Thai Meteorological Department, 2010).

1.5.4 Land use in 2008

According to land use data of Land Development Department (LDD) in 2008, it was found that two main land use types in the study area were agricultural land (62.21%) and urban and built-up area (24.60%) and the rests were miscellaneous land, forest land and water body as summary in Table 1.2 and Figure1.5.

Table 1.2 Major land use types in the study area (sq. m) based on LDD in 2008.

Land use	Kham Thale So	Sung Noen	Mueang Nakhon Ratchasima	Chaloem Phra Kiat	Total	Percent
Urban and built-up area	7,671,875	1,645,000	86,728,125	1,676,250	97,721,250	24.60
Agricultural land	69,041,875	16,450,625	152,201,875	9,414,375	247,108,750	62.21
Forest land	1,191,875	17,500	994,375	-	2,203,750	0.55
Miscellaneous land	10,074,375	355,000	27,183,750	1,230,000	38,843,125	9.78
Water body	2,643,750	268,125	7,931,875	523,125	11,366,875	2.86
Total	**90,623,750**	**18,736,250**	**275,040,000**	**12,843,750**	**397,243,750**	**100.00**

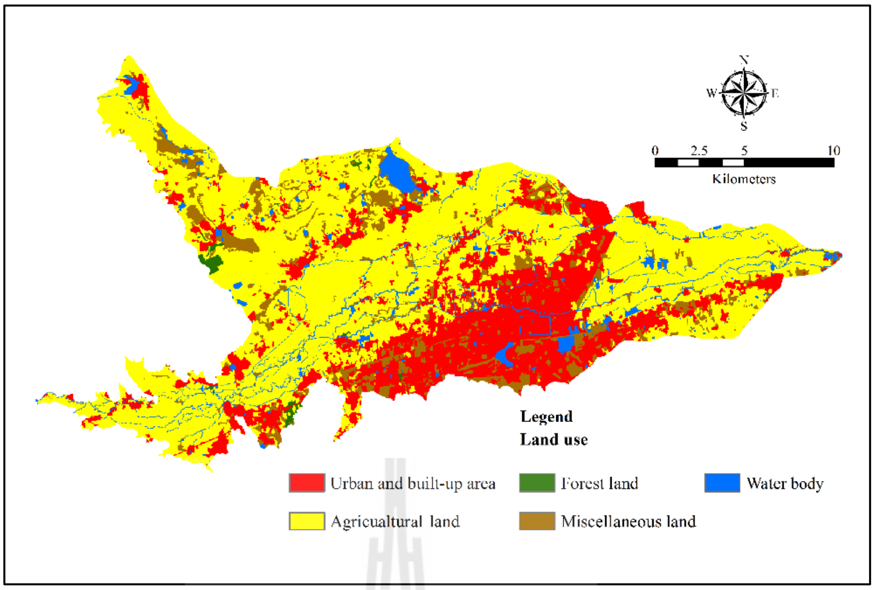

Figure 1.5 Distribution of land use in 2008.

1.5.5 Transportation network

Transportation network in study area consists of highway no.2 with bypass and four main roads. Highway no.2 is the main important access from Bangkok via Nakhon Ratchasima to northeastern provinces. While sub-highway no. 205 (route from Non Thai district), no. 224 (route from Chok Chai district), no. 226 (route from Nang Rong district, Burirum province) and no. 304 (route from Pak Thong Chai district) join into Nakhon Ratchasima City Municipality as show in Figure 1.6. Furthermore, route no. 2068 is a secondary highway in the South -North link between Kham Thale So to Dan Khun Thot District , Nakhon Ratchasima while, no. 2198 is provincial highway from west to east direction which is link Kham Thale So to Khok Sung district.

In addition, no. 99 is railway that has a direction from west to east pass by Sung Noen to Chaloem Phra Kiat districts, while other direction is split to Non Sung district, Nakhon Ratchasima (Saravisutra, 2010).

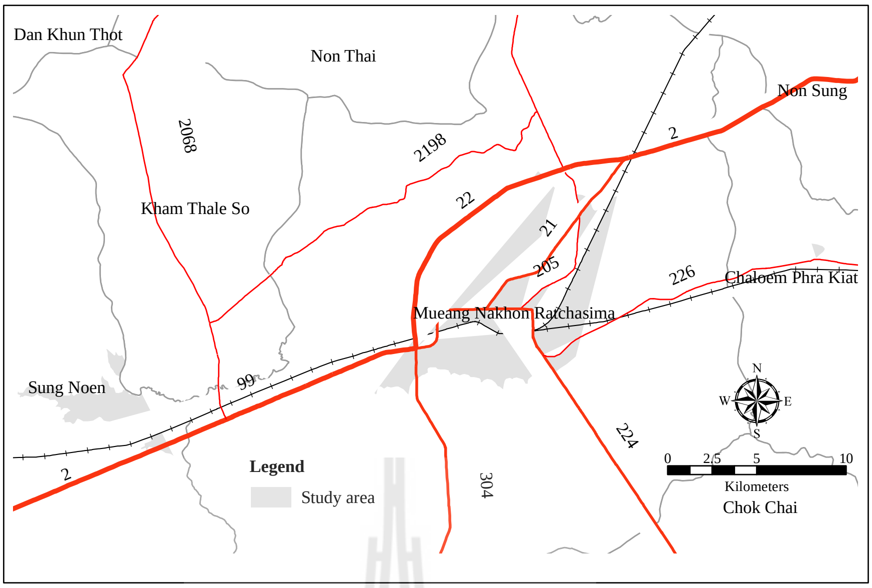

Figure 1.6 Transportation network.

1.5.6 Demographic data

The study area have covered part of four districts include Kham Thale So, Sung Noen, Mueang Nakhon Ratchasima, and Chaloem Phra Kiat districts. Kham Thale So district is subdivided into five sub-districts. This district have total population 18,336 in 2010. Sung Noen is subdivided into 11 sub-districts which are further divided into 127 administrative villages. This district has total population 51,331 in 2010. Mueang Nakhon Ratchasima district has total population in 2010 with 433,123 persons and the density was 567.86 person/ sq. km. The highly population appeared in Nai Mueang and Ban Kho sub-district with 152,429 persons followed by Suranaree and Ban Mai (33,614 persons) and Cho Ho (27,686 persons). The lowest population were Talat (6,187 persons), Phanao (4,872 persons), and Phon Krang (4,796 persons) (Nakhon Ratchasima City Municipality, Online, 2010). Chaloem Phra Kiat is subdivided into 5 sub-districts with 24,073 of total population in 2010. The township is covers parts of Tha Chang and Chang Thong sub-districts.

Detail of number of population and density in 2010 of each sub-district are provided in Table 1.3 while distribution of sub-district of four districts in the study area is presented in Figure 1.7.

Table 1.3 Number of population and density in each sub-district in 2010.

No	Sub-district	District	Area (sq. km)	Number of Population	Population Density
1	Nong Suang	Kham Thale So	45.90	5,783	126.00
2	Phan Dung	Kham Thale So	36.70	5,277	143.79
3	Bueng O	Kham Thale So	54.09	5,386	99.57
4	Pong Daeng	Kham Thale So	33.32	5,156	154.74
5	Kham Thale So	Kham Thale So	37.60	2,944	78.30
6	Sung Noen	Sung Noen	66.29	8,383	126.45
7	Sema	Sung Noen	84.18	9,192	109.19
8	Khorat	Sung Noen	7.19	2,638	366.71
9	Bung Khilek	Sung Noen	35.95	4,405	122.54
10	Non Kha	Sung Noen	92.42	4,829	52.25
11	Khong Yang	Sung Noen	17.45	2,713	155.45
12	Makluea Kao	Sung Noen	173.94	12,249	70.42
13	Makluea Mai	Sung Noen	115.70	7,783	67.27
14	Na Klang	Sung Noen	58.32	8,271	141.83
15	Nong Takai	Sung Noen	111.88	6,674	59.65
16	Nong Khai Nam	Mueang Nakhon Ratchasima	39.82	6,678	167.69
17	Khok Sung	Mueang Nakhon Ratchasima	45.95	9,758	212.37
18	Cho Ho	Mueang Nakhon Ratchasima	34.97	27,686	791.68
19	Putsa	Mueang Nakhon Ratchasima	57.50	9,512	165.44
20	Ban Pho	Mueang Nakhon Ratchasima	39.58	8,931	225.67
21	Talat	Mueang Nakhon Ratchasima	13.60	6,187	454.86
22	Muen Wai	Mueang Nakhon Ratchasima	13.71	10,077	734.88
23	Phon Krang	Mueang Nakhon Ratchasima	15.39	4,796	311.59
24	Nong Krathum	Mueang Nakhon Ratchasima	10.00	6,957	695.53
25	Nai Mueang and Ban Koh	Mueang Nakhon Ratchasima	42.11	152,429	3,619.89
26	Si Mum	Mueang Nakhon Ratchasima	24.75	6,301	254.56
27	Paru Yai	Mueang Nakhon Ratchasima	10.92	9,365	857.45
28	Nong Rawiang	Mueang Nakhon Ratchasima	49.82	10,828	217.34
29	Phanoa	Mueang Nakhon Ratchasima	8.81	4,872	552.77
30	Hua Thale	Mueang Nakhon Ratchasima	23.63	24,587	1,040.47

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Table 1.3 Number of population and density in each sub-district in 2010 (Continued).

No	Sub-district	District	Area (sq. km)	Number of Population	Population Density
31	Maroeng	Mueang Nakhon Ratchasima	8.55	7,063	826.20
32	Suranaree and Ban Mai	Mueang Nakhon Ratchasima	62.28	33,614	539.70
33	Nong Phai Lom	Mueang Nakhon Ratchasima	13.75	19,744	1,435.47
34	Khok Kruat	Mueang Nakhon Ratchasima	74.64	12,576	168.49
35	Pho Koang	Mueang Nakhon Ratchasima	43.82	25,632	584.93
36	Nong Chabok	Mueang Nakhon Ratchasima	19.84	11,637	586.62
37	Nong Bua Sala	Mueang Nakhon Ratchasima	47.64	17,155	360.10
38	Chai Mongkhon	Mueang Nakhon Ratchasima	61.64	6,738	109.31
39	Nong Yang	Chaleom Pra Kiat	85.40	6,726	78.76
40	Tha Chang	Chaleom Pra Kiat	108.84	3,051	28.03
41	Phra Phut	Chaleom Pra Kiat	24.45	5,898	241.24
42	Chang Thong	Chaleom Pra Kiat	26.13	4,589	175.61
43	Nong Ngu Lueam	Chaleom Pra Kiat	36.56	9,586	262.17

Source: Nakhon Ratchasima city municipality (2012).

Figure 1.7 Distribution of sub-district of four district in the study area.

1.5.7 Historical record of urban flood

The flooded area was mainly located along the main river of province, namely Lam Takhong River, in Lam Takhong Watershed of Mun River Basin. During past four decades, Nakhon Ratchasima province has suffered from flood repeated in 1978, 1996, 2002, and 2010 (Weeraya and Jirawat, 2012). The flood occurred in the 2010 resulted from the amount of rain that fell more than 100 mm per day, and low capacity of drainage system. Moreover, Lam Takhong reservoir has over contained water storage levels (Reservoir's storage capacity is 10.3 million cubic meters), thus, the reservoir had to immediately drained water volume to downstream areas, directly to Mueang Nakhon Ratchasima. Furthermore, the main rivers include Lam Takhong and Lam Boriboon Rivers have shallow condition and intruded riverside area.

1.6 Benefits of the study

The benefits of the study have influence with stakeholders, in particular those who have an interest in urban flood management, as follows:

(1) It performs the process of data collection for the indicators of urban flood severity (flood depth, flood velocity, and flood duration) and urban flood vulnerability analysis.

(2) It provides the methods for urban flood vulnerability analysis to generate the urban flood vulnerability index (UFVI), specifically for cities with characteristics similar to Mueang Nakhon Ratchasima district, Nakhon Ratchasima province.

(3) It illustrates magnitude of discharge that related to urban flood extent and economic value loss, which also offers the further suggestion on urban flood mitigation and prevention.

1.7 Thesis structure

The thesis is organized in five chapters: Chapter I to V. Chapter I "Introduction" present the background problem and significance of the study, research objectives, scope and limitations of study, basic assumption, study area, benefits of the study, and thesis structure.

Chapter II "Basic Concepts and Literature Reviews" consists of (1) technical term for urban flood study, (2) types of hydrodynamic model, (3) DHI MIKE 21 flow model, and (4) literature reviews.

Chapter III "Equipment, Data and Methodology" summarize about equipment, data, and methodology. Herein, three components of research methodology with data collection and preparation includes (1) flood simulation and urban flood severity analysis, (2) urban flood vulnerability analysis, and (3) urban flood simulation scenario for flood mitigation and prevention are described in this chapter.

Chapter IV "Results and Discussion" consists of the derived data from data preparation and major results and findings of the study. Major results consists of urban flood simulation by DHI MIKE 21 model, urban flood severity analysis, urban flood vulnerability analysis, and urban flood simulation for flood mitigation and prevention.

Chapter V "Conclusion and Recommendation" contains conclusion of the study and recommendations.

CHAPTER II

BASIC CONCEPTS AND LITERATURE REVIEWS

2.1 Technical term for urban flood study

2.1.1 Urban flood

A flood is an excess of water on land that's normally dry and it is a situation. A flood can strike anywhere without warning, occurs when a large volume of rain falls within a short time. Urban is characteristic of a city or town, occurring or taking place in. It is taken to be any built up area from a village upwards. Consequently, urban flooding is an overflowing of water over land in a built up area which is usually not submerged (Will, 2007). The urban area is paved with roads and building for example and the discharge of heavy rain cannot absorbed into the ground due to drainage constraints leads to flooding of streets, underpasses, low lying areas and storm drains.

Causes of urban flood can be separated into 2 main causes; natural causes and human causes.

The natural causes mostly happened with; (1) Heavy rainfall/ flash flood, water of Heavy rainfall concentrates and flows quickly through urban paved area and impounded in to low lying area raising the water level. It creates more havoc when a main drain or a river passing through the area over-flows or breaches. (2) Lack of dams or reservoirs, these can store the excess water and regulate the flow of water. When dams become smaller, their ability to regulate the flow become less and leads to flooding. (3) Silting, the drains carry large amounts of sediments and deposited in the lower courses making beds shallower thus channel capacity is reduced. When there is heavy rain, these silted drains can't carry full discharge and result in flooding. The human causes are mostly occurred with; (1) Population and the need of materials are increase (e.g. wood, land, food, etc). This aggravates overgrazing, over cultivation and soil erosion which increases the risk of flooding. (2) Deforestation, large area of forests near the rivers and catchment of cities are used to make rooms for settlements, roads and farmlands and is being cleared due to which soil is quickly lost to drains. This raises the drain bed causing overflow and in turn urban flooding. (3) Trespassing on water storm drains, the areas which were essentially created by the storm water drains to let their flood waters pass freely being tress-passed for developmental purposes result in obstruction of water flow and thus contributed immensely to the fury of floods. (4) Urbanization leads to paving of surfaces which decreases ground absorption and increases the speed and amount of surface flow. The water rushes down suddenly into the streams from their catchment areas leading to a sudden rise in water level and flash floods. Unplanned urbanization is the key cause of urban flooding. Numerous kinds of depression and low lying areas near or around the cities which were act as cushions and flood absorbers are gradually filled up and built upon due to urbanization pressure. This results in inadequate channel capacity causing urban flooding. (5) Poor Water and Sewerage Management, old drainage and sewerage system has not been renovated .All the drainage and sewer system in many parts of Mueang Nakhon Ratchasima has poor capacity and it resulted in flood.

2.1.2 Urban flood simulation

Flooding on urban basin is intensifying due to rapid urbanization. Rapid urbanization is causing a major change in rainfall-runoff phenomenon and the drainage system. The overland flow pattern is becoming complex due to building development. Traditional 1D model such as DHI MIKE 11 could able to simulate flooded area and directions. Unfortunately, the traditional 1D modeling approach is unable to answer the requirement of urban flood severity assessment as water depth, velocity, and duration. Therefore, 2D hydrodynamic modelling as DHI MIKE 21 and DHI MIKE Flood have been improved in order to response all issue of flooding situation in urban area.

2.1.3 Urban flood severity

Urban flood severity in term of this study can be defined as qualitative description of how severe a possible flood could be (e.g. low, medium, high) depends on water depth, velocity, and duration etc. (Barroca, Bernardara, Mouchel, and Hubert, 2006)

2.1.4 Urban flood vulnerability

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The term of urban flood vulnerability has been defined from many different sources. According to Kumpulainen (2006), urban flood vulnerability is a human condition or process resulting from physical, social, economic, and environmental factors which determine the likelihood and scale of damage from the impact of a given hazard.

According to Kumpulainen (2006), the indicators for measuring urban flood vulnerability have shown in Table 2.1.

Table 2.1 Urban flood vulnerability indicators.

Vulnerability	Indicators
Physical	Urban flood depth, velocities, and duration.
Social	Affected person by urban flood (%).
Economic	City and commercial
	Residential
	Institutional
	Industrial
	Transportation
	Others (Agricultural product)
Environmental	Significant natural area (can be considered vulnerable due to unique and possibly home to rare spices of flora or fauna), waste water treatment area, and waste disposal area.

Modified from: Kumpulainen (2006).

2.2 Types of hydrodynamic model

Hydrodynamic model is used to explain water movement. It focuses on the ways difference forces affect the motion of liquids in different places such as oceans and rivers. Saint Venant equation is one of hydrodynamic models that mostly used to clarify water flows. There are three types of hydrodynamic model for flood study. 1-dimensional model is focused on flow direction from node to node (Δx). Thus, every point is marked with characteristic cross section information. 2-dimensional model is provided on depth average and velocity. The area of calculation is divided into triangular or rectangular columns covering the total depth of the water. 3-dimensional model is using cubic or triangular pyramid to calculate water level and velocity components of all spatial dimensions (Figure 2.1). It is now only applied in a few special cases such as planning hydraulic structures.

2-dimensional model will be considered as a primary model for this research due to capability to provide depth and velocity which will be used for the next step in urban flood vulnerability analysis.

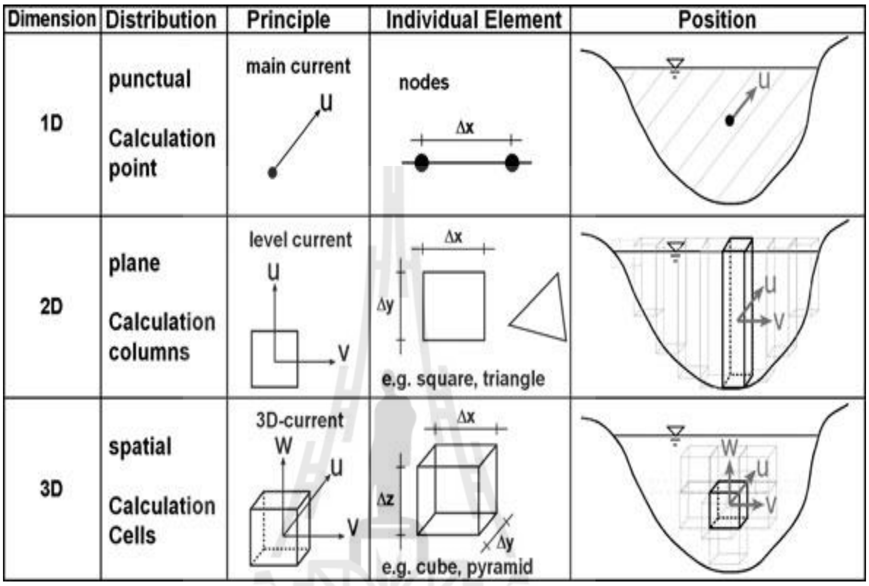

Figure 2.1 Distribution of the calculation nodes of various models.

Source: Schumann (2011).

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2.3 DHI MIKE 21 flow model

2D hydrodynamic model has been quickly developing nowadays, the relatively high data requirements would limit capacity of the application. The pure 2D model required input DEM contains of river bed profiles details as a basic of the model. However, the river bed profiles are not available in most cases due to a lack of sonar instruments to detect the reverbed. Towards this end, the role of flood modelling is become more important, because of the increasing computation capacity and more understanding of hydrologic system. The overall flooding study could be divided into three steps:

(1) To construct hydrologic model, DEM, land use map and hydro-methodological information of study area are needed as input data.

(2) Generating of flood information such as inundation area, water depth, velocity, and duration.

Relevant mitigation measures are proposed according to the results from previous step (Chen, 2007).

DHI MIKE 21 flow model is a modeling system for 2D free-surface flows. It is applicable to the simulation of hydraulic and environmental phenomena in lakes, estuaries, bays, coastal areas and seas. It may be applied wherever stratification can be neglected. DHI MIKE 21 flow model can be used to simulate a wide range of hydraulic and related items including tidal exchange and currents, storm surges, heat and recirculation, and water quality. Though, this study is attempted to use such model in the case of urban flood.

The Saint Venant equation has been used to explain flood flow as unsteady flow. The equation consists of continuity and momentum for gradually varied unsteady flow (Mujumdar, 2001). The conservation of mass and momentum integrated over the vertical, describe the flow and water level variations (DHI water & environment, 2011) as:

Continuity equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \qquad (2.1)$$

Momentum equation in the x direction:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial x} + \frac{gp\sqrt{p^2+q^2}}{C^2.h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx}) + \frac{\partial}{\partial y}\left(h\tau_{xy}\right)\right] -$$

$$\Omega q - fVV_x + \frac{h}{\rho_w}\frac{\partial}{\partial_x}(p_a) = 0 \qquad (2.2)$$

Momentum equation in the y direction:

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial y} + \frac{gq\sqrt{p^2+q^2}}{C^2.h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial y}\left(h\tau_{yy}\right) + \frac{\partial}{\partial_x}\left(h\tau_{xy}\right)\right] +$$

$$\Omega_p - fVV_y + \frac{h}{\rho_w}\frac{\partial}{\partial_y}(p_a) = 0 \qquad (2.3)$$

The following symbols are used in the equations:

$h(x, y, t)$ is water depth (m)

$d(x, y, t)$ is time varying bottom elevation (m)

$\zeta(x, y, t)$ is surface elevation (m)

$p, q(x, y, t)$ is flux densities in x- and y-directions (m3/s/m) = (uh,vh); (u,v) = depth averaged velocities in x- and y-directions respectively

$C(x, y)$ is Chezy resistance (m^{½}/s) $= \frac{1}{n}R^{\frac{1}{6}}$

R is the hydraulic radius (m)

n is Manning's n number = $\frac{1}{M}$

M is Manning's M number

g is acceleration due to gravity (9.8 m/s^2)

$\int(V)$ is wind friction factor

$V, V_X, V_y(x, y, t)$ is wind speed and components in x- and y directions (m/s)

$\Omega(x, y)$ is Coriolis parameter, latitude dependent (s^{-1})

$P_a(x, y, t)$ is atmospheric pressure ($kg/m/s^2$)

ρ_w is density of water (kg/m^3)

(x, y) is space coordinates (m)

t is time (s)

$\tau_{xx}, \tau_{xy}, \tau_{yy}$ is components of effective shear stress

The hydrodynamic (HD) module is the basic module in the DHI MIKE 21 Flow Model. It provides the hydrodynamic basis for the computations performed in the Environmental Hydraulics modules. The hydrodynamic module simulates water level variations and flows in response to a variety of forcing functions in lakes, estuaries and coastal regions. The effects and facilities under the urban flood condition include:

Bathymetry: before start a simulation, the bathymetry has to prepare in a data file or, in other words, digitizes the model area. By using digital elevation model (DEM), users can create a program which writes the 2D bathymetry matrix to an ASCII file and enter this file into the standard data file format (.dfs2) using the Grid Editor.

Bottom shear stress: The bed roughness is the resistance against the flow. It is included for calculating the bottom shear stress. The bed roughness depends on the shape of the bed (dunes, ripples, etc.) and the grain size. Despite the dynamic nature of the dunes and ripples the bed roughness is constant in time since the local bed shape change is considered constant in time on average. The bed roughness is independent of the other bed parameters.

Coriolis force: The effect of the Coriolis force can be used in three different ways as: no Coriolis force, constant in domain, and varying in domain. If the constant in domain option is selected, the Coriolis force will be calculated using a constant specified reference latitude (in Degree). If the varying in domain option is selected, the coriolis force will be calculated based on the geographical information given in the mesh file.

Sources and sinks: In the model, it can have up to a total of 300 unconnected (isolated) sources/sinks or connected source/sink pairs. The sources and sinks are then numbered in succession and you specify each of them by giving the corresponding number. For each source/sink specify as:

(1) The location (in grid coordinates). Sources/sinks must be placed at a computational point (a wet grid point, not on land or below seabed).

(2) The discharge (m^3/s), the flow speed (m/s) and the direction at which it is discharged. The name of a type 0 data file containing discharge, speed and directions must be entered under the DHI MIKE 21 flows model. The time step for these data does not need to be the same as it is for simulation. The only requirement is that the type 0 data file covers the complete simulation period. An isolated sink is specified as a source with negative discharge.

Precipitation: The default numerical scheme in DHI MIKE 21 Flow Model, HD handles evaporation and rainfall/precipitation only at wet computational cells. To activate calculations in dried cells, the users need to enable “Precipitation on dry land”. Please note that when including rainfall, the user assumes 100% runoff, which may or may not be appropriate if significant infiltration and storage can occur in the soil or ground material.

Evaporation: This is done either as a constant value or as a time series (type 0 data file), which then is applied to the entire model area, or as a time series of maps (type 2 data file) in which case each grid point is assigned its own value. The evaporation rate is specified in mm/day. Evaporation can be used in two different ways under the simulation as:

(1) If the simulation does not include any density variations, the users can include evaporation by specifying the evaporation rate in the source and sink dialog.

(2) Users can also use the precipitation facility to include evaporation in simulation. This is simply done by selecting the "included as net-precipitation" option and specifying a negative precipitation.

Flooding and drying: If the model is located in an area where flooding and drying occurs, the users can enable the flood and dry facility. In this case, a drying depth, and flooding depth must to specify (DHI water & environment, 2011a).

2.3.1 The important requirement data for DHI MIKE 21

Digital elevation model (DEM), hydrological data includes precipitation, evaporation, and discharge, and hydrodynamic parameters are the important requirements. In order to run DHI MIKE 21 flow model, bathymetry must be created at the first step from DEM. Also, the hydrological data have to prepare as the attribute data under the dfs.2 fields, whereas hydrodynamic parameters must be set before running the simulation.

2.4 Literature reviews

In 2002, the physical vulnerability of residences to flood disasters was introduced by Kelman (2002). This study was located in coastal, eastern England to examine the lateral pressure from flood depth differential between the inside and outside of a residence and flood velocity. Field surveys determined characteristics of the physical vulnerability of residences in locations to floods. The analysis indicated the failure modes of most prominent concern to be analyzed in detail included the rate of increase of flood water inside a residence, analysis of glass failure, and analysis of wall failure. The observations and calculations were applied to developing a new form of vulnerability profiling: two-dimensional (vulnerability matrices) with flood depth differential along one axis, flood velocity along the others axis, and the matrix cells displaying a damage outcome.

A new studied of parameterization under the 2D Hydrodynamic model and flood hazard mapping had introduced by Tennakoon (2004) for Nag city, Philippines. High resolution DTMs were the core data which generated from detailed topographic maps that collected from various utility organizations (Figure 2.2). Delft FLS (2D) and SOBEK (1D & 2D) hydrodynamic model were used for simulations. The model results were evaluated for three different scenarios varying the spatial resolution between 5, 7.5 and 10 m, while maintaining the same boundary and initial conditions. A multiple parameters flood hazard map was created by combination three parameters: kinetic energy, depth of inundation and duration inundation.

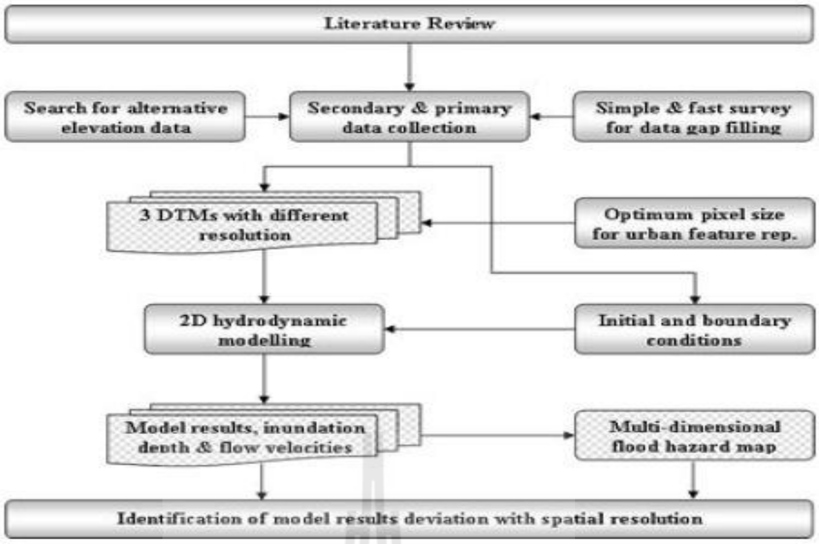

Figure 2.2 Basic step of the study by Tennakoon (2004).

Joyce and Scott (2005) had undertaken a vulnerability modeling effort using FEMA's HAZUS-MH hazard vulnerability analysis modeling software. The Flood Information Tool (FIT) was designed to support the integration of local data, also the maps and table of Maryland's potential for loss related to buildings from flooding on a county by county basis had constructed. This potential for loss, or the degree of vulnerability, was measured using four different factors: amount of county land area in susceptible to a 100 year flood, the amount of square footage of buildings potentially damaged, the number of buildings potential damaged, and the amount of direct economic losses related to buildings. These four measures of loss help give a more complete picture of the very complex issue of vulnerability to floods.

Barroca, Bernardara, Mouchel, and Hubert (2006) had demonstrated a new support tool of urban flooding vulnerability includes a set of indicators, referring to widely shared functions of urban systems that allow the final users to simplify them as much as possible while demonstrating their implementation in relevant case studies. A comprehensive list of vulnerability indicators would be irrelevant for a given situation (Figure 2.3). Consequently, the methodology to evaluate physical flood vulnerability is strongly context dependent. For example, characteristics of housing used to evaluate vulnerability, depend on local architectural traditions. The tool is used before the vulnerability evaluation, as it helps to draft a preliminary analysis presenting the main indicators to be studied.

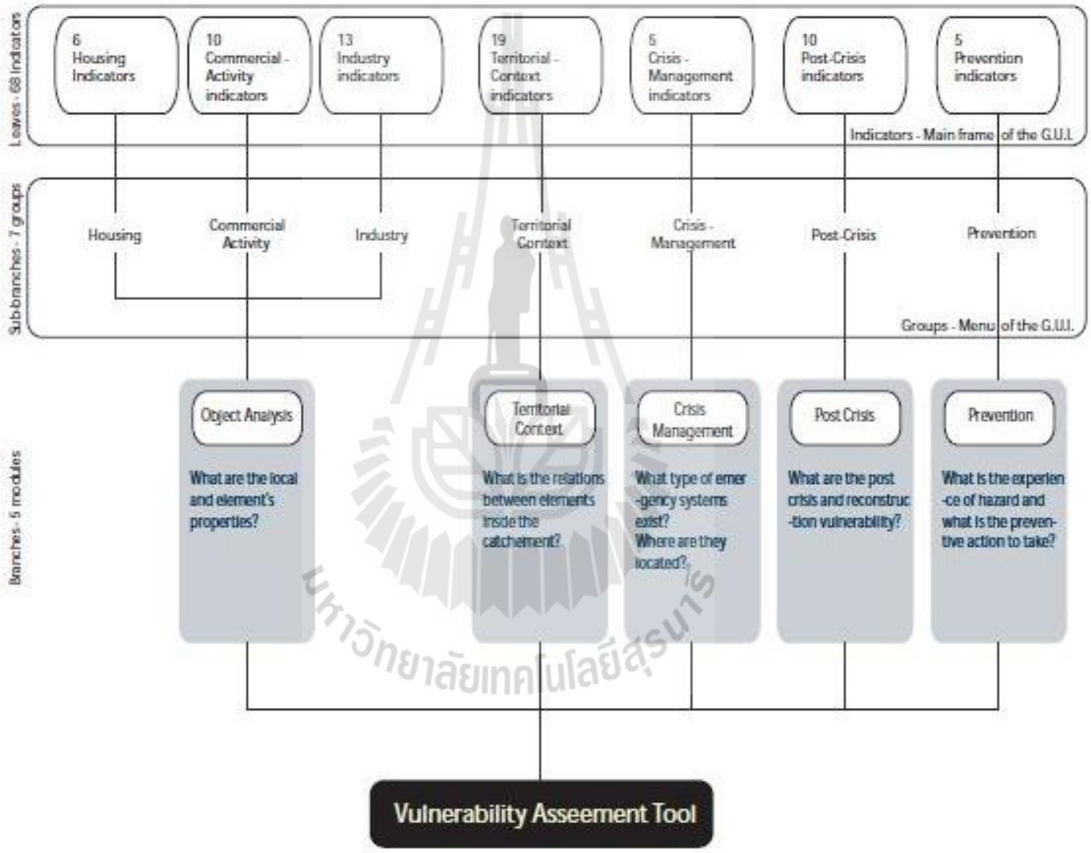

Figure 2.3 Urban flood vulnerability assessment tool introduced by Barroca et al. (2006).

According to LAWA (2006), water depth is considered to be the most important parameter of urban flood. This is represented in all urban flood maps. Water velocity is another key of flood intensity parameter. Areas with relatively steep slopes are particularly prone to high flow rates that can result in severe harm to buildings and infrastructures. Flow rates of 0.5 m/s that combined with the water depth were associated with an increased risk of injury and fatalities. Flood duration is also one of significant parameters with levels of flood severity, as flood duration extends, the levels of severity will be increased. However, it is different due to event and specific area.

Wang and Hartnack (2006) had studied simulation of flood inundation in Jilin City, Songhua river project. The combination of DHI MIKE 11, DHI MIKE flood and DHI MIKE 21 flow model were used to produces flood extents map, flood depth maps, spatial representation flood flow distributions, and spatial representation of flood inundation. Due to the implementation between 1D and 2D, the input data were included; 1D network of river, river digitization, cross-section coordinates, outflow hydrographs, and inflow boundary conditions while a depth/discharge (rating curve) formulation is assumed valid at the outflow boundary.

Chen (2007) had used 1D and 2D hydrodynamic model to simulate the Bangkok's flood scenarios for return periods of 5, 10, and 25 years. The steps of study were focused in three steps; (1) Construct hydrologic model, DEM, LULC, hydromethodological information of study area as input data. (2) Generation of flooding information such as water depth, velocity, and duration and, (3) propose the relevant of flood mitigation, whereas the step of hydrologic model was provided in Figure 2.4. A multi parameter flood impact assessment was proposed to categorize the flood impact according to different interests, such as human safety and property/estate damage. Another flood impact assessment method which integrates depth and velocity was carried out and compared with the proposed one. According to the different emphasis on flood impact, flood impact maps for three visions; human safety, properties and estates, and equal were created. Thus, the visions of flood impact maps could help to indicate the disturbance caused by floods to the diverse aspects of the society. The methodology used in flood impact assessment should be adjusted according to local situation.

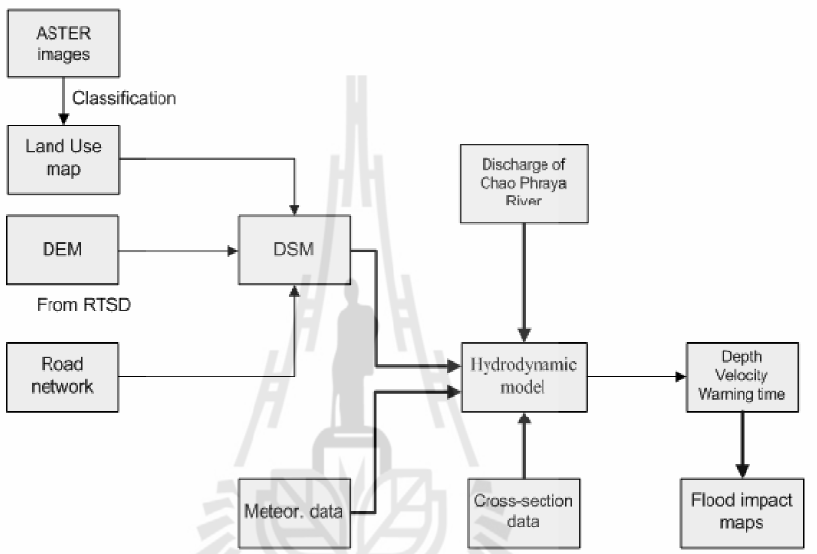

Figure 2.4 Hydrodynamic modelling for generate water depth, warning time, and flood impact maps by Chen (2007).

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Cancado, Brasil, Nascimento, and Guerra (2008) discussed the three major elements related to the flood potential damages: hazard, vulnerability and risk. The flood maps of the urban area were firstly developed with local cartographic information allowing the association of data generated by hydrologic and hydraulic modeling and land use characteristics. The hazard map was produced by a function of flood water depth and velocity as Table 2.2. Furthermore, the total risk of flood in Manhuacu was measured by an index defined according to two dimensions, the hazard and the vulnerability as:

$$R_T = H \times V_T \tag{2.4}$$

$$V_T = \text{function}\ (E, I) \tag{2.5}$$

When,

R_T = Total risk

H = Hazard index

V_T = Population vulnerability index

E = Socioeconomic vulnerability index

I = Impact index

The hazard (H) is the natural pressure factor or a community's potential danger due to the possible occurrence of a natural phenomenon. This parameter represents the characteristics of the flood as flood depth, flood velocity, and flood probability.

The population vulnerability index (V_T) is the combination of two sub-indexes as index of socioeconomic vulnerability (E) and impact index (I).

The parameter E refers to different population levels of income and education. The low income families usually possess homes of low constructive standards and therefore more susceptible to the flood damages. They usually don't possess insurance or have low covering insurance. Their limited household budget makes difficult a fast and effective disaster recovery.

The second index (I) represents the factors that intensify the adverse effects of the flooding such as old people and children exposed to flooding, displacement capacity, larger dependence, and smaller resistance to diseases and frequently they do have fewer resources.

Syme (2008) had used 2D modelling to study flooding in urban areas for buildings and fences. For such analysis, buildings and fences were firstly represented by blocking out of 2D element. Here, Manning number between buildings, parks, canal and river, and road were introduced in Table 2.3.

Table 2.2 Hazard as a function of flood water depth and velocity.

Hazard	Depth (D) and Velocity (V)
High	D > 1.50 m. or V > 1.50 m/s.
Medium	0.50 m. < D < 1.50 m or 0.50 m/s. < V < 1.50 m/s.
Low	0.10 m. < D < 0.50 m or 0.10 m/s. < V < 0.50 m/s.

Source: Cancado, Brasil, Nascimento, and Guerra (2008).

Table 2.3 Manning Number between buildings, parks, canal and river, and road.

Scenario	Land use	Manning's n number	Manning's M number
1	Building	0.3300	3.0000
2	Parks	0.0500	20.0000
3	Canals and river	0.0133	76.0000
4	Road	0.0140	71.0000

Source: Syme (2008).

Kreibich et al. (2009) had introduced depth and flow velocity as significant parameter in flood damage modeling. Flow velocity is generally presumed to influence flood damage. However, this influence is hardly quantified and virtually no damage models take it into account. Therefore, the influences of flow velocity, water depth and combinations of these two impact parameters on various types of flood damage were investigated in five communities affected by the Elbe catchment flood in Germany in 2002. 2D hydraulic models and medium spatial resolutions were used to calculate the impact parameters at the sites in which damage occurred. A significant influence of flow velocity on structural damage particularly on roads could be shown in contrast to a minor influence on monetary losses and business interruption. Forecasts of structural damage to road infrastructure should be based on flow velocity alone. The water depth is suggested as a suitable flood impact parameter for reliable forecasting of structural damage to residential buildings above a critical impact level of 2 m. of water depth. However, general consideration of flow velocity in flood damage modeling, particularly for estimating monetary loss, cannot be recommended.

Patro, Chatterjee, Singh, and Raghuwanshi (2009) had presented flood modeling of a large flood prone river system in India with limited data. The difficult tasks to model this case were; the lack of high resolution of DEM, hard to measured cross section data of the rivers, lack of sufficient and accurate calibration, and validation data sets. Moreover, detailed field surveys for deriving such information on topography are often time consuming and expensive. The calibration and validation results of DHI MIKE 11 shown that model performed quite satisfactorily in simulating the river flow in the delta region of Mahanadi River basin for a wide range of peak inflow discharge at the inlet of the delta. However, it was observed that during low flow, there were differences in model simulated and observed water levels as well as discharges. This may be attributed to the absence of the details of structures such as barrages, and their regulations in the present model setup. As the gates of the barrages were fully raised during severe floods, a condition of natural river flow was created that result in good model performance during peak flows. The developed hydrodynamic model maybe used to generate different flooding scenarios for a possible solution to the flooding problem in this region.

Liu, Wen, Yang, Shang, and Zhang (2011) had studied GIS-based analysis of flood disaster risk in LECZ of China and population exposure. ArcGIS had used as the main data analysis platform, this study utilized data of disaster risks from hotspots, world population gridded data (GPWv3), and data of Chinese coastal lowlands to analyze characteristics of flood disasters and the exposed population at the coastal lowlands of china. The data of the flood disaster included: the frequency and distribution of the global flood disaster, the total economic loss of global flood disaster and the risk of the economic loss. The spatial resolution of the aforementioned grid data was 2.50 x 2.50 minute of arc and the levels of risk were divided into 10 from low to high.

Mah, Putuhena, and Lai (2011) had presented a practical way to envisage the flood vulnerability in deltaic region, Kuching city of Malaysia, particularly on the concern of sea level rise. Ground model and hydrodynamic model were built based on the area along Sarawak River while the estimation of flood vulnerability in deltaic Kuching city has concurrence with sea level rise.

Furthermore, the used of GIS for flooding analysis in urban drainage was applied in 2012 by Fuchs, Beeneken, and Lindenberg (2012). 1D and 2D simulation model were used as key tool to analyzed hazard and risk assessment. In this case, a manhole-related classification was introduced in order to characterize the hazard for a drainage area into five classes (Table 2.4).

Table 2.4 Manhole-related classification.

Hazard classes	Classification	Reason
0	No hazard	Water level ≤ 2.5 m. under ground level
1	Slight hazard	Water level ≤ 1m. under ground level
2	Moderate hazard	Water level between 1 m. under ground level and overflow volume ≤ 5 m^3
3	Great hazard	Overflow < 1,000 m^{3*}
4	Very great hazard	Overflow ≥ 1,000 m^{3*}

* Or assessment in the form of a flood test

In 2012, the used of DHI MIKE 21 for urban flooding was studied in Gothenburg (Filipova, Rana, and Singh, 2012). The purpose of this study was to developed flood risk maps of the Central part of Gothenburg using the DHI model MIKE 21, topography and precipitation data. By using measured data for three precipitation events, the water level and flood velocity in the area are determined. These flood risk maps could be further used in city planning for the analysis of the flood management practices. The proximity of Gothenburg to the Gota River and the North Sea and the possibility of extreme precipitation are factors that increase the risk of flooding. In this study, only flooding due to high amount of precipitation was considered. Furthermore, it was assumed that (1) the high amount of rainfall, (2) the drainage system was blocked and not included in the model, and (3) ignored infiltration. The water level and velocity in Gota River and the two canals Rosenlund and Stora Hamn could not be accurately analyzed because no hydrograph data was available and also because 1D flow was better simulated in DHI MIKE11.

In 2013, remote sensing and spatial data analysis had used to extract a building typology for contributed to flood vulnerability assessment was presented by Angela, Norbert, and Jochen (2013). The assessment of potential flood impacts on buildings must not be done one by one, because the survey would cost a fortune. Therefore a building typology was required in order to transfer knowledge from the assessment of in-depth investigations of individual buildings to other buildings with similar characteristics. Furthermore, building parameter for a building typology was here introduced as building height, building size, building form, building roof structure, building topological relation to the neighbors, and building topological relation to the open space. The synthesis of review literature was represented in Table 2.5.

Table 2.5 Synthesis of revisions, showing the related point of interests.

Year	Authors	Point of interests
2002	Kelman	Combination between an observation and calculation in order to develop new form of vulnerability outline: vulnerability matrices have created using flood depth & velocity and the matrix cells displaying a damage outcome.
2004	Tennakoon	A combination of three parameters as kinetic energy, depth of inundation, and duration inundation was used to create a multiple parameters flood hazard map using 2D Hydrodynamic model.
2005	Joyce and Scott	Vulnerability model, using FEMA's HAZUS-MH hazard vulnerability analysis modeling software. Introduce the Flood Information Tool (FIT) to support the integration of local data, the maps, and table of Maryland's potential for loss related to buildings from flooding on a county by county.
2006	Barroca et al.	Demonstrate a new support tool of urban flooding vulnerability includes a set of indicator.
2006	LAWA	Illustrated the most important flood damage parameter as water depth and water velocity.

Table 2.5 Synthesis of revisions, showing the related point of interests (Continued).

Year	Authors	Point of interests
2006	Wang and Hartnack	The combination of MIKE 11, MIKE flood and MIKE 21 flow model were used to produces flood extents map, flood depth maps, spatial representation flood flow distributions, and spatial representation of flood inundation.
2007	Chen	The use of 1D and 2D hydrodynamic model to simulate the Bangkok's flood scenarios for return periods. The steps of study were; (1) Construct hydrologic model, DEM, LULC, hydro methodological information of study area as input data. (2) Generation of flooding information such as water depth, velocity, and duration and, and (3) Propose the relevant of flood mitigation.
2008	Cancado et al.	Discussed the three major elements related to the flood potential damages as hazard, vulnerability, and risk. The measurement of; (1) Total risk (R_T) (2) Hazard index (H) (3) Population vulnerability index (V_T) (4) Socioeconomic vulnerability index (E) (5) Impact index (I)
2008	Syme	The use of 2D modelling to study flooding in urban areas for buildings and fences. Buildings and fences were firstly represented by blocking out of 2D element. An introduction of the effect of varying Manning's n between building and garden

Table 2.5 Synthesis of revisions, showing the related point of interests (Continued).

Year	Authors	Point of interests
2009	Kreibich et al.	Demonstrations of depth and flow velocity are significant parameter in flood damage modeling.
		Introduces a function of flood water depth and velocity for levels of hazard.
2011	Liu et al.	The data of the flood disaster included the frequency and distribution of the global flood disaster, the total economic loss of global flood disaster, and the risk of the economic loss.
2011	Mah et al.	Flood vulnerability particularly on the concern of sea level rise based on ground model and hydrodynamic
2012	Fuchs et al.	1D and 2D simulation model were used as key tool to analyzed hazard and risk assessment.
		Introduces a manhole-related classification to characterize the hazard for a drainage area.
2012	Filipova et al.	Develops flood risk maps of the Central part of Gothenburg using the DHI model MIKE 21, topography, and precipitation data.
2013	Angela et al.	A used of remote sensing and spatial data analysis for extracted a building typology for contributed to flood vulnerability assessment.

CHAPTER III

EQUIPMENT, DATA AND METHODOLOGY

Under this chapter three main sections are explained including equipment, data, and methodology. For first two sections, hardware and software and data are here summarized. Meanwhile research methodology which includes three main components: (1) flood simulation and urban flood severity analysis (2) urban flood vulnerability analysis and (3) urban flood simulation scenario for flood mitigation and prevention are here described.

3.1 Equipment

Basic hardware and advance software which are used in this research are summarized in Table 3.1. The main functions of these software are as follows:

(1) DHI MIKE 21 is used as top priority software for the analysis to simulate physical flood indicators includes flood extent, depth, and velocity.

(2) ERDAS Imagine 9.2 is used to validate and mosaic DEM, image rectification, and manage remotely sensed data.

(3) ERSI ArcMap 9.2 is use to digitize land use data, analyze urban flood severity and vulnerability and to produce output maps.

(4) MS Excel is use to prepare the attribute data for GIS analysis.

Table 3.1 Basic hardware and advance software.

Equipment	**Remarks**
1. Hardware	
- Notebook	Personal
- GPS	Remote Sensing Laboratory, SUT
- Desktop computer	Remote Sensing Laboratory, SUT
2. Software	
- DHI MIKE 21	Support License from DHI, Denmark
- ESRI ArcMap 9	Remote Sensing Laboratory, SUT
- ERDAS Imagine 8.7	Remote Sensing Laboratory, SUT
- MS Excel	Remote Sensing Laboratory, SUT

3.2 Data

The required data for flood simulation and urban flood severity analysis, urban flood vulnerability analysis and urban flood simulation for flood mitigation and prevention include topography, hydrology, land use, and social data are collected and prepared as summary in Table 3.2 - 3.3. In addition, major preparation processes are separately described in the following section.

Table 3.2 Data collection.

Data categories	Data	Year	Number	Scale/Resolution	Sources
Primary dataset	DEM	2004	233	5.0×5.0 m	MOAC
	World view-II Imagery	2012	1	0.5×0.5 m^2	NRM
	SPOT-5 Imagery	2008	1	2.5×2.5 m^2	NRM
	THEOS Imagery	2010	4	2.0×2.0 m^2	GISTDA
Secondary datasets	Land use data	2008	-	1: 25,000	LDD
	Administrative boundary	2008	-	1: 25,000	LDD
	Lam Takhong Watershed	2010	1		NRCT
	Actual flood map	2010	1		GISTDA
	Precipitation	2010	-	-	TMD
	Evaporation	2010	-	-	TMD
	Discharge	2010	-	-	LTOMP
	Watergates	2010	-	-	LTOMP
	Number of population affected flood	2010	-	-	NRM
	Standard compensate value of OIC	2010	-	-	OIC
	Standard compensate value of agricultural loss	2011			PMO

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Table 3.3 Data preparation.

Data categories	Data	Preparation process
Primary dataset	DEM	Error checking, Error correction, and mosaicking by ERDAS image
	World view-II Imagery	Reference image for image rectification
	SPOT-5 Imagery	Rectification with image to image
	THEOS Imagery	Rectification with image to image
	LULC	Visual interpretation of multi-date remote sensing data
	Precipitation	Conversion to dfs2 by MIKE zero tool
	Evaporation	Conversion to dfs2 by MIKE zero tool
	Discharge	Conversion to dfs2 by MIKE zero tool

Notification*

GISTDA	Geo-Informatics and Space Technology Development Agency
LDD	Land Development Department
LTOMP	Lam Takhong Operation and Maintenance Project
MOAC	Ministry of Agriculture and Cooperatives
NRM	Nakhon Ratchasima Municipality
NRCT	National Research Council of Thailand
OIC	Office of Insurance Commission
PMO	Prime Minister Office
TMD	Thai Meteorological Department

3.2.1 DEM Verification and Mosaicking

The collected DEM of LDD is firstly checked the missing value and error with ERDAS Imagine software. After that all dataset have mosaicked as the single image. Herein, 233 scenes of DEM have used to mosaic for the whole study area. The basic specification of DEM scene is summarized in Table 3.4. The coverage of DEM represents 4 topographic map of Royal Thai Survey Department, scale 1:50,000 with sheet number: 5338-I, 5339-II, 5438-IV, and 5439-III.

Table 3.4 Specification of LDD's DEM dataset based on LDD in year 2012.

Specification	Detail
Ground Sampling Distance	5.0 m.
Coverage	2.0 x 2.0 km.
Coordinate Reference System	UTM
Datum	WGS84
Scale	1:4,000
Horizontal accuracy	1 m. or better
Vertical accuracy	2 - 4 m. or better

3.2.2 Visual interpretation for land use in 2010

Land use data in 2008 from LDD have been used as baseline data for visual interpretation of land use in 2010 with more specific detail for building types (Table 3.5). The performance of the method is demonstrated on real satellite images from three different sensors: THEOS in 2010, Worldview-2 in 2012, and SPOT-5 in 2008. The recognition elements have included: shape, size, pattern, shadow, tone or colour, texture, association, and site (Campbell, 2002; Jensen, 2007; Ongsomwang, 2007; Bhatta, 2008). In practice, land use categories have visually interpreted by screen digitizing method under ESRI ArcMap at the scale of 1:4,000.

In addition the interpreted land use data are assessed accuracy using stratified random sampling with approximately 323 sampling points (n) based on binomial probability theory as shown in Equation 3.1 for standard measurement values: overall accuracy, producer's accuracy (omission error), and user's accuracy (commission error) and kappa hat coefficient of agreement (Ongsomwang, 2007).

$$n = \frac{Z^2(1-P)P}{d^2} \tag{3.1}$$

When,

n = Sample points

P = the proportion factor (0.3)

Z = 95 percent of confidence level (1.96)

d = the margin of error (0.05)

Table 3.5 Land use classification system for visual interpretation.

Land use of LDD		Land use of visual interpretation
Level I	**Level II**	**Level III**
Urban and built-up area	City and commercial	Commercial with 1 floor*
		Commercial buildings with 2 floors*
		Commercial buildings with 3 floors*
		Commercial buildings with 4 floors*
		Shopping mall with 1-3 floors*
	Industrial	Small industrial and warehouse*
		Large industrial (more than 10,000 m^2)*
		Large warehouse*
	Institutional Land	Office building with 1 floor*
		Office building with 2-3 floors*
		Office building with 4-5 floors*
		Office building with 6-9 floors*
	Residential	Concrete and wooden house*
		House with 1 floor*
		House with 2 floors*
		Townhouse with 2 floors*
		Townhouse with 4 floors*
		Dormitory/Condominium with 4-5 floors*
	Transportation	Bus station/Gasoline*
		Road*
		Railway station*
Agricultural land	Aquaculture land	
	Animal farm house	

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Table 3.5 Land use classification system for visual interpretation (Continued).

Land use of LDD		Land use of visual interpretation
Level I	**Level II**	**Level III**
Agricultural land	Aquaculture land	
	Animal farm house	
	Field crop	
	Horticulture	
	Orchard	
	Paddy field	
	Pasture	
	Perennial trees	
Forest land	Disturbed deciduous forest	
	Dense forest Plantation	
Miscellaneous land	Rangeland	
	Wetland	
	Others	Cemetery
		Garbage dump
		Golf course
		Grass*
		Recreation and green area*
		Landfill*
		Marsh and swamp*
		Pit*
		Shrub/Scrub*
Water body	Artificial water body	
	Natural water body	

Notification * Adopted classes from LDD with updating theirs boundaries based on remote sensing data in 2010.

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3.3 Methodology

To serve the objectives, three main components of research methodology including data collection and preparation are (1) flood simulation and urban flood severity analysis (2) urban flood vulnerability analysis, and (3) urban flood simulation scenario for flood mitigation and prevention. The overview research methodology is presented in Figure 3.1 while the details of each component are further explained in following section.

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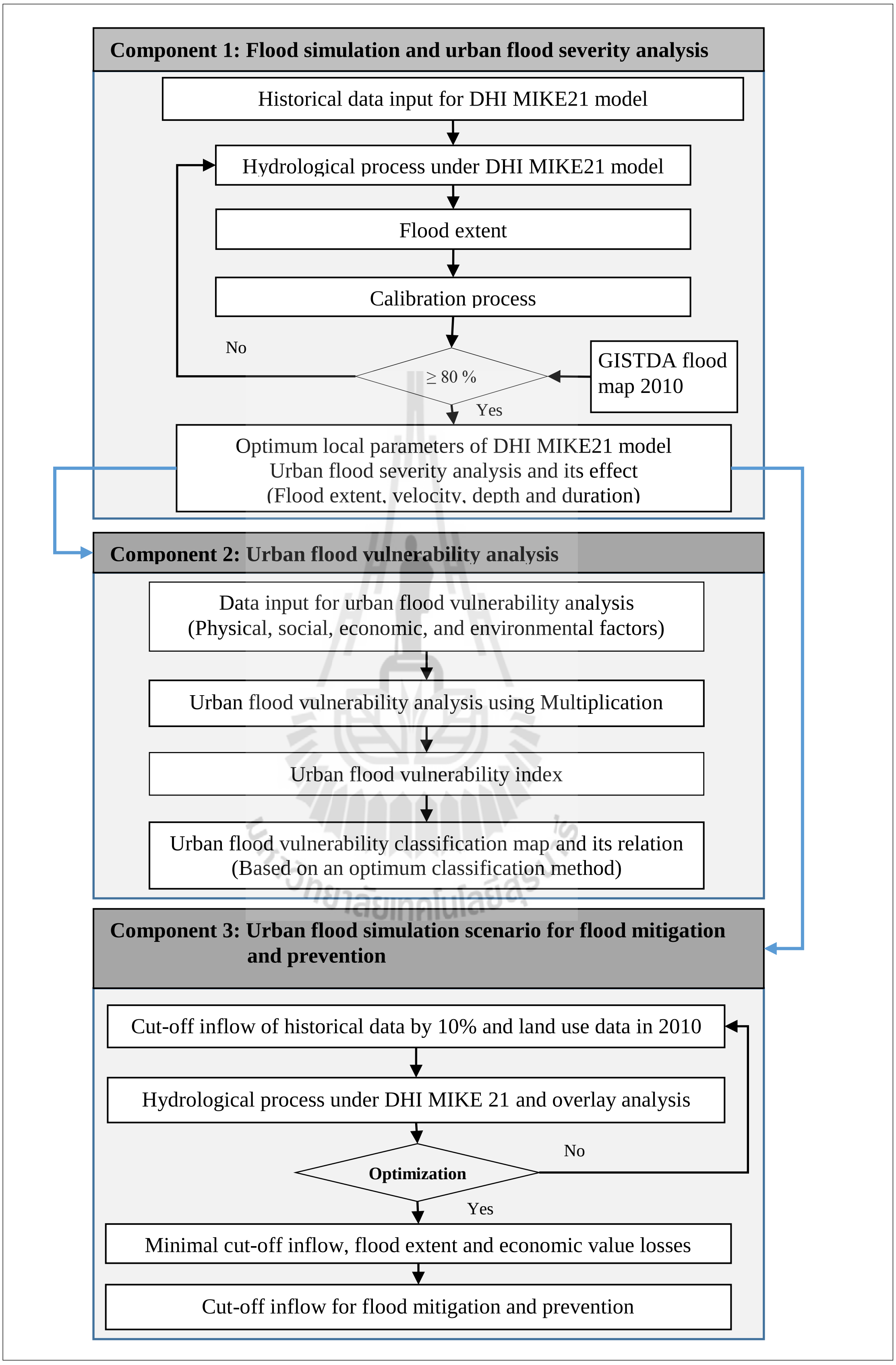

Figure 3.1 Overview of research methodology.

3.3.1 Component 1: Flood simulation and urban flood severity analysis

Schematic work flow of flood simulation and urban flood severity analysis is displayed in Figure 3.2. In practice, the prepared input data included DEM, precipitation, discharge, watershed boundary, and watergates are firstly used to simulate flood extent, depth, water velocity, and its duration by using DHI MIKE 21 model with an optimum local parameter. Then, the derived flood data are further used to analyze urban flood severity and its effects.

For flood simulation by DHI MIKE 21 model, bathymetry has to create at the first step in order to define the new working area. Herein, DEM has been used to create new grid of working area using bathymetry management (define bathymetry area). Then, interpolation technique has to use to extract foreground. After that, the boundary file is verified. Herewith, precipitation and discharge is considered as add up parameters for this case. Water levels are then detected from stations and also used to generate water level boundary condition.

In this study, Manning's n or bed roughness is the main parameter to adjust based on land cover. It is a friction that causes the water to flow faster or slower, which affects the water level to increase or decrease (DHI water & environment, 2011). The adjustment can be either a single value or a constant value for each spatial distribute. The Manning's M is the inverse of the more conventional Manning's n (DHI water & environment, 2011) as:

$$M = \frac{1}{n} \tag{3.2}$$

The value of n is typically in the range of 0.01 (smooth channels) to 0.10 (thickly vegetated channels). This corresponds to values of M between 100 and 10, respectively. Generally, lower values of Manning's M are used for overland flow compared to channel flow (Holden, Kirkby, Lane, Milledge, Brookes, Holden, and Mcdonald, 2008). Herein, the Manning's n values and Manning's M values of specific land use type are adopted from Chow (1959), Syme (2008), and Kalyanapu et al. (2009) as shown in Table 3.6.

After that, the simulated flood area from DHI MIKE 21 model is then accessed accuracy with flood map of GISTDA as confusion matrix (Table 3.7). Herein, overall accuracy, flood detection rate, and false alarm rate are calculated and considered for optimized calibration process and local parameter of DHI MIKE 21 model identification (Wang, Qu, and Hao, 2008).

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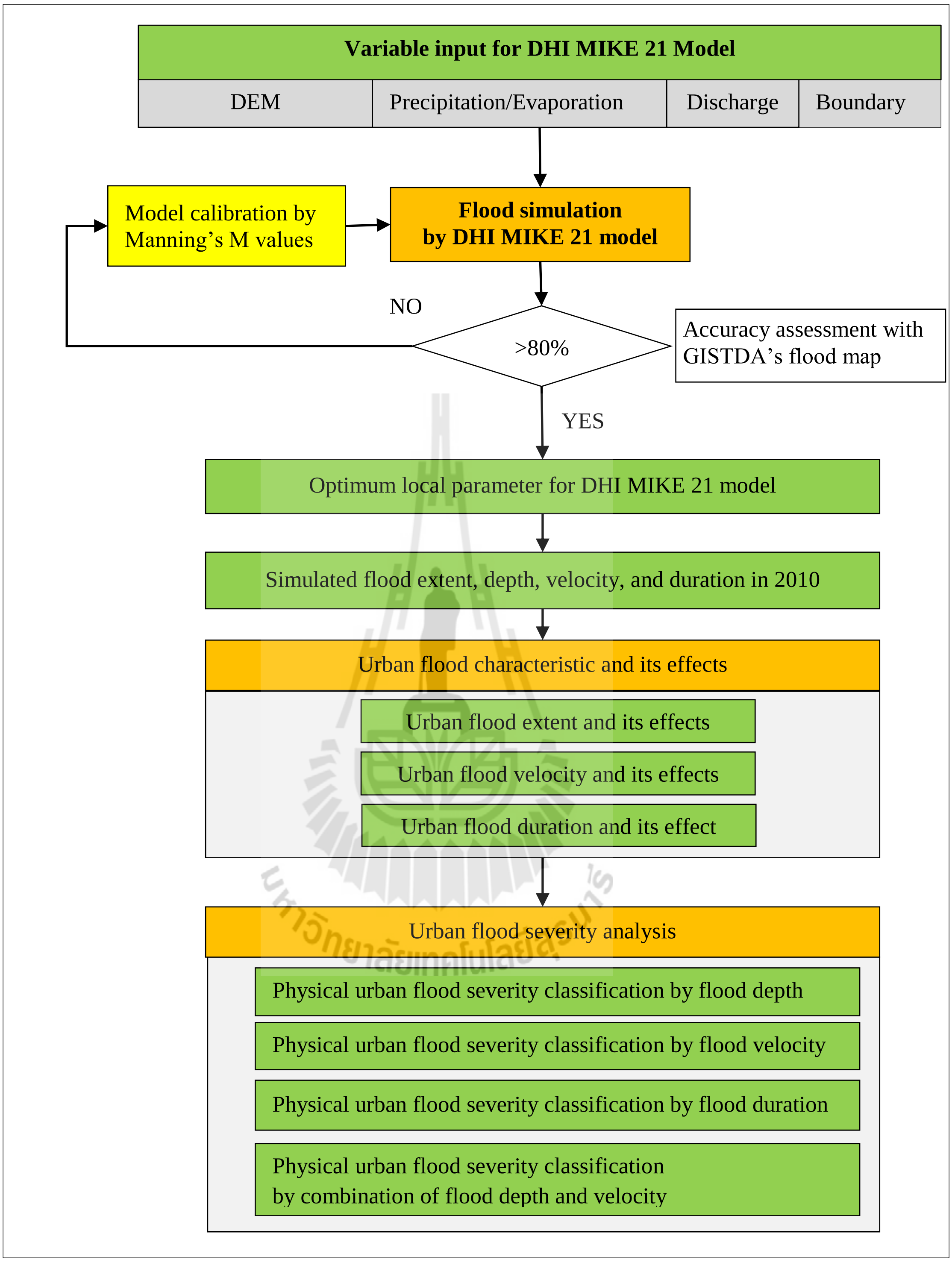

Figure 3.2 Schematic workflow of flood simulation and urban flood severity analysis.

Table 3.6 The Manning's M number based on Chow (1959), Syme (2008), and Kalyanapu et al. (2009).

Level 1	Land use	Min	Normal	Max	Source
U	Bus station/Gasoline station	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Commercial buildings with 1 floor	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Commercial buildings with 2 floors	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Commercial buildings with 3 floors	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Commercial buildings with 4 floors	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Concrete and wooden house	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Dormitory/Condominium with 4-5 floors	14.75	19.75	24.75	Kalyanapu et al., 2009
U	House with 1 floor	14.75	19.75	24.75	Kalyanapu et al., 2009
U	House with 2 floors	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Large industrial (more than 10,000 sq. m.)	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Large warehouse	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Office building with 1 floor	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Office building with 2-3 floors	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Office building with 4-5 floors	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Office building with 6-9 floors	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Railway station	14.75	19.75	24.75	Syme, 2008
U	Road	14.75	19.75	24.75	Syme, 2008
U	Shopping mall (levels 1-3)	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Small industrial and warehouse	14.75	19.75	24.75	Kalyanapu et al., 2009
U	Townhouse with 2 floors	14.75	19.75	24.75	Kalyanapu et al., 2009
A	Abandoned aquaculture land	28.57	28.57	28.57	Chow, 1959
A	Abandoned field crop	25.00	33.33	50.00	Kalyanapu et al., 2009
A	Abandoned paddy field	88.50	88.50	88.50	Kalyanapu et al., 2009
A	Animal farm house	3.03	3.03	3.03	Syme, 2008
A	Field crop	2.78	25.00	33.33	Kalyanapu et al., 2009
A	Horticulture	22.22	28.57	40.00	Chow, 1959
A	Orchard	2.78	2.78	2.78	Kalyanapu et al., 2009
A	Pasture	3.08	3.08	3.08	Kalyanapu et al., 2009
A	Perennial trees	2.50	2.50	2.50	Kalyanapu et al., 2009
A	Rice paddy	5.48	22.22	40.00	Kalyanapu et al., 2009
F	Dense forest Plantation	5.00	5.00	5.00	Kalyanapu et al., 2009
F	Disturbed deciduous forest	5.00	5.00	5.00	Kalyanapu et al., 2009
M	Cemetery	88.50	88.50	88.50	Kalyanapu et al., 2009
M	Garbage dump	88.50	88.50	88.50	Kalyanapu et al., 2009
M	Golf course	2.72	2.72	2.72	Kalyanapu et al., 2009
M	Grass	2.72	2.72	2.72	Kalyanapu et al., 2009
M	Recreation and green area	24.75	24.75	24.75	Kalyanapu et al., 2009
M	Landfill	88.50	88.50	88.50	Kalyanapu et al., 2009

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Table 3.6 The Manning's M number based on Chow (1959), Syme (2008), and Kalyanapu et al. (2009) (Continued).

Level 1	Land use	Min	Normal	Max	Source
M	Marsh and swamp	11.63	11.63	11.63	Kalyanapu et al., 2009
M	Pit	28.57	28.57	28.57	Kalyanapu et al., 2009
M	Shrub/Scrub	2.50	2.50	2.50	Kalyanapu et al., 2009
W	Water body	28.57	75.19	100.00	Chow, 1959

Table 3.7 Confusion matrix for accuracy assessment.

GISTDA data	**DHI MIKE 21 model**		**Row Total**
(Reference data)	Flood	Non-flood	
Flood	a	b	m_1
Non-Flood	c	d	m_0
Column Total	n_1	n_0	n

Modified from: Wang, Qu, and Hao (2008)

As shown in Table 3.7, the total numbers of correct flood hits and non-flood hits are represented by a, and d, respectively. In this case DHI MIKE 21 model indicates a non-flood event at a certain location which disagrees with the GISTDA flood map, the event is labeled as “flood missing”. The total number of flood missing is summed up as b. When DHI MIKE 21 model result indicates flood but the GISTDA flood map is flood free, the event is labeled as “false alarm”. The total number of false alarms is denoted by c.

The overall accuracy of the flood detection rate can be evaluated as the proportion of the total number of correct hits:

$$\text{Overall accuracy} = \frac{(a+d)}{(a+b+c+d)} \tag{3.3}$$

The flood detection rate is defined as the ratio of flood areas from DHI MIKE 21 model that are correctly detected by GISTDA to the total number of flood areas in 2010:

$$\text{Flood detection rate (omission error)} = \frac{a}{(a+b)} \tag{3.4}$$

The false alarm rate is the proportion of non-flood areas from GISTDA that are incorrectly generated as flood from DHI MIKE 21 model as:

$$\text{False alarm rate (commission error)} = \frac{c}{(c+d)} \tag{3.5}$$

In this study, if the result of overall accuracy is equal or more than 80 percent, the simulated flood by DHI MIKE 21 is accepted due to strong agreement between the DHI MIKE 21 product and GISTDA flood.

After that, urban flood severity is analyzed based on depth and velocity. The urban flood severity is analyzed at two levels. At Level I, urban flood severity is separately classified by each indicator (depth, velocity, and duration) according to its flood severity classification as shown in Table 3.8, Table 3.9, and Table 3.10.

Table 3.8 Classification of urban flood severity according to depth.

Urban flood severity level	Maximum depth (m)
Very low	≤ 0.20
Low	≤ 0.40
Moderate	≤ 1.00
High	≤ 1.50
Very High	> 1.50

Source: Chen (2007).

Table 3.9 Classification of urban flood severity according to velocity.

Urban flood severity level	Maximum velocity (m/second)
Very low	≤ 0.25
Low	≤ 0.50
Moderate	≤ 1.00
High	≤ 2.00
Very high	> 2.00

Source: Chen (2007).

Table 3.10 Classification of urban flood severity according to duration.

Urban flood severity level	Flood duration (days)
Very low	1-3
Low	4-6
Moderate	7-9
High	10-12
Very high	13-14

Applied from: DHI MIKE 21 result.

At Level II physical urban flood severity is combined from two factors (the normalized flood depth and velocity) using additive method of Index model (Afshari, Mojahed, and Yusuff, 2010). Herein available classification methods (equal interval, defined interval, quantile, natural break, geometrical interval and standard deviation) under ESRI ArcMap are examined to identify an optimum classification method for urban flood severity classification into 5 classes: very low, low, moderate, high, and very high using consistency test with percentage of affected population by flood (PAPF) as coincident matrix.

The derived physical urban flood severity by depth and velocity is further used as one of the four factors for urban flood vulnerability analysis in the next component.

3.3.2 Component 2: Urban flood vulnerability analysis

Schematic work flow of urban flood vulnerability analysis which focuses on physical, social, economic and environmental aspects is displayed in Figure 3.3. In practice, the representative of the selected factor or criterion based on literature review (Kumpulainen, 2006, Sagala, 2006) for urban flood vulnerability analysis is firstly prepared with benefit criterion normalization (Malczewski, 1999) as:

$$\text{Benefit criterion normalization} = x_{ij}^{'} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \quad (3.6)$$

When;

$x_{ij}^{'}$ is the standardized score for the i^{th} object and the j^{th} attribute,

x_{ij} is the raw score, $x_j^{\max}$ is the maximum score for the j^{th} attribute,

$x_j^{\min}$ is minimum score for the j^{th} attribute,

$x_j^{\max} - x_j^{\min}$ is the range of a given criterion.

After that all four normalized factors (physical, social, economic and environmental) are directly used as score under multiplication method, here the important weighting is no applied for each factor.

The details of each factor preparation are described in the following section.

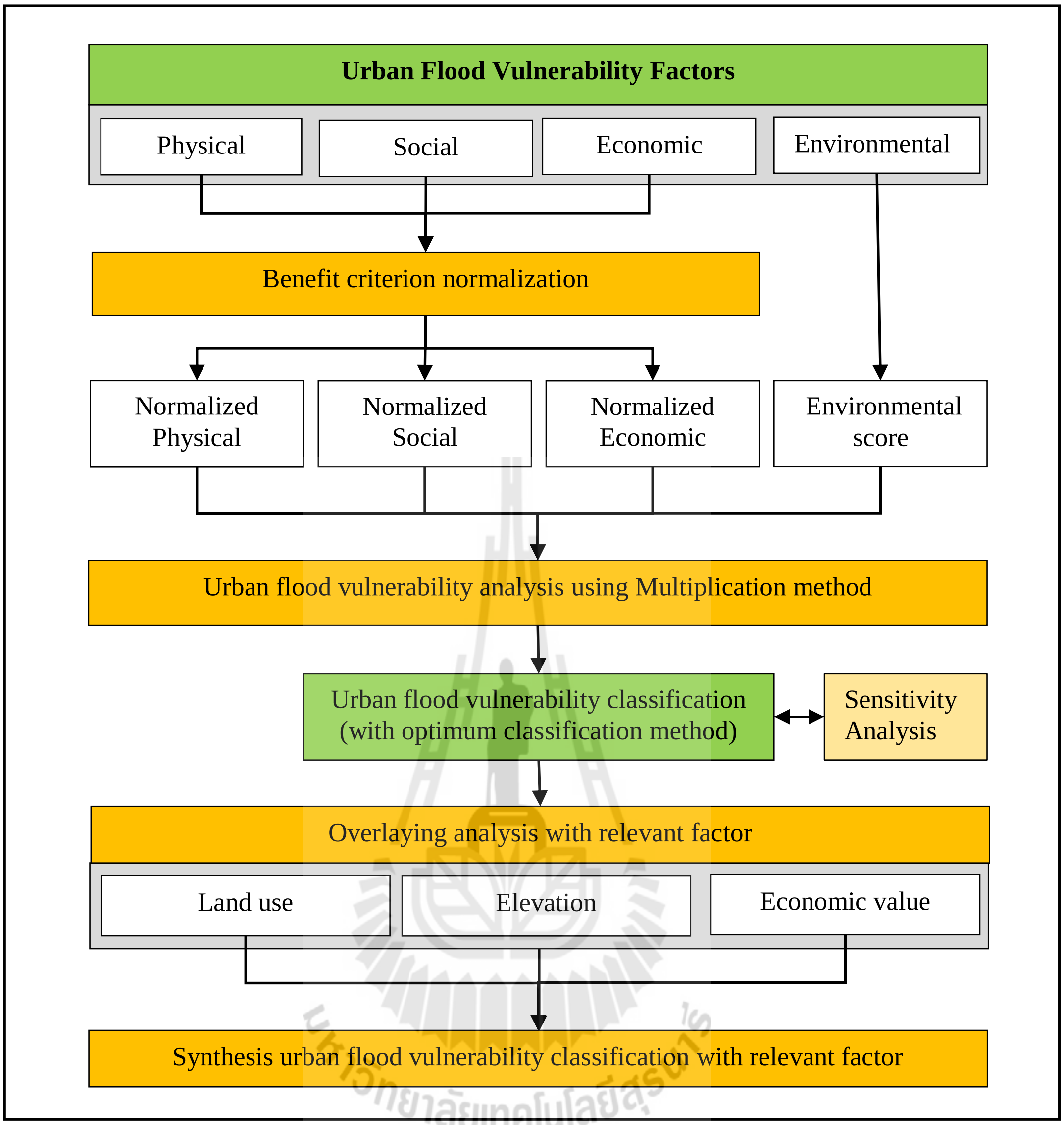

Figure 3.3 Schematic workflow for urban flood vulnerability analysis.

(1) Physical factor. The derived urban flood severity data, which is created from flood depth and velocity from the Component I, are here adopted as raw score and then normalized using benefit criterion normalization as normalized score for index model.

(2) Social factor. This factor represents by percentage of population affected by flood (PAPF) in sub districts based on statistic of Nakhon Ratchasima

municipality in 2010. Herewith, percentage of affected population by flood is calculated according to number of actual affected person by flood and flood extent in 2010 for each sub-district as:

$$PAPF\ (\%) = \frac{actual\ affceted\ person\ by\ flood}{Flooded\ extent\ in\ sub{-}district\ (sq.m)} \times 100 \qquad (3.7)$$

The derived values of $PAPF$ are then normalized using benefit criterion normalization as normalized score for index model.

(3) Economic factor. This factor has created to represent as Economic value loss for compensation due to a flood occurring. The compensate rate for urban and built-up types at Level II and agricultural land type at Level II are calculated according to standard payment from Office of Insurance Commission (OIC) and Cabinet Resolutions on August 25, 2011, respectively as shown in Table 3.11. The derived values for compensate payment as economic factor are then normalized using benefit criterion normalization as normalized score for index model.

(4) Environmental factor. This consists of positive and negative environmental impact on human during flooding. Natural areas include forest land, water body, grass, recreation and green space, marsh and swamp, pit, and shrub/scrub are here chosen as positive environment impact while artificial constructions include waste water treatment and waste disposal are here chosen as negative environmental impact. Both of positive and negative is assigned as significant environmental factor with value of 1. Others land use classes are assigned an insignificant environmental factor with value of 0.

After that, multiplication method is applied to create urban flood vulnerability index and reclassify urban flood vulnerability into five classes. In this study, available classify methods under ESRI ArcMap are also examined to identify an optimum classify method for urban flood vulnerability classification into 5 classes: very low, low, moderate, high, and very high using consistency test with flood duration as occurring in 2010 as coincident matrix. Finally, the optimum classify method are then used generate urban flood vulnerability data. This derived output are then overlay with relevant GIS data including land use, elevation from DEM and economic values losses as compensate payment for urban and built-up land and agricultural land to present flood information and its vulnerability.

Furthermore simple sensitivity analysis of urban flood vulnerability data based on leave-one-out technique is performed to identify the significant factor on its vulnerability.

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Table 3.11 Rate of compensate payment for urban and built-up area and agricultural land.

Level I	Level II	Level III	Compensate rate (Baht/sq. m)
Urban and built-up area	City and Commercial	Commercial building with 1 floor	3,661
		Commercial buildings with 2 floors	6,978
		Commercial buildings with 3 floors	6,595
		Commercial buildings with 4 floors	5,912
		Shopping mall with 1-3 floors	11,669
	Residential	Concrete and wooden house	9,577
		House with 1 floor	9,330
		House with 2 floors	10,619
		Townhouse with 2 floors	7,824
		Townhouse with 4 floors	6,177
		Dormitory/Condominium with 4-5 floors	9,191
	Institutional	Office building with 1 floor	9,330
		Office building with 2-3 floors	9,988
		Office building with 4-5 floors	9,883
		Office building with 6-9 floors	9492
	Industrial	Small industrial and warehouse	6,278
		Large industrial (more than 10,000 m^2)	8,866
		Large warehouse	5,579
	Transportation	Building and car park	6,881
		Road	6,881
		Railway station	6,881
	Others	Recreation and green area	Non compensate
		Golf course	Non compensate
		Cemetery	Non compensate
Agricultural land	Paddy field		1.38875
	Field crop		1.96875
	Perennial trees		3.18625
	Orchard		3.18625
	Horticulture		3.18625
	Pasture		1.96875
Miscellaneous* land			Non compensate
Forest land*			Non compensate
Water body*			Non compensate

Notification * These classes are considered as environmental factor.

3.3.3 Component 3: Urban flood simulation scenario for flood mitigation and prevention.

Under this component, the simulated urban flood scenario by each 10% cut-off inflow data from historical record in 2010 without precipitation was processed to generate flood extents and its extents then used to evaluate economic value losses on urban and built-up areas and agricultural land by overlay analysis. This process is reiterate operate to identify the minimal cut-off inflow and minimize the flood extent and economic value losses. After that the derived information include inflow (discharge), flood extent, and economic value loss are simultaneously plotted to identify an optimum value of minimal inflow, flood extent and economic value loss (Figure 3.4).

The result is here used as a guideline to reference and control the discharge that able to create minimize urban flood affected on land use. Further study could concern with appropriate areas as a new drainage area or a new artificial floodways might be introduced with the intention of reduce inflow volume and the flood severity.

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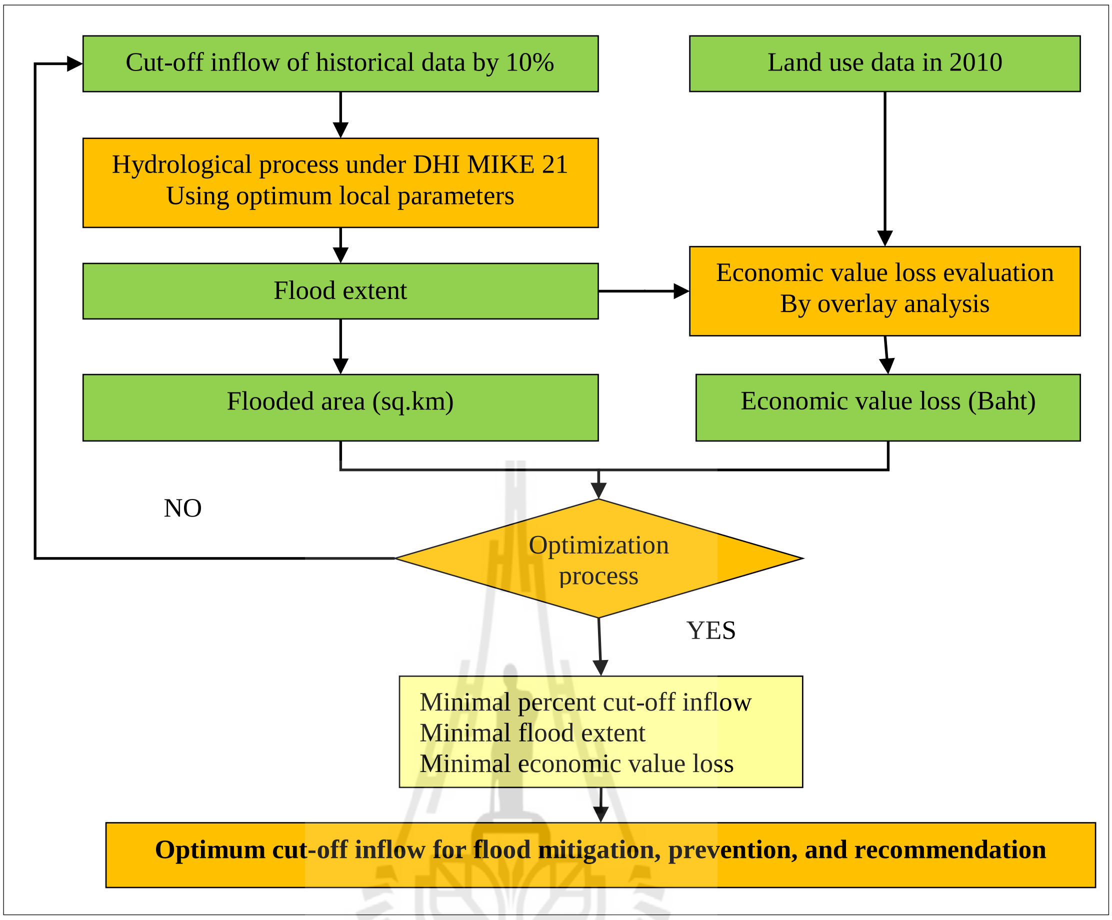

Figure 3.4 Schematic workflow of flood simulation scenario for flood mitigation and prevention.

CHAPTER IV

RESULTS AND DISCUSSIONS

The main results for simulation of 2D hydrodynamic model for urban flood severity and vulnerability mapping and flood reduction had been separately explained in each specific objective and significant finding.

4.1 Data preparation

The used datasets in this study were prepared in advanced consisted of (1) DEM, (2) multi-Satellite imagery, (3) precipitation and evaporation, (4) hydrological data, (5) stream network, (6) watergates, (7) actual flood map of GISTDA, and (8) LULC data Manning's M values based on LULC.

4.1.1 Digital Elevation Model (DEM)

Digital Elevation Model (DEM) with 5.00 x 5.00 m resolution from Ministry of Agriculture and Cooperatives (MOAC) was used as the input data for 2D hydrodynamic model of MIKE 21. In fact, it was recorded in the TIFF format (Figure 4.1).

For data preparation, error checking and fixing were undertaken pixel by pixel under ERDAS Imagine software by conversion of image to ASCII file format. After that all data with no error were projected into UTM Zone 48 with datum and spheroid of WGS 1984. Finally, all data was mosaicked into one large raster file of DEM as shown in Figure 4.2.

Figure 4.1 Example of original DEM of MOAC.

In addition, an optimized grid size was resampled to fit with the recommendation of DHI MIKE 21 software that is "number of row and column should not be more than 1000 × 1000 pixels". This study was decided using the optimized grid size as 25.00 m × 25.00 m while the comparison between original data and optimized DEM had shown in Table 4.1.

Table 4.1 Comparison of basic data of original and an optimized DEM.

DEM	Grid Size (m)	Elevation (m)			Number of grid	
		Maximum	**Minimum**	**Mean**	**Row**	**Column**
Original	5.00	215.59	162.27	184.91	4,625	8,983
Optimized	25.00	215.59	162.27	184.91	950	1,850

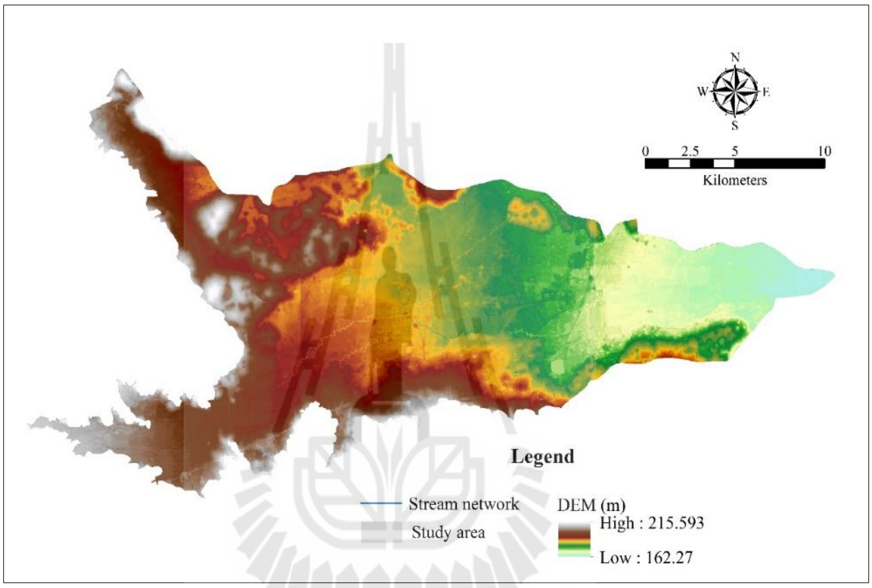

Figure 4.2 Digital elevation model.

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4.1.2 Multi-Satellite imagery

THEOS in 2010, World view II in 2012, and SPOT-5 in 2008 had prepared and used in visual interpretation technique. Ground control points (GCPs) were visually identified for image rectification, such as an intersection of road, corner of roads. In this case, 9 points of GCPs had used for spatial transformation with polynomial equation and intensity resampling with nearest neighbor which provided

RMS error equals 0.67 pixel. The summary of multi-satellite resolution had shown in Table 4.2.

Table 4.2 Summary of multi-satellite resolution and image example.

Satellite	Resolution (m)	Years	Example
SPOT-5	2.50	2008	
THEOS	2.00	2010	
World view-II	0.46	2012	

4.1.3 Precipitation and evaporation

Precipitation as rainfall and evaporation from TMD had been collected over flooding event in December 2010 and prepared for 2D simulation model of DHI MIKE 21 (Table 4.3 and Figure 4.3). Herewith original data were imported to DHI MIKE21 using new time series file in .dfs0 format.

4.1.4 Hydrological data

Similar to precipitation and evaporation, inflow volume or discharge (Q) from Lam Takhong Operation and Maintenance Project (LTOMP) had been collected and prepared for 2D simulation model of DHI MIKE 21. For the reduce discharge volume had prepared by reduced ten percent each of historical inflow volume and created .dfs0 as data input for DHI MIKE21 (Table 4.4).

4.1.5 Stream network

Stream network was generated from DEM 5.00 m. using ArcHydro module under ArcGIS software. Meanwhile, Lam Takhong Watershed boundary from the National Research Council of Thailand (2010) was used to intersect with Boundary of Mueang Nakhon Ratchasima District in order to represent the study area, inflows and outflows grid as shown in Figure 4.4.

4.1.6 Watergates

13 point locations of watergates were made by ground survey in 2011 using handheld GPS as shown in Table 4.5 and the distribution point watergates was also presented in Figure 4.4.

Table 4.3 Precipitation and evaporation data from TMD.

Date	P (mm/day)	E (mm/day)	Net-Precipitation
14 Oct 2010	25.50	2.40	23.10
15 Oct 2010	116.30	0.00	116.30
16 Oct 2010	52.60	0.90	51.70
17 Oct 2010	6.60	1.00	5.60
18 Oct 2010	7.50	2.10	5.40
19 Oct 2010	2.20	4.00	-1.80
20 Oct 2010	0.00	4.60	-4.60
21 Oct 2010	0.00	3.60	-3.60
22 Oct 2010	0.50	4.80	-4.30
23 Oct 2010	0.00	3.90	-3.90
24 Oct 2010	0.00	3.50	-3.50
25 Oct 2010	0.00	4.20	-4.20
26 Oct 2010	0.00	4.60	-4.60
27 Oct 2010	0.00	4.60	-4.60
28 Oct 2010	0.00	5.30	-5.30
Total	**211.20**	**49.50**	

Source: Thai Meteorological Department (2010).

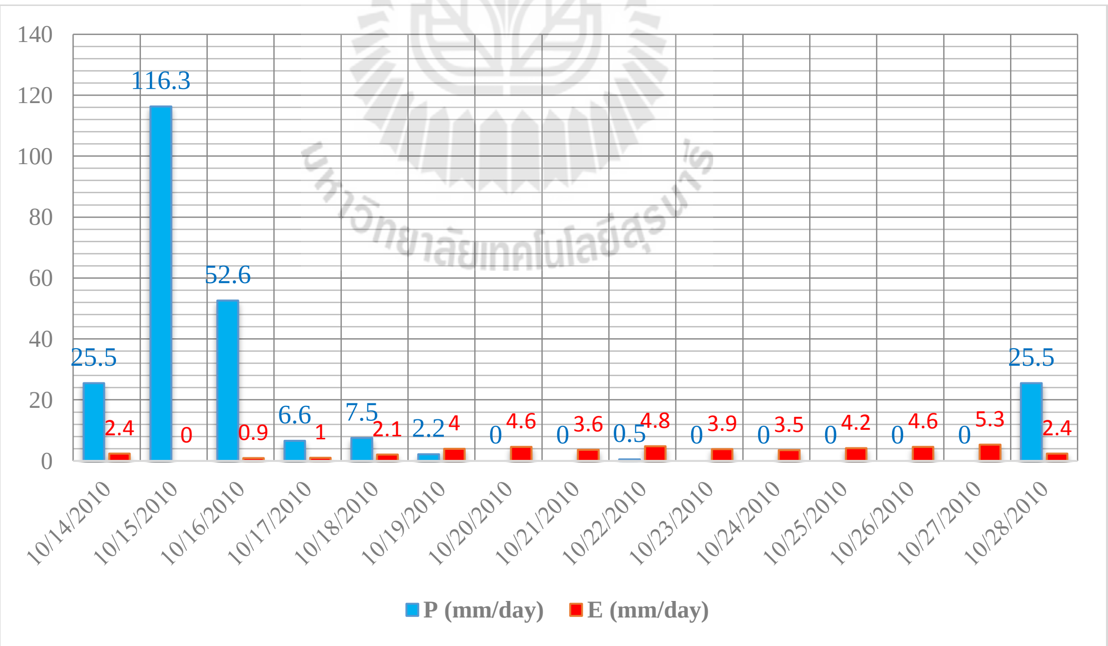

Figure 4.3 Distribution of precipitation and evaporation during 14 to 28 October 2010.

Table 4.4 Hydrological data for urban flood simulation.

Date	Kud Hin Q (m^3/s)	RQ 10%	RQ 20%	RQ 30%	RQ 40%	RQ 50%	RQ 60%	RQ 70%	RQ 80%	RQ 90%
2010-10-14	44.54	40.09	35.63	31.18	26.72	22.27	17.82	13.36	8.91	4.45
2010-10-15	49.55	44.60	39.64	34.69	29.73	24.78	19.82	14.87	9.91	4.96
2010-10-16	55.71	50.14	44.57	39.00	33.43	27.86	22.28	16.71	11.14	5.57
2010-10-17	79.93	71.94	63.94	55.95	47.96	39.97	31.97	23.98	15.99	7.99
2010-10-18	73.5	66.15	58.80	51.45	44.10	36.75	29.40	22.05	14.70	7.35
2010-10-19	67.07	60.36	53.66	46.95	40.24	33.54	26.83	20.12	13.41	6.71
2010-10-20	82.22	74.00	65.78	57.55	49.33	41.11	32.89	24.67	16.44	8.22
2010-10-21	82.22	74.00	65.78	57.55	49.33	41.11	32.89	24.67	16.44	8.22
2010-10-22	81.44	73.30	65.16	57.02	48.88	40.74	32.60	24.46	16.32	8.18
2010-10-23	77.58	69.82	62.06	54.31	46.55	38.79	31.03	23.27	15.52	7.76
2010-10-24	73.03	65.73	58.42	51.12	43.82	36.52	29.21	21.91	14.61	7.30
2010-10-25	71.53	64.38	57.22	50.07	42.92	35.77	28.61	21.46	14.31	7.15
2010-10-26	67.11	60.40	53.69	46.98	40.27	33.56	26.84	20.13	13.42	6.71
2010-10-27	68.57	61.71	54.86	48.00	41.14	34.29	27.43	20.57	13.71	6.86
2010-10-28	62.78	56.50	50.22	43.95	37.67	31.39	25.11	18.83	12.56	6.28
Total	1,036.78	933.11	829.43	725.76	622.08	518.41	414.74	311.06	207.39	103.71
Maximum	82.22	74.00	65.78	57.55	49.33	41.11	32.89	24.67	16.44	8.22
Minimum	44.54	40.09	35.63	31.18	26.72	22.27	17.82	13.36	8.91	4.45
Mean	69.12	62.21	55.30	48.38	41.47	34.56	27.65	20.74	13.83	6.91

*RQ is reduce discharge

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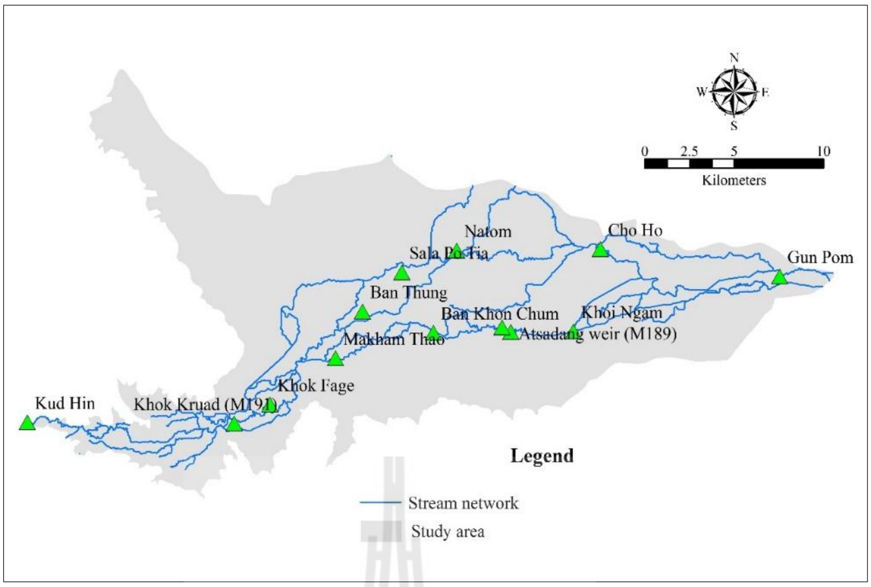

Figure 4.4 Distribution of watergates and stream network in the study area.

Table 4.5 Location of watergates ground surveying in 2013.

No	STATION	Easting	Northing	UTM
1	Kud Hin	80427.00	1650927.00	Z47
2	Khok Kruad bridge (M191)	172323.00	1653466.00	Z48
3	Atsadang weir (M189)	187814.00	1658431.00	Z48
4	Makham Thao Watergates	177992.00	1657009.00	Z48
5	Ban Khon Chum Watergates	183467.00	1658379.00	Z48
6	Assumption school (M164)	187312.00	1658675.00	Z48
7	Khoi Ngam Watergates	191314.00	1658450.00	Z48
8	Gun Pom Watergates	202863.00	1661429.00	Z48
9	Khok Fage Watergates	174316.00	1654501.00	Z48
10	Ban Thung Watergates	179505.00	1659537.00	Z48
11	Sala Po Tia Watergates	181703.00	1661650.00	Z48
12	Natom Watergates	184780.00	1662830.00	Z48
13	Cho Ho Watergates	192825.00	1662903.00	Z48

4.1.7 Flood extend map of GISTDA

Flood extend map of GISTDA which was visually interpreted from Radarsat-2 imagery acquiring on 22 Oct 2010 (Figure 4.5), and 23 October 2010 (Figure 4.6) were converted into raster files with grid size 25.00 m and used as data for DHI MIKE 21's parameter calibration. Area and percent of flood extends was summarized as shown in Table 4.6.

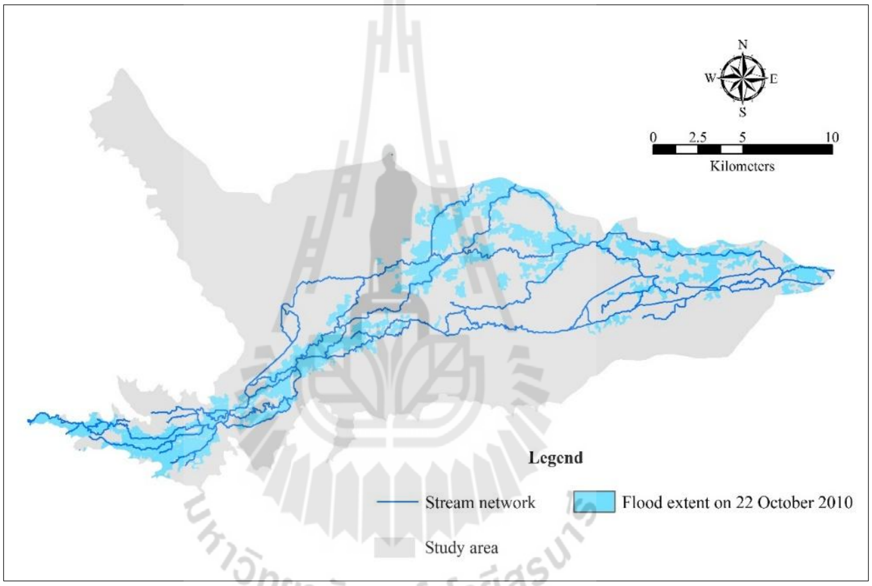

Figure 4.5 Flood extend map on 22 October 2010 by GISTDA in the study area.

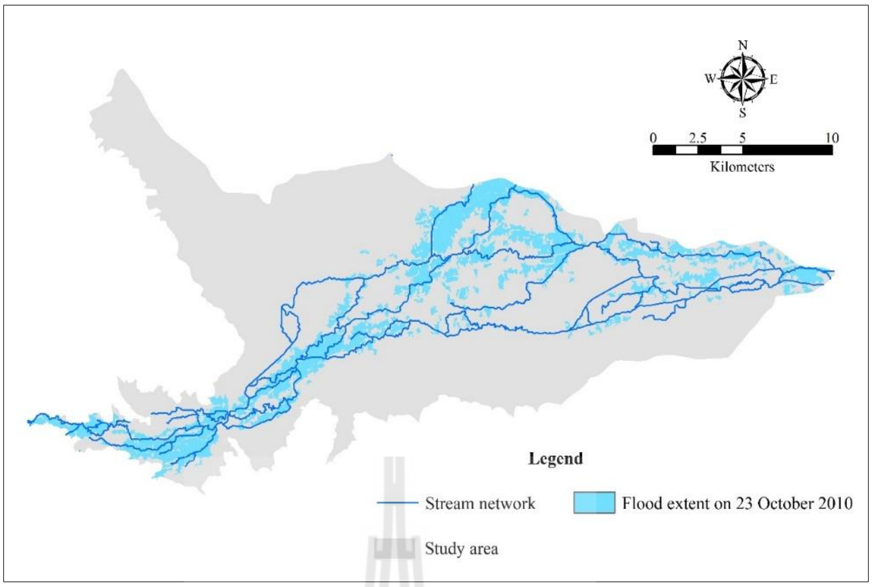

Figure 4.6 Flood extend map on 23 October 2010 by GISTDA in the study area.

Table 4.6 Area and percentage of flood extend in 2010 by GISTDA (sq. m).

Sub districts	**Study area**	**GISTDA 22 Oct**	**GISTDA 23 Oct**
Kham Thale So	90,623,750	5,176,250	4,750,625
Sung Noen	18,736,250	10,374,375	8,492,500
Mueang Nakhon Ratchasima	275,040,000	40,067,500	40,048,125
Chaloem Phra Kiat	12,843,750	2,508,750	2,766,250
Total	**397,243,750**	**58,126,875**	**56,057,500**
Percent (%)	**100.00**	**14.63**	**14.11**

4.1.8 Land use data in 2010

Land use data in 2011 from Land Development Department (LDD) was used as baseline data for visual interpretation of land use in 2010 with multi-date satellite imageries (SPOT-5, THEOS and World View-II) for more specific detail of urban and built-up areas. In practice, urban and built-up classes at Level 2 of LDD further visually interpreted for land use classes at Level 3 from the high spatial satellite imageries and the detailed ground survey block by block in 2012 and 2013. The result of land use interpretation was summarized in Table 4.7 with area of 42 land use visualizations, while the distribution of 5 main land use classes was shown in Table 4.8 and Figure 4.7. Meanwhile, error matrix which represents contingency classes between the interpreted and ground survey land use classes for accuracy assessment was summarized in Table 4.9. Some stratified random sampling points for accuracy assessment was displayed in Figure 4.8.

Considering the majority of land use under the study area, the three majorities were rice paddy (160.97 sq. km), concrete and wooden house (4.99 sq. km), and field crop (4.71 sq. km). These three land use classes had covered 258.08 sq. km or over a half of study area and they mostly situated in floodplain. These would be assumed that if the flood occurred, rice paddy, concrete and wooden house, and field crop might have high percentage to effect on flood. At the same time, the minorities of land use were abandoned aquaculture land (only 9,375 sq. m or 0.0093 sq. km), large warehouse (0.05 sq. km), and garbage dump (0.06 sq. km), These small parts of study area mostly had positions far from stream networks except the abandoned aquaculture land which had the position closed to stream network but only had a small area. It would be assumed that these might have low percentage to effect on flood during the flood occurs as well. However, these assumptions must be verified with the flooded area in the step of overlaying process with land use.

The overall accuracy and kappa coefficient of agreement was 88.39%, 88.11%, respectively. at the same time, the highest producer's accuracy (100%) of land use classes were 27 classes include abandoned aquaculture, abandoned field crop, abandoned paddy field, animal farm house, bus station/gasoline station, cemetery, dense forest plantation, disturbed deciduous forest, dormitory/condominium with 4-5 floors, garbage dump, golf course, horticulture, large industrial (more than 10,000 sq. m or 0.01 sq. km), large warehouse, marsh and swamp, office building with 4-5 floors, office building with 6-9 floors, orchard, pasture, perennial trees, pit, railway station, recreation and green area, road, shopping mall (levels 1-3), small industrial and warehouse, and townhouse with 2 floors. while the lowest producer's accuracy of land use classes were 3 classes include shrub/scrub (38.46%), landfill (41.67%), and house with 1 floor (54.55%).

For user's accuracy, the highest user's accuracy (100%) of land use classes were 21 classes included animal farm house, bus station/gasoline station, cemetery, dense forest plantation, disturbed deciduous forest, dormitory/condominium with 4-5 floors, golf course, horticulture, large industrial (more than 10,000 sq. m or 0.01 sq. km), large warehouse, office building with 4-5 floors, office building with 6-9 floors, orchard, pasture, perennial trees, railway station, road, shopping mall (levels 1-3), small industrial and warehouse, townhouse with 2 floors, and water body. while the lowest user's accuracy of land use classes were 3 classes included shrub/scrub (62.50%), landfill (62.50%), and house with 1 floor (62.50%).

Table 4.7 Detail of urban and built-up area interpretation (sq. m).

Level 1	Land use	Total area (sq. m)	Kham Thale So	Sung Noen	Mueang Nakhon Ratchasima	Chaloem Phra Kiat
U	Bus station/Gasoline station	300,000	-	18,750	273,125	8,125
U	Commercial buildings with 1 floor	741,250	-	-	741,250	
U	Commercial buildings with 2 floors	565,625	-		565,625	
U	Commercial buildings with 3 floors	889,375	-	-	889,375	-
U	Commercial buildings with 4 floors	4,678,750	-	-	4,678,750	-
U	Dormitory/Condominium with 4-5 floors	141,250	-	-	141,250	-
U	Townhouse with 2 floors	1,110,625	175,000	-	935,625	-
U	Concrete and wooden house	49,925,625	4,973,125	1,351,250	42,016,250	1,585,000
U	House with 1 floor	1,693,125	386,250	-	1,306,875	-
U	House with 2 floor	19,620,000	625	-	19,619,375	-
U	Large industrial (more than 10,000 sq. m)	3,341,875	605,000	-	2,700,000	36,875
U	Large warehouse	53,750	-	-	53,750	-
U	Small industrial and warehouse	78,125	14,375	-	53,750	10,000
U	Shopping mall (levels 1-3)	270,625	-	-	270,625	-
U	Office building with 1 floor	2,561,875	336,875	77,500	2,147,500	-
U	Office building with 2-3 floors	6,233,750	1,180,625	-	5,026,875	26,250
U	Office building with 4-5 floors	1,461,250	-	-	1,461,250	-
U	Office building with 6-9 floors	888,125	-	-	888,125	-
U	Railway station	216,250	-	-	216,250	-
U	Road	2,163,750	-	103,750	2,060,000	-
A	Abandoned aquaculture	9,375	-	-	9,375	-
A	Abandoned field crop	596,250	204,375	-	391,875	-
A	Abandoned paddy field	2,280,625	133,750	-	2,146,875	-
A	Animal farm house	443,125	202,500	625	240,000	-
A	Field crop	47,190,000	27,523,125	91,875	19,063,125	511,875
	Horticulture	14,840,000	91,250	1,250	14,747,500	-
A	Orchard	6,605,000	966,875	392,500	5,221,875	23,750
A	Pasture	3,039,375	413,125	-	2,518,125	108,125
A	Perennial trees	3,130,000	1,220,625	-	1,829,375	80,000
A	Rice paddy	160,971,250	37,258,125	15,253,750	100,098,125	8,361,250
F	Dense forest Plantation	823,125	805,625	-	17,500	-
F	Disturbed deciduous forest	1,366,250	371,875	17,500	976,875	-
M	Cemetery	447,500	-	-	447,500	-
M	Garbage dump	61,875	61,875	-	-	-
M	Golf course	359,375	-	-	359,375	-
M	Grass	2,826,875	407,500	-	2,256,250	163,125
M	Landfill	1,633,125	136,875	122,500	1,325,000	48,750
M	Marsh and swamp	6,818,125	2,906,250	-	3,911,875	-
M	Pit	1,520,625	1,162,500	-	358,125	-
M	Recreation and green area	8,133,750	41,250	-	8,068,125	24,375
M	Shrub/Scrub	16,610,000	5,331,875	176,250	10,200,625	901,250
W	Water body	20,603,125	3,712,500	1,128,750	14,806,875	955,000
Total		**397,243,750**	**90,623,750**	**18,736,250**	**275,040,000**	**12,843,750**

Table 4.8 Distribution of 5 main land use classes in 2010 by visual interpretation based on 4 districts (sq. m).

Land use level I	Kham Thale So	Sung Noen	Mueang Nakhon Ratchasima	Chaloem Phra Kiat
Urban and built-up area	7,671,875	1,551,250	86,045,625	1,666,250
Agricultural land	68,013,750	15,740,000	146,266,250	9,085,000
Forest land	1,177,500	17,500	994,375	-
Miscellaneous land	10,048,125	298,750	26,926,875	1,137,500
Water body	3,712,500	1,128,750	14,806,875	955,000
Total	**90,623,750**	**18,736,250**	**275,040,000**	**12,843,750**

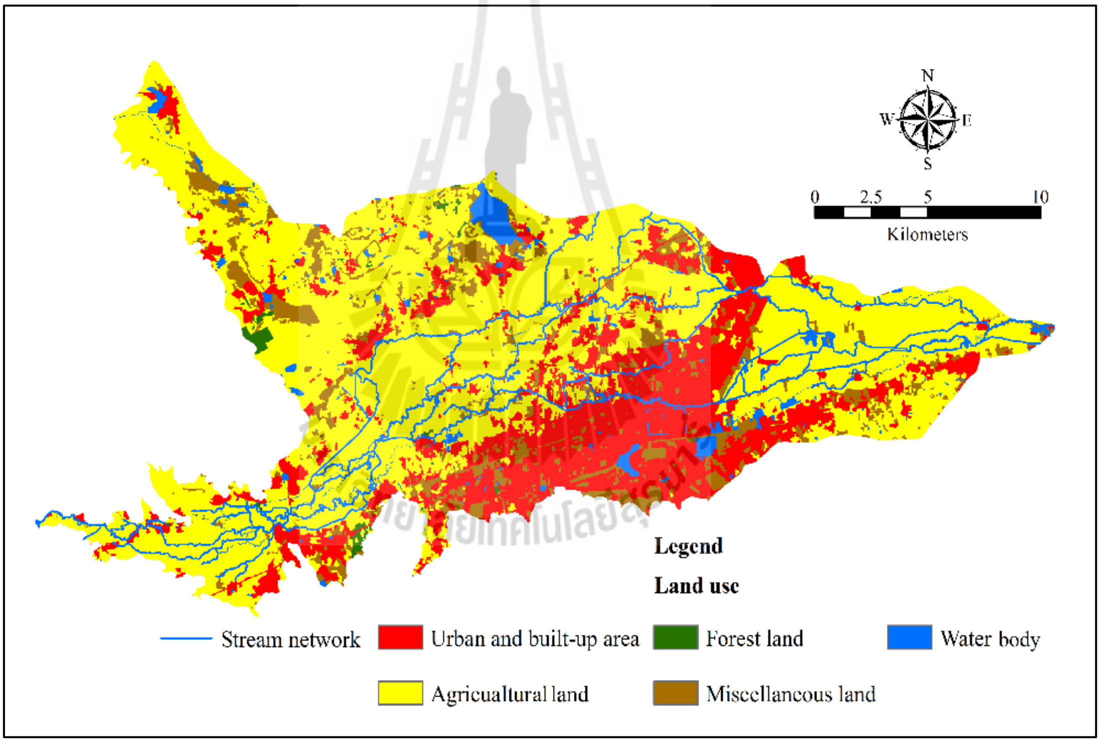

Figure 4.7 Distribution of 5 main land use classes in 2010 by visual interpretation.

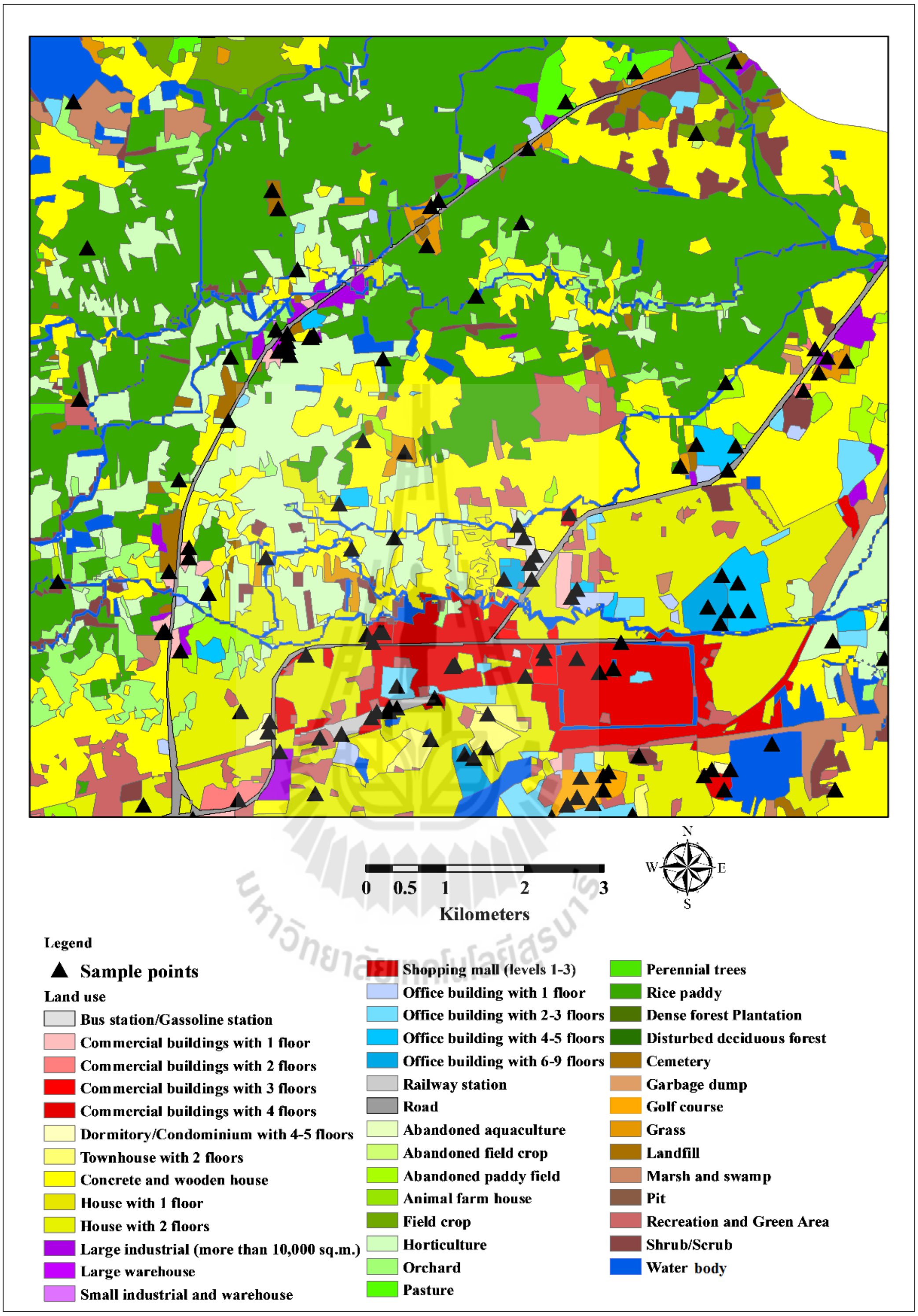

Figure 4.8 Distribution of some sampling points over land use classes for accuracy assessment.

Table 4.9 Error matrix of 42 land use classes' classification.

		Ground survey																																												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C 10	C 11	C 12	C 13	C 14	C 15	C 16	C 17	C 18	C 19	C 20	C 21	C 22	C 23	C 24	C 25	C 26	C 27	C 28	C 29	C 30	C 31	C 32	C 33	C 34	C 35	C 36	C 37	C 38	C 39	C 40	C 41	C 42	Total	UA	PA
Interpreted land use classes	C1	8																																										8	1.000	0.889
	C2	1	7																																									8	0.875	1.000
	C3			7													1																											8	0.875	1.000
	C4				6																																	2						8	0.750	1.000
	C5					8																																						8	1.000	1.000
	C6						8																																					8	1.000	1.000
	C7							8																																				8	1.000	1.000
	C8								6	2																																		8	0.750	0.857
	C9								1	7																																		8	0.875	0.778
	C10										7	1																																8	0.875	0.778

Table 4.9 Error matrix of 42 land use classes' classification (Continued).

Interpreted land use classes		Ground survey																																												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C 10	C 11	C 12	C 13	C 14	C 15	C 16	C 17	C 18	C 19	C 20	C 21	C 22	C 23	C 24	C 25	C 26	C 27	C 28	C 29	C 30	C 31	C 32	C 33	C 34	C 35	C 36	C 37	C 38	C 39	C 40	C 41	C 42	Total	UA	PA
	C11										2	6																																8	0.750	0.857
	C12												5									3																						8	0.625	0.714
	C13													8																														8	1.000	1.000
	C14														8																													8	1.000	1.000
	C15															8																												8	1.000	1.000
	C16																5							2																	1			8	0.625	0.833
	C17																	7						1																				8	0.875	1.000
	C18																		8																									8	1.000	1.000
	C19																			6																					2			8	0.750	0.667
	C20																				8																							8	1.000	1.000

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Table 4.9 Error matrix of 42 land use classes' classification (Continued).

		Ground survey																																												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C 10	C 11	C 12	C 13	C 14	C 15	C 16	C 17	C 18	C 19	C 20	C 21	C 22	C 23	C 24	C 25	C 26	C 27	C 28	C 29	C 30	C 31	C 32	C 33	C 34	C 35	C 36	C 37	C 38	C 39	C 40	C 41	C 42	Total	UA	PA
Interpreted land use classes	C21												1									6	1																					8	0.750	0.545
	C22												1									2	5																					8	0.625	0.833
	C23																							5																	3			8	0.625	0.417
	C24																								8																			8	1.000	1.000
	C25																									8																		8	1.000	1.000
	C26																							1			7																	8	0.875	1.000
	C27																											7	1															8	0.875	0.778
	C28																											2	6															8	0.750	0.857
	C29																													8														8	1.000	1.000
	C30																														8													8	1.000	1.000

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Table 4.9 Error matrix of 42 land use classes' classification (Continued).

Interpreted land use classes	Ground survey																																												
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C 10	C 11	C 12	C 13	C 14	C 15	C 16	C 17	C 18	C 19	C 20	C 21	C 22	C 23	C 24	C 25	C 26	C 27	C 28	C 29	C 30	C 31	C 32	C 33	C 34	C 35	C 36	C 37	C 38	C 39	C 40	C 41	C 42	Total	UA	PA
C31																															8												8	1.000	1.000
C32																																8											8	1.000	1.000
C33																																	8										8	1.000	1.000
C34																							1											7									8	0.875	1.000
C35																																			8								8	1.000	1.000
C36																																				6				2			8	0.750	1.000
C37																							2														6						8	0.750	0.750
C38																																						8					8	1.000	1.000
C39																																							8				8	1.000	1.000
C40																			3																					5			8	0.625	0.385

Table 4.9 Error matrix of 42 land use classes' classification (Continued).

		Ground survey																																										
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C 10	C 11	C 12	C 13	C 14	C 15	C 16	C 17	C 18	C 19	C 20	C 21	C 22	C 23	C 24	C 25	C 26	C 27	C 28	C29	C 30	C 31	C 32	C 33	C 34	C 35	C 36	C 37	C 38	C 39	C 40	C 41	C 42	Total	UA	PA
Interpreted land use classes	C41																																									8		8	1.000	1.000
	C42																																										8	8	1.000	1.000
	Total	9	7	7	6	8	8	8	7	9	9	7	7	8	8	8	6	7	8	9	8	11	6	12	8	8	7	9	7	8	8	8	8	8	7	8	6	8	8	8	13	8	8	297		

Overall accuracy = 88.39% Kappa coefficient = 88.11 %

Notification*

C1 = Water body, C2 = Abandoned aquaculture, C3 = Abandoned field crop, C4 = Abandoned paddy field,
C5 = Animal farm house, C6 = Bus station/Gasoline station, C7 = Cemetery, C8 = Commercial buildings with 1 floor,
C9 = Commercial buildings with 2 floors, C10 = Commercial buildings with 3 floors, C11 = Commercial buildings with 4 floors, C12 = Concrete and wooden house,
C13 = Dense forest Plantation, C14 = Disturbed deciduous forest, C15 = Dormitory/Condominium with 4-5 floors, C16 = Field crop,
C17 = Garbage dump, C18 = Golf course, C19 = Grass, C20 = Horticulture,
C21 = House with 1 floor, C22 = House with 2 floor, C23 = Landfill, C24 = Large industrial (more than 10,000 sq. m),
C25 = Large warehouse, C26 = Marsh and swamp, C27 = Office building with 1 floor, C28 = Office building with 2-3 floors,
C29 = Office building with 4-5 floors, C30 = Office building with 6-9 floors, C31 = Orchard, C32 = Pasture,
C33 = Perennial trees, C34 = Pit, C35 = Railway station, C36 = Recreation and green area,
C37 =Rice paddy, C38 = Road, C39 = Shopping mall (levels 1-3), C40 = Shrub/Scrub,
C41 = Small industrial and warehouse, C42 =Townhouse with 2 floors.

4.2 Urban flood simulation by DHI MIKE 21 model

4.2.1 Optimum parameters for urban flood simulation by DHI MIKE 21

DHI MIKE 21's parameters were consisted of two main parameters, basic and hydrodynamic parameters. This study assumed that an important parameters that lead to the change of flooded area was the Manning' M number according to land use types. For model calibration, the different values of Manning' M number were examined as hydrodynamic parameter in order to provide the maximal overall accuracy and flood detection rate when the simulated flood was compared with actual flood map in 2010 of GISTDA. The important parameters of DHI MIKE 21 model had been divided into 2 main groups as basic parameters and hydrological parameters. The summary of both parameters was provided in Table 4.10.

In this study, 6 final trials of Manning's M number with minimum, normal (mean), maximum, and three modified value which applied in model calibration was summarized as shown in Table 4.11. The result of accuracy assessment in each trial was displayed as confusion matrix between two actual flood map of GISTDA (22 - 23 October 2010) and the simulated flood map by DHI MIKE 21 model in Tables 4.12 - 4.23.

Table 4.10 Summary of basic and hydrological parameter for MIKE 21.

Basic Parameters	
Module selection	Hydrodynamic only with inland flooding
Bathymetry	25m.dfs2
Simulation Period	Time step last 40,320 Time step interval 30
	Simulation start date 2010010014 0:06:00
	Simulation end date 2010010028 0:06:00
Boundary	First point: 0 - 160 Last point: 0 - 162
	First point: 1,849 - 471 Last point: 1,849 - 475
	First point: 1,849 - 457 Last point: 1,849 - 461
	Frist point: 1,849 - 484 Last point: 1,849 - 487
Flood and dry	Drying depth 0.03
	Flooding depth 0.05
Hydrodynamic Parameter	
Initial Surface Elevation	initiallevel25m.dfs2
Boundary	Boundary1:(0,160) - (0,162)
	Formulation: Flux
	Type 0 data file: Q.dfs0
	Boundary2: (1,849, 471) - (1,849, 475)
	Formulation: Level: 160
	Boundary3: (1,849, 457) - (1,849, 475)
	Formulation: Level: 160
	Boundary4: (1,849, 484) - (1,849, 487)
	Formulation: Level: 160
Source and sink	-
Eddy Viscosity	2.08
Resistance	Manning's M based on land use.dfs2
Result	Number of output area: 1

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Table 4.11 Summary of Manning's M number for 6 final trials of model calibration.

		Manning's M number					
Level1	**Land use**	**Min.**	**Normal**	**Max.**	**Mod.1**	**Mod.2**	**Mod.3**
U	Bus station/Gasoline station	14.75	19.75	24.75	24.75	24.75	24.75
U	Commercial buildings with 1 floor	14.75	19.75	24.75	24.75	24.75	24.75
U	Commercial buildings with 2 floors	14.75	19.75	24.75	24.75	24.75	24.75
U	Commercial buildings with 3 floors	14.75	19.75	24.75	24.75	24.75	24.75
U	Commercial buildings with 4 floors	14.75	19.75	24.75	24.75	24.75	24.75
U	Dormitory/Condominium with 4-5 floors	14.75	19.75	24.75	24.75	24.75	24.75
U	Townhouse with 2 floors	14.75	19.75	24.75	24.75	24.75	24.75
U	Concrete and wooden house	14.75	19.75	24.75	24.75	24.75	24.75
U	House with 1 floor	14.75	19.75	24.75	24.75	24.75	24.75
U	House with 2 floor	14.75	19.75	24.75	24.75	24.75	24.75
U	Large industrial (more than 10,000 sq. m)	14.75	19.75	24.75	24.75	24.75	24.75
U	Large warehouse	14.75	19.75	24.75	24.75	24.75	24.75
U	Small industrial and warehouse	14.75	19.75	24.75	24.75	24.75	24.75
U	Shopping mall (levels 1-3)	14.75	19.75	24.75	24.75	24.75	24.75
U	Office building with 1 floor	14.75	19.75	24.75	24.75	24.75	24.75
U	Office building with 2-3 floors	14.75	19.75	24.75	24.75	24.75	24.75
U	Office building with 4-5 floors	14.75	19.75	24.75	24.75	24.75	24.75
U	Office building with 6-9 floors	14.75	19.75	24.75	24.75	24.75	24.75
U	Railway station	14.75	19.75	24.75	24.75	24.75	24.75
U	Road	71.00	71.00	71.00	71.00	71.00	71.00
A	Abandoned aquaculture	28.57	75.19	100.00	75.19	100.00	100.00
A	Abandoned field crop	88.50	88.50	88.50	88.50	88.50	88.50
A	Abandoned paddy field	88.50	88.50	88.50	88.50	88.50	88.50
A	Animal farm house	3.03	3.03	3.03	3.03	3.03	3.03
A	Field crop	2.78	25.00	33.33	33.33	33.33	33.33
A	Horticulture	22.22	22.22	22.22	22.22	22.22	22.22
A	Orchard	2.78	2.78	2.78	2.78	2.78	2.78
A	Pasture	3.08	3.08	3.08	3.08	3.08	3.08
A	Perennial trees	2.50	2.50	2.50	2.50	2.50	2.50
A	Rice paddy	5.48	22.00	40.00	50.00	50.00	25.00
F	Dense forest Plantation	5.00	5.00	5.00	5.00	5.00	5.00
F	Disturbed deciduous forest	5.00	5.00	5.00	5.00	5.00	5.00
M	Cemetery	88.50	88.50	88.50	88.50	88.50	88.50
M	Garbage dump	88.50	88.50	88.50	88.50	88.50	88.50
M	Golf course	2.72	2.72	2.72	2.72	2.72	2.72
M	Grass	2.72	2.72	2.72	2.72	2.72	2.72
M	Landfill	88.50	88.50	88.50	88.50	88.50	88.50
M	Marsh and swamp	11.63	11.63	11.63	11.63	11.63	11.63
M	Pit	28.57	28.57	28.57	28.57	28.57	28.57
M	Recreation and green area	24.75	24.75	24.75	24.75	24.75	24.75
M	Shrub/Scrub	2.50	2.50	2.50	2.50	2.50	2.50
W	Water body	28.57	75.19	100.00	75.19	100.00	100.00

Table 4.12 The confusion matrix of flood extent between GISTDA data (22 Oct 2010) and simulated data based on minimum Manning's M number.

GISTDA	MIKE 21		Row total (Pixels)
	Flood (Pixels)	Non-flood (Pixels)	
Flood	59,357	33,791	93,148
Non-flood	70,549	471,893	542,442
Column total	129,906	505,684	635,590
Overall accuracy	83.58%		
Flood detection rate	63.72%		
False alarm rate	13.01%		

Table 4.13 The confusion matrix of flood extent between GISTDA data (23 Oct 2010) and simulated data based on minimum Manning's M number.

GISTDA	MIKE 21		Row total (Pixels)
	Flood (Pixels)	Non-flood (Pixels)	
Flood	63,364	26,328	93,148
Non-flood	88,724	457,174	542,442
Column total	152,088	483,502	635,590
Overall accuracy	81.90%		
Flood detection rate	70.65%		
False alarm rate	16.25%		

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Table 4.14 The confusion matrix of flood extent between GISTDA data (22 Oct 2010) and simulated data based on normal Manning's M number.

GISTDA	MIKE 21		Row total (Pixels)
	Flood (Pixels)	Non-flood (Pixels)	
Flood	58,117	35,031	93,148
Non-flood	81,396	461,046	542,442
Column total	139,513	496,077	635,590
Overall accuracy	81.68%		
Flood detection rate	62.39%		
False alarm rate	15.01%		

Table 4.15 The confusion matrix of flood extent between GISTDA data (23 Oct 2010) and simulated data based on normal Manning's M number (Pixels).

GISTDA	MIKE 21		Row total (Pixels)
	Flood (Pixels)	Non-flood (Pixels)	
Flood	56,899	32,793	89,692
Non-flood	84,626	461,272	545,898
Column total	141,525	494,065	635,590
Overall accuracy	81.53%		
Flood detection rate	63.44%		
False alarm rate	15.50%		

Table 4.16 The confusion matrix of flood extent between GISTDA data (22 Oct 2010) and simulated data based on maximum Manning's M number.

GISTDA	MIKE 21		Row total (Pixels)
	Flood (Pixels)	Non-flood (Pixels)	
Flood	54,823	38,325	93,148
Non-flood	79,684	462,758	542,442
Column total	134,507	501,083	635,590
Overall accuracy	81.43%		
Flood detection rate	58.86%		
False alarm rate	14.69%		

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Table 4.17 The confusion matrix of flood extent between GISTDA data (23 Oct 2010) and simulated data based on maximum Manning's M number.

GISTDA	MIKE 21		Row total (Pixels)
	Flood (Pixels)	Non-flood (Pixels)	
Flood	53,922	35,770	89,692
Non-flood	81,274	464,624	545,898
Column total	135,196	500,394	635,590
Overall accuracy	81.58%		
Flood detection rate	60.12%		
False alarm rate	14.89%		

Table 4.18 The confusion matrix of flood extent between GISTDA data (22 Oct 2010) and simulated data based on the 1st modified maximum Manning's M number.

GISTDA	MIKE 21		Row total
	Flood (Pixels)	**Non-flood (Pixels)**	**(Pixels)**
Flood	54,272	38,876	93,148
Non-flood	80,203	462,239	542,442
Column total	134,475	501,115	635,590
Overall accuracy	81.26%		
Flood detection rate	58.26%		
False alarm rate	14.79%		

Table 4.19 The confusion matrix of flood extent between GISTDA data (23 Oct 2010) and simulated data based on the 1st modified maximum Manning's M number.

GISTDA	MIKE 21		Row total
	Flood (Pixels)	**Non-flood (Pixels)**	**(Pixels)**
Flood	52,217	37,475	89,692
Non-flood	80,140	465,758	545,898
Column total	132,357	503,233	635,590
Overall accuracy	81.50%		
Flood detection rate	58.22%		
False alarm rate	14.68%		

Table 4.20 The confusion matrix of flood extent between GISTDA data (22 Oct 2010) and simulated data based on the 2nd modified maximum Manning's M number.

GISTDA	MIKE 21		Row total
	Flood (Pixels)	**Non-flood (Pixels)**	**(Pixels)**
Flood	58,290	34,858	93,148
Non-flood	83,198	459,244	542,442
Column total	141,488	494,102	635,590
Overall accuracy	81.43%		
Flood detection rate	62.58%		
False alarm rate	15.34%		

Table 4.21 The confusion matrix of flood extent between GISTDA data (23 Oct 2010) and simulated data based on the 2nd modified maximum Manning's M number.

GISTDA	**MIKE 21**		**Row total**
	Flood (Pixels)	**Non-flood (Pixels)**	**(Pixels)**
Flood	54,287	35,405	89,692
Non-flood	80,216	465,682	545,898
Column total	134,503	501,087	635,590
Overall accuracy	81.81%		
Flood detection rate	60.53%		
False alarm rate	14.69%		

Table 4.22 The confusion matrix of flood extent between GISTDA data (22 Oct 2010) and simulated data based on the 3rd modified maximum Manning's M number.

GISTDA	**MIKE 21**		**Row total**
	Flood (Pixels)	**Non-flood (Pixels)**	**(Pixels)**
Flood	57,229	35,919	93,148
Non-flood	81,771	460,671	542,442
Column total	139,000	496,590	635,590
Overall accuracy	81.48%		
Flood detection rate	61.44%		
False alarm rate	15.07%		

Table 4.23 The confusion matrix of flood extent between GISTDA data (22 Oct 2010) and simulated data based on the 3rd modified maximum Manning's M number.

GISTDA	**MIKE 21**		**Row total**
	Flood (Pixels)	**Non-flood (Pixels)**	**(Pixels)**
Flood	55,956	33,736	89,692
Non-flood	83,407	462,491	545,898
Column total	139,363	496,227	635,590
Overall accuracy	81.57%		
Flood detection rate	62.39%		
False alarm rate	15.28%		

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The results have clearly demonstrated that six varying of Manning's M number for flood simulation can provide overall accuracy greater than 80% as acceptance value. Herein, flood simulation by the minimum Manning's M number can provides the best flood extent based on overall accuracy, flood detection rate, and false alarm rate when compare with actual flood map on 22 October 2010 and 23 October 2010 of GISTDA (Figure 4.9).

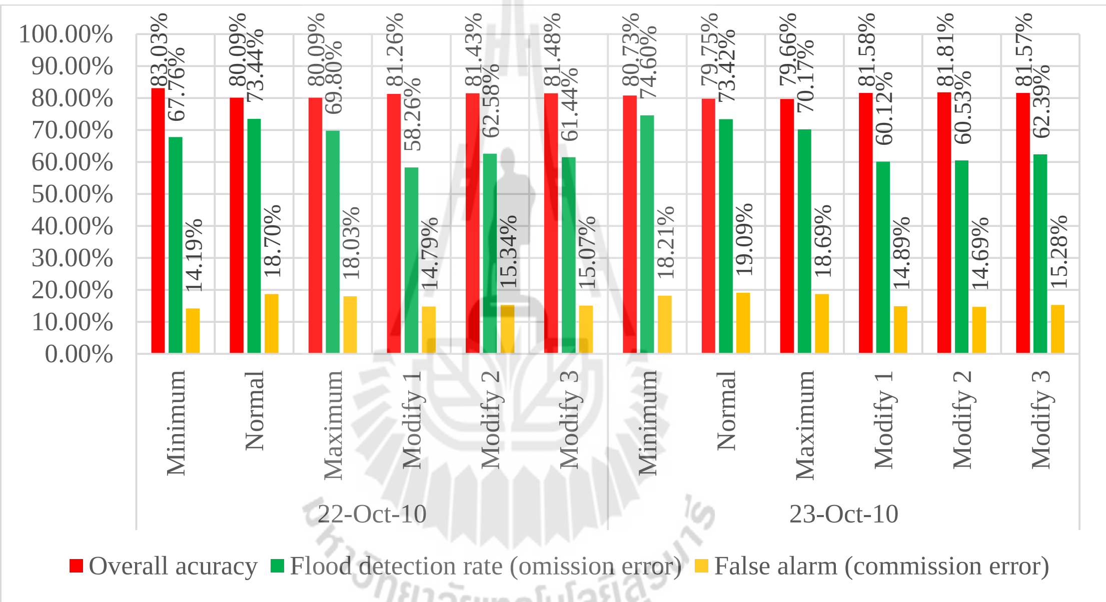

Figure 4.9 Comparision of overall accuracy, flood detection rate, and false alarm rate with actual flood map of GISTDA.

However, when the simulated flood extent from six varying of Manning's M number had compared with known locations of flood record in 2010 from various government agencies and ground survey in 2014 and 2015 (Table 4.24). Herein, the simulated flood extent were compared with three categories of flood records in 2010: (1) landmark with flood depth and time record, (2) landmark with flood depth and no time records, and (3) landmark with non-flood record (Figure 4.10). It was found that the simulated flood data by normal Manning's M number can provide more realistic flood event in 2010 than others trials. The details of all comparison had summarized in Table 4.25 - 4.26.

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Table 4.24 Historical flood data of landmark in 2010.

		Landmarks with flood depth and time record					
NO	**Land use (level II)**	**Landmarks**	**Easting**	**Northing**	**Depth (m)**	**Arrival date**	**Source**
1	Residential	Ban Don, Concrete and wooden house	161275.11	1653647.07	0.70	14/10/2010	SAO
2	Institutional land	Ban Don, School Child Development Center	161322.81	1653712.06	0.67	14/10/2010	Affected persons
3	Residential	Ban Non Ka	161378.43	1653689.40	0.55	14/10/2010	SAO
4	Residential	Concrete and wooden house	165447.68	1653175.91	0.74	14/10/2010	SAO
5	Residential	Concrete and wooden house	162726.82	1653486.15	0.72	14/10/2010	SAO
6	Residential	Concrete and wooden house	161389.98	1653744.62	0.88	14/10/2010	SAO
7	Residential	Ban Mueang Li	164666.92	1653773.84	0.30	14/10/2010	Affected persons
8	Residential	Ban Kong Yang	172077.17	1654340.06	0.48	15/10/2010	Affected persons
9	Residential	V.I.P house estate	186851.25	1659209.80	0.40	21/10/2010	RTAF (Wing1) and GS
10	Institutional land	Saint Marys Hospital	187217.42	1659190.31	0.30	21/102010	RTAF (Wing1) and GS
11	Institutional land	Wat Taklong Kao	192956.72	1658216.17	0.20	24/10/2010	RTAF (Wing1) and GS

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Table 4.24 Historical flood data of landmark in 2010 (Continued).

Landmarks with flood depth, no time record							
NO	**Land use (level II)**	**Landmarks**	**Easting**	**Northing**	**Depth (m)**	**Arrival date**	**Source**
1	City and commercial	Ban Nong Ya Ngam	186439.19	1659919.49	0.10	-	RTAF (Wing1) and GS
2	City and commercial	Ban Pong Dang	164389.53	1652625.81	0.15	-	RTAF (Wing1) and GS
3	City and commercial	Makham Tho pumping	178028.13	1656890.79	0.20	-	RTAF (Wing1) and GS
4	City and commercial	Ban Thung Kra Don	179353.19	1659962.89	0.20	-	RTAF (Wing1) and GS
5	City and commercial	Ban Kho Woods	187729.83	1660642.36	0.20	-	RTAF (Wing1) and GS
6	City and commercial	Morality 31, Nakhon Ratchasima Foundation	183891.58	1661238.42	0.20	-	RTAF (Wing1) and GS
7	City and commercial	The Administrative Court, Nakhon Ratchasima	184712.67	1662201.68	0.20	-	RTAF (Wing1) and GS
8	City and commercial	Ban Wang Won	164348.80	1652594.17	0.25	-	RTAF (Wing1) and GS
9	Institutional land	Ban Kong Yang	169654.68	1654388.46	0.25	-	SAO
10	Institutional land	Home Garden Ville	192472.46	1662875.07	0.25	-	RTAF (Wing1) and GS
11	Institutional land	Ban Num Cha	169690.42	1654371.38	0.30	-	RTAF (Wing1) and GS
12	Institutional land	Ban Kud Pla Kheng	165763.62	1653544.88	0.30	-	RTAF (Wing1) and GS
13	Institutional land	Ban Kud Pla Kheng	165981.08	1653551.92	0.30	-	RTAF (Wing1) and GS
14	Institutional land	Ban Khok kruat	173339.98	1653126.09	0.30	-	RTAF (Wing1) and GS
15	Institutional land	Khok Kruat railway station	172900.91	1652942.12	0.30	-	RTAF (Wing1) and GS
16	Institutional land	Ban Kham Thale So	175064.98	1657451.09	0.30	-	RTAF (Wing1) and GS
17	Residential	Ban Nong Ped Num	175925.78	1654760.20	0.30	-	SAO
18	Residential	Ban Nong Pho	187227.96	1662327.72	0.30	-	SAO
19	Residential	Nakhon Ratchasima bus terminal	187455.83	1659164.33	0.30	-	SAO
20	Residential	Wat Chong Eu	192184.26	1663387.54	0.30	-	SAO

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Table 4.24 Historical flood data of landmark in 2010 (Continued).

Landmarks with flood depth, no time record							
NO	**Land use (level II)**	**Landmarks**	**Easting**	**Northing**	**Depth (m.)**	**Arrival date**	**Source**
21	Residential	Cho Ho	192189.66	1663224.60	0.30	-	SAO
22	Residential	Nakhon Ratchasima Rajabhat University	189538.92	1658610.43	0.30	-	RTAF (Wing1) and GS
23	Residential	Rajamangala University of Technology Isan	190133.30	1658984.76	0.35	-	SAO
24	Residential	Ban Kong Yang	164957.77	1652706.69	0.38	-	SAO
25	Residential	Ban Makok	187550.02	1665186.41	0.40	-	SAO
26	Residential	Vongchavalitkul University	189863.02	1660811.26	0.40	-	SAO
27	Residential	Makro supermarket	187994.75	1659793.94	0.40	-	SAO
28	Residential	Big C supercenter	187110.93	1658434.89	0.50	-	SAO
29	Residential	Save one market	182153.31	1655673.69	0.50	-	SAO
30	Residential	Ban Si Mum	175725.19	1660765.88	0.50	-	RTAF (Wing1) and GS
31	Residential	Suranakhon market	187931.66	1659210.53	0.50	-	SAO
32	Residential	Dusit Princess Korat	191486.05	1660097.46	0.60	-	SAO
33	Residential	Ban Kon Chum	187974.98	1665809.84	0.65	-	RTAF (Wing1) and GS
34	Residential	Ban Kong Yang	167077.48	1651518.61	0.72	-	SAO
35	Residential	Maharat Nakhon Ratchasima Hospital community	188515.73	1658704.74	0.75	-	SAO
36	Residential	Ban Mueang Li	165274.90	1653236.89	0.80	-	SAO
37	Residential	Home pro	182880.94	1658296.34	0.80	-	RTAF (Wing1) and GS
38	Residential	Ban Kho	191562.41	1660286.01	1.00	-	SAO
39	Residential	PTT bypass Korat	182936.56	1658987.32	1.00	-	SAO
40	Transportation	Ban Lalom Noue	181464.98	1661976.09	1.10	-	RTAF (Wing1) and GS
41	Road	Ban Pong Dang	172176.92	1654290.80	1.50	-	SAO

Table 4.24 Historical flood data of landmark in 2010 (Continued).

		Landmarks with non-flood					
NO	**Land use (level II)**	**Landmarks**	**Easting**	**Northing**	**Depth (m)**	**Arrival date**	**Source**
1	Institutional land	Makham Tho scool	178710.34	1656404.16	Non-flood	-	RTAF (Wing1) and GS
2	City and commercial	The Mall Nakhon Ratchasima	185561.92	1658299.34	Non-flood	-	RTAF (Wing1) and GS
3	Institutional land	Wat Suan Prik Thai	182858.43	1656894.09	Non-flood	-	RTAF (Wing1) and GS
4	Institutional land	Ubolratana Rajakanya Ratchawittayalai	179834.95	1655438.66	Non-flood	-	RTAF (Wing1) and GS

Notification*

SAO Sub-district Administrative

RTAF Royal Thai Air Force Base (Wing 1)

GS Ground survey

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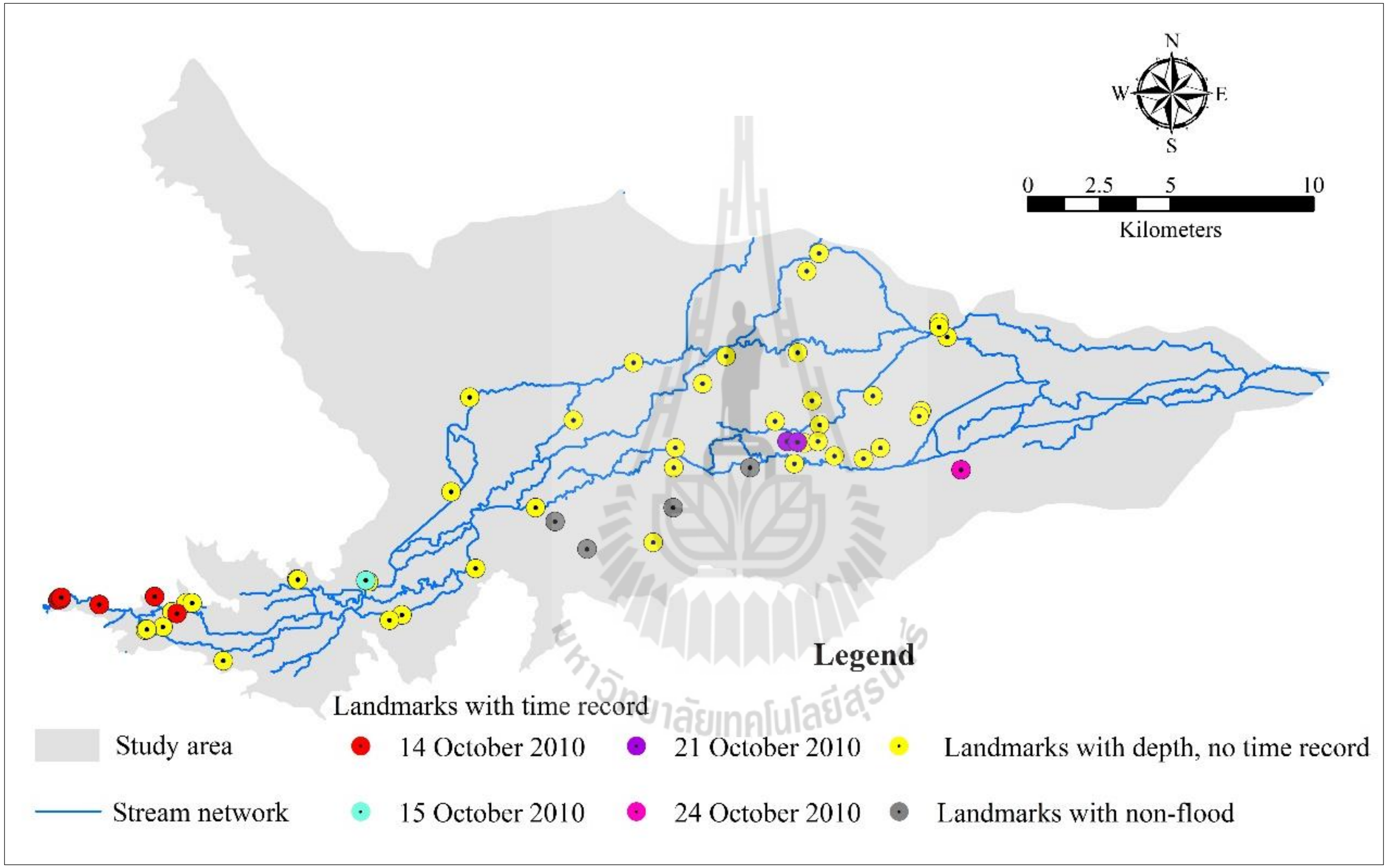

Figure 4.10 Distribution of flood records in 2010.

Table 4.25 Comparison of six simulated flood extents based on varying of Manning's M number with landmarks with flood and time record in 2010.

Flood extent	No of points	Number of corrected points					
		Min	Normal	Max	Modify 1	Modify 2	Modify 3
14-Oct-10	7	5	5	5	5	5	5
15-Oct-10	1	0	1	0	0	1	0
21-Oct-10	2	0	2	0	0	0	0
24-Oct-10	1	1	1	0	0	0	0

Table 4.26 Comparison of six simulated flood extents based on varying of Manning's M number with landmark with flood and no time records, and landmark with non-flood record in 2010.

Flood extent	No of points	Number of corrected points					
		Min	Normal	Max	Modify 1	Modify 2	Modify 3
Flood	52	43	42	35	35	36	40
Non-flood	4	4	4	4	4	4	4

In addition, the simulated flood extent of normal Manning's M number also provided the flood arrival date records on important landmarks which was similar to historical data in 2010. For example, the flood arrived to School Child Development Center at Ban Don, on 14 October 2010, Ban Kong Yang on15 October 2010, V.I.P house estate, and Saint Mary hospital on 21 October 2010, and Wat Taklong Kao on 24 October 2010. Therefore, further step of analyzing physical flood information (depth, velocity, and duration) were simulated using the normal Manning's M number as optimum values with statistics of overall accuracy 81.68%, flood detection rate 62.39% and false alarm 15.01% on 22 October 2010, and overall accuracy 81.53%, flood detection rate 63.44%, and false alarm 15.50% on 23 October 2010.

4.2.2 Urban flood simulation in 2010 by DHI MIKE 21 model

In this part, urban flood extent, depth and velocity and its duration which were simulated using an optimum local parameters by DHI MIKE 21 model during 14 October 2010 - 27 October 2010 were here separately described and discussed.

4.2.2.1 Physical urban flood extent

The results of physical urban flood extent during 14 to 27 October 2010 which provided flood movement was presented in Figure 4.11. The urban flood extent was dramatically increased during 14 to 21 October 2010 and gradually increased to the maximum extent on 24 October 2010 which covered area of 88.36 sq. km before slowly decreased and on 27 October 2010 with 82.00 sq. km (Figure 4.12).

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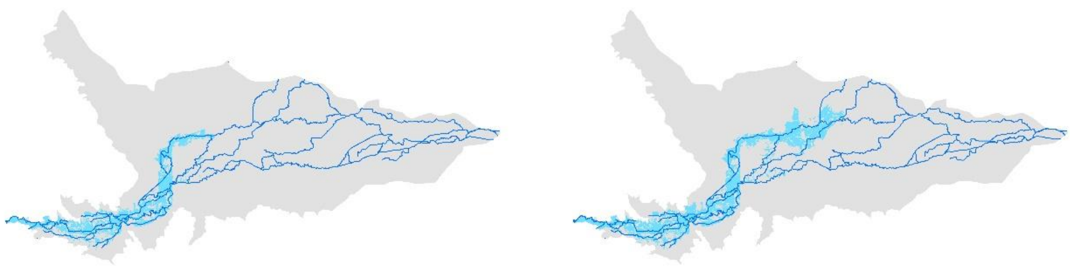
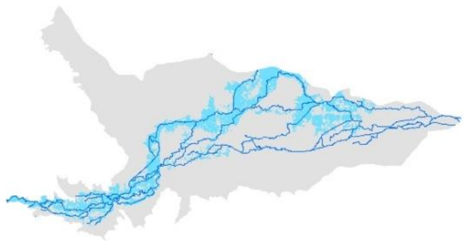
(a) 14 October 2010. (b) 15 October 2010.



(c) 16 October 2010 (d) 17 October 2010

Figure 4.11 Flood extent map during 22 - 27 October 2010 from (a) to (n).

(e) 18 October 2010



(f) 19 October 2010

(g) 20 October 2010

(h) 21 October 2010

(i) 22 October 2010

(j) 23 October 2010

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(k) 24 October 2010

(l) 25 October 2010

(m) 26 October 2010

(n) 27 October 2010

Figure 4.11 Flood extent map during 22 - 27 October 2010 from (a) to (n) (Continued).

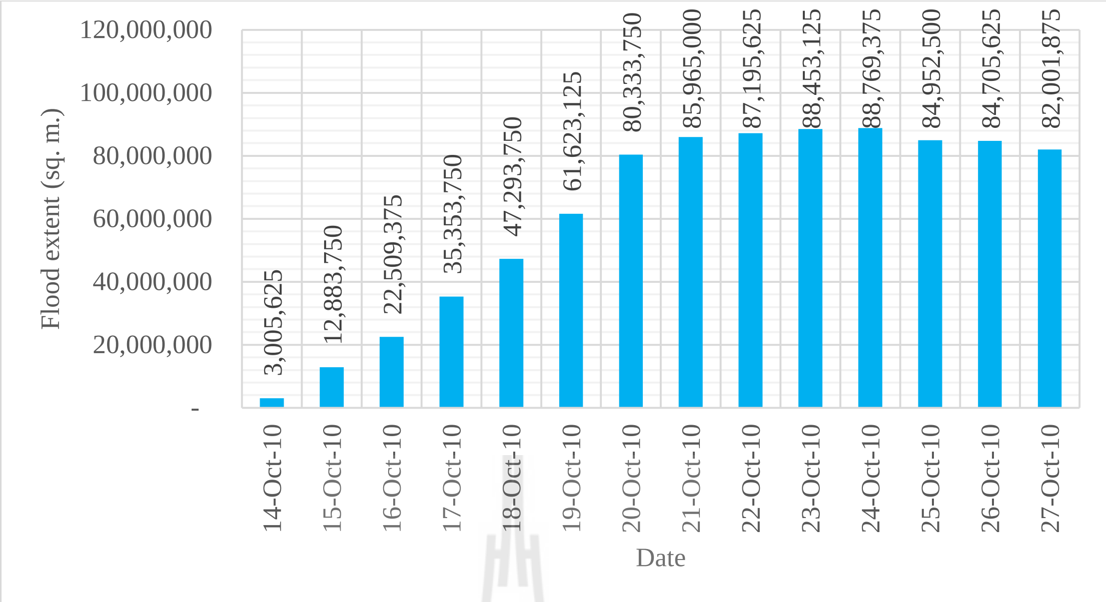

Figure 4.12 Urban flood area during 14 to 27 October 2010.

In other points, flood extent can be displayed effect on 26 sub-districts administrative as show in Table 4.27. As results of daily flood extent, it can be seen that the highest flooded areas on 14 October 2010 have appeared in Bung Khilek sub-district, Sung Noen district with area of 1.27 sq. km. At the same time, it was found two inundated area with area of 1,250 sq. m. in Tha Chang sub-district, Chaleom Pra Kiat districts, which situates far from the originate point of urban flood over Lam Takhong River. These inundated areas are generated by precipitation. These effect have also taken place on 14 –19 October 2010. During urban flood on 15 October 2010, the highest flooded areas have moved to KongYang sub-district, Sung Noen district with area of 4.29 sq. km. The urban flood had highly increased on 16 October 2010 and flow into Kham Thale So sub-district, Kham Thale So district with area of 6.77 sq. km and reached Khok Kruat sub-district, Mueang Nakhon Ratchasima district with area of 2.48 sq. km On 17 October 2010, urban flood was spread the extent to 7 sub-districts of Mueang Nakhon Ratchasima district and expanded over 17 sub-districts of Mueang Nakhon Ratchasima on 20 October 2010. Furthermore, urban flood extent was also moved to Tha Chang sub-district, Chaleom Pra Kiat district with area of 2.07 sq. km.

Interestingly, the maximum flood extent during 14 to 27 October 2010 have displayed on 24 October 2010 and rapidly spread over 26 sub-districts of 4 districts. The maximum flood extent had major effected to Mueang Nakhon Ratchasima district especially in Putsa, Ban Pho, and Nai Mueang and Ban Kho sub-districts with area of 9.98, 8.45, and 7.82 sq. km respectively. The effected flood area on 24 October in each sub-district and its distribution with historical flood record were displayed in Figure 4.13.

As results in Figure 4.14, it can be observed that bypass Mitraphap Khon Kean road plays an important role as flood barrier to prevent the flood flow from west to east. In contrary, Mitraphap road through the city of Mueang Nakhon Ratchasima to bypass Mitraphap Khon Kean road cannot prevent the flood. It can easily see the flood flow over at (a) Bypass Mitraphap Khon Kean road, (b) Big C supercenter, (c) V.I.P house estate, (d) Saint Mary Hospital (front view), (e) Saint Mary Hospital (top view), (f) Nakhon Ratchasima bus terminal, (g) Toyota, Mitraphap road (h) Makro Superstore, (i) Vongchavalitkul University, (j) Wat Chong Eu, (k) Cho Ho junction, (l) Home Garden Ville, (m) Ban Kho, Suranarai road, (n) Wat Taklong Kao (See historical photographs in Figure 4.15).

Table 4.27 Details of urban flood extent effects on 26 sub-districts of four districts (sq. m)

		Date													
District	**Sub-districts**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Sung Noen	Bung Khilek	1,274,375	1,293,750	1,325,000	1,346,875	1,330,625	1,337,500	1,353,125	1,350,000	1,346,875	1,340,625	1,336,875	1,318,125	1,317,500	1,312,500
	Non Kha	946,875	990,625	1,057,500	1,120,000	1,079,375	1,088,125	1,135,625	1,131,875	1,122,500	1,101,875	1,088,125	1,045,000	1,041,250	1,019,375
	Kong Yang	783,125	4,296,250	4,800,000	5,568,125	5,220,000	5,149,375	5,633,125	5,621,875	5,611,875	5,432,500	5,292,500	4,652,500	4,660,625	4,278,125
	Na Klang	0	142,500	215,000	292,500	258,750	243,125	300,625	305,000	311,875	276,875	260,625	198,125	198,750	167,500
Kham Thale So	Kham Thale So	0	2,930,000	6,770,000	7,502,500	7,521,250	7,388,125	7,579,375	7,601,875	7,602,500	7,570,625	7,495,625	7,072,500	7,075,000	6,882,500
	Pong Dang	0	1,909,375	2,005,000	2,155,000	2,101,250	2,075,000	2,168,750	2,165,625	2,160,625	2,135,000	2,105,000	1,956,875	1,958,125	1,869,375
Mueang Nakhon Ratchasima	Khok Kruat	0	1,320,000	2,488,750	2,774,375	2,748,750	2,675,625	2,823,750	2,833,125	2,835,000	2,811,250	2,744,375	2,585,000	2,583,750	2,514,375
	Suranaree and Ban Mai	0	0	0	265,000	673,750	722,500	737,500	763,125	788,750	790,000	777,500	683,750	689,375	655,000
	Si Mum	0	0	0	4,070,625	4,669,375	4,571,250	4,807,500	4,998,750	5,013,750	5,010,000	4,878,125	4,370,000	4,332,500	4,092,500
	Phon Krang	0	0	0	1,840,000	1,924,375	1,873,125	1,896,875	1,933,750	1,933,750	1,928,750	1,910,000	1,838,125	1,833,125	1,809,375
	Nong Krathum	0	0	0	770,000	2,315,000	2,280,000	2,254,375	2,343,125	2,378,125	2,570,625	2,809,375	2,714,375	2,646,875	2,501,250
	Putsa	0	0	0	5,513,125	9,962,500	9,853,125	9,830,000	10,050,000	10,030,000	10,046,250	9,980,000	9,620,000	9,535,000	9,346,250
	Paru Yai	0	0	0	2,134,375	2,380,625	2,682,500	2,820,000	2,916,250	2,953,125	2,970,000	2,956,875	2,872,500	2,828,750	2,766,875
	Khok Sung	0	0	0	0	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250
	Cho Ho	0	0	0	0	3,202,500	5,430,000	5,463,750	5,565,625	5,568,125	5,578,125	5,567,500	5,491,875	5,463,750	5,420,625
	Muen Wai	0	0	0	0	1,903,125	3,958,750	3,930,625	4,057,500	4,252,500	4,625,000	4,793,125	4,935,625	4,805,000	4,670,625
	Hua Thale	0	0	0	0	0	58,125	1,138,125	1,276,250	1,315,625	1,443,750	1,731,875	1,378,125	1,365,000	1,216,250
	Nai Mueang and Ban Kho	0	0	0	0	0	4,206,250	4,998,125	6,614,375	7,613,125	7,821,250	7,823,125	7,756,875	7,593,125	7,438,750
	Ban Pho	0	0	0	0	0	1,456,875	8,018,750	8,278,125	8,279,375	8,423,750	8,456,875	8,166,875	8,207,500	7,975,625
	Talat	0	0	0	0	0	4,571,250	6,166,250	6,881,875	6,355,000	6,475,625	6,474,375	6,203,750	6,486,250	6,261,875
	Nong Rawiang	0	0	0	0	0	0	1,215,625	1,230,625	1,248,750	1,269,375	1,271,875	1,255,000	1,252,500	1,233,125
	Phanoa	0	0	0	0	0	0	843,125	892,500	988,125	1,102,500	1,196,875	1,261,875	1,261,875	1,211,875
	Maroeng	0	0	0	0	0	0	189,375	251,875	312,500	351,250	378,750	340,625	341,875	289,375
Chaleom Pra Kiat	Tha Chang	1,250	1,250	1,250	1,250	1,250	1,250	2,076,875	3,743,750	3,901,250	3,996,250	4,031,875	3,960,000	3,960,625	3,899,375
	Nong Yang	0	0	0	0	0	0	355,000	373,125	391,250	406,250	408,125	378,750	377,500	348,750
	Phra Phut	0	0	0	0	0	0	2,596,250	2,783,750	2,880,000	2,974,375	2,998,750	2,895,000	2,888,750	2,819,375
	Total	**3,005,625**	**12,883,750**	**18,662,500**	**35,353,750**	**47,293,750**	**61,623,125**	**80,333,750**	**85,965,000**	**87,195,625**	**88,453,125**	**88,769,375**	**84,952,500**	**84,705,625**	**82,001,875**

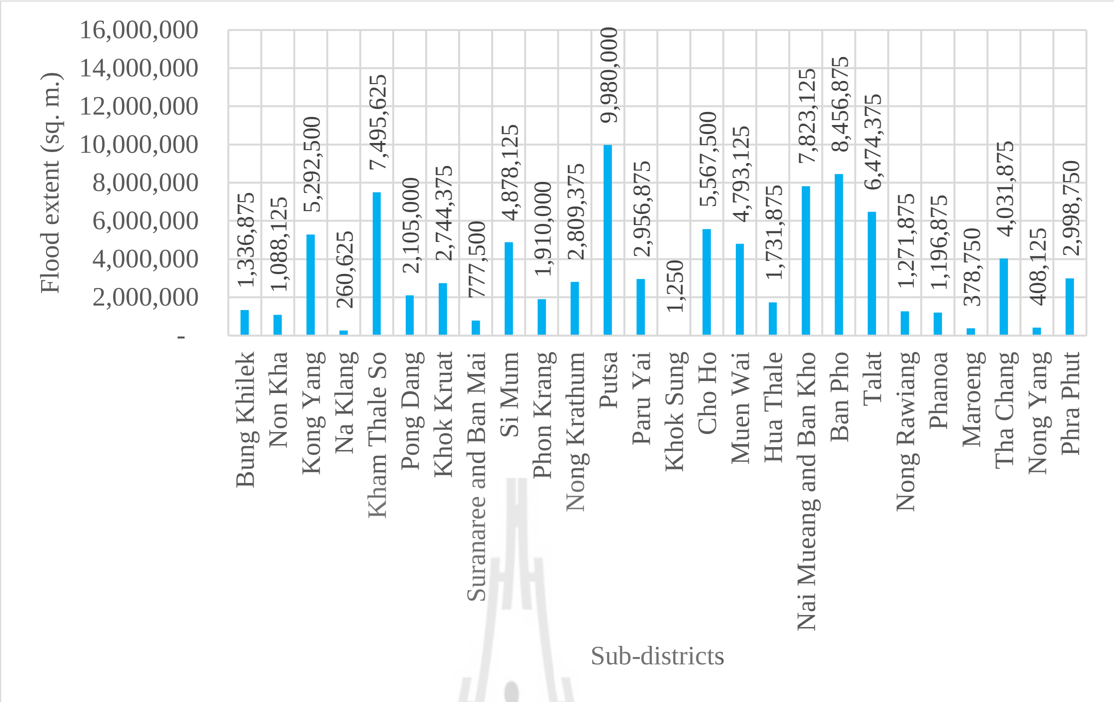

Figure 4.13 The details of urban flood extent arrived sub-districts on 24 October 2010.

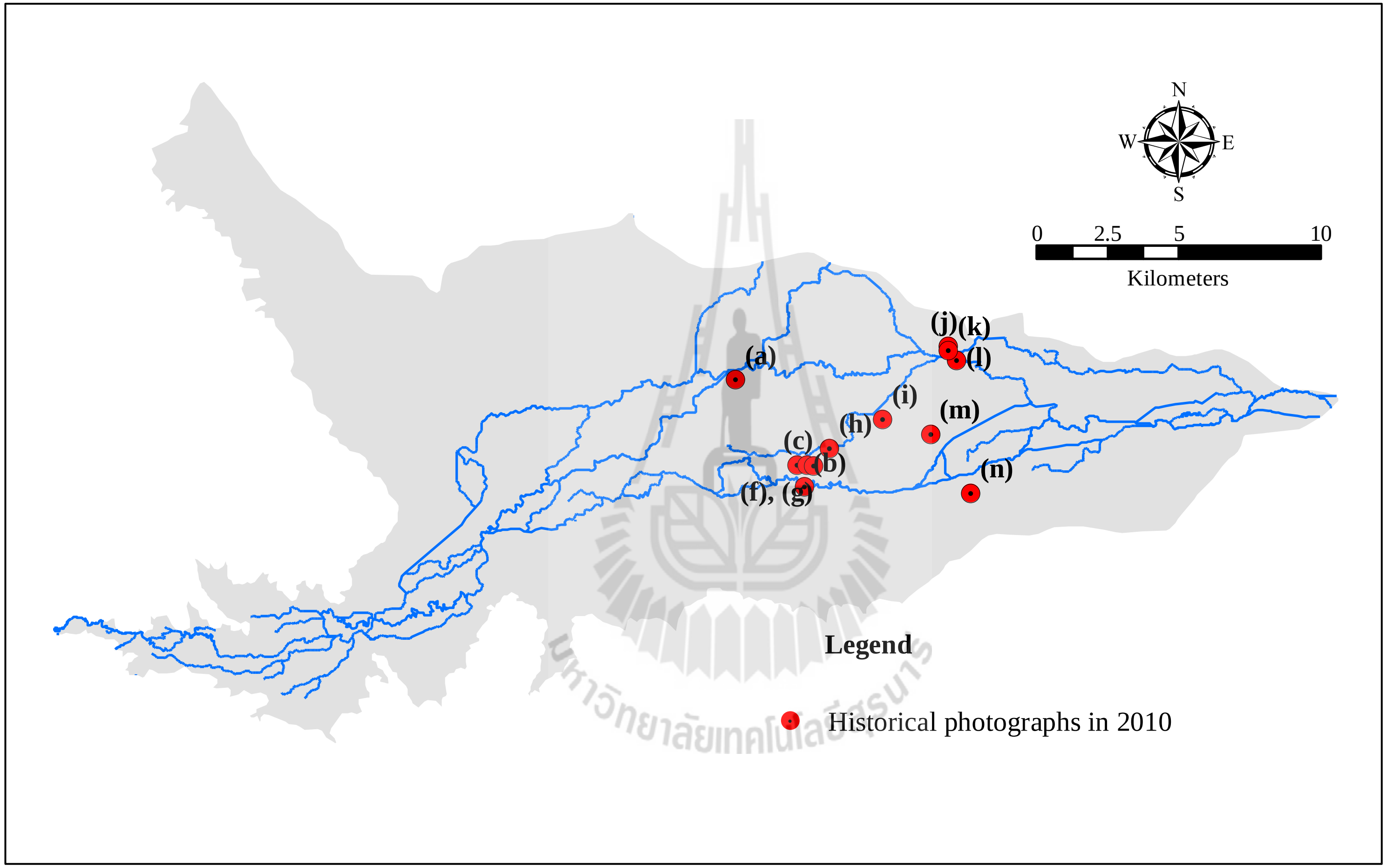

Figure 4.14 Distribution of urban flood extent with historical flood record on 24 October 2010.

(a) Bypass Mitraphap Khon Kean road

(b) Big C supercenter

(c) V.I.P house estate

(d) Saint Mary Hospital (front view)

(e) Saint Mary Hospital (top view)

(f) Nakhon Ratchasima bus terminal

(g) TOYOTA, Mitraphap road

(h) Makro Superstore

Figure 4.15 Historical picture of Mueang Nakhon Ratchasima flood in 2010.

(i) Vongchavalitkul University

(j) Wat Chong Eu

(k) Cho Ho junction

(l) Home Garden Ville

(m) Ban Kho, Suranarai road

(n) Wat Taklong Kao

Figure 4.15 Historical picture of Mueang Nakhon Ratchasima flood in 2010 (Continued).

4.2.2.2 Effect of urban flood extent on land use

The results of urban flood affected on land use had illustrated that agricultural land as the main land use was affected from flood with area of 76.89 sq. km, followed by urban and built-up area with area of 7.74 sq. km on 24 October 2010 (Figure 4.16).

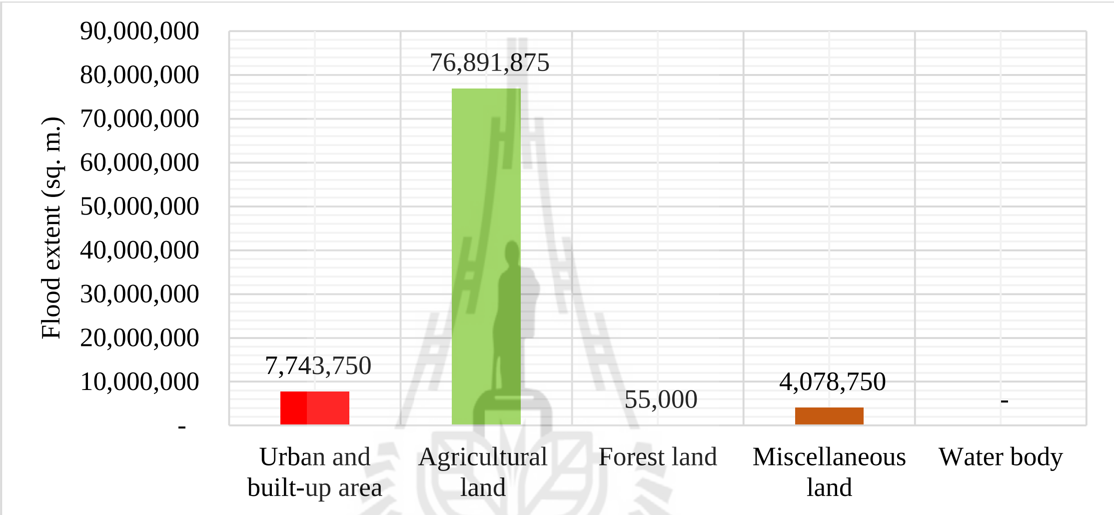

Figure 4.16 Effect of urban flood on 5 main land use types.

Furthermore, the urban and built–up area was demonstrated spatial location according to levels of elevation. Herewith, most of effected urban and built-up area had located between 172 to 183 m above mean sea level (amsl) with area of 6.57 sq. km or 84.85% of total urban and built-up area as shown in Figure 4.17 and Figure 4.18. These area was placed at center of the study area, it was characterized as drainage and surrounded with stream networks.

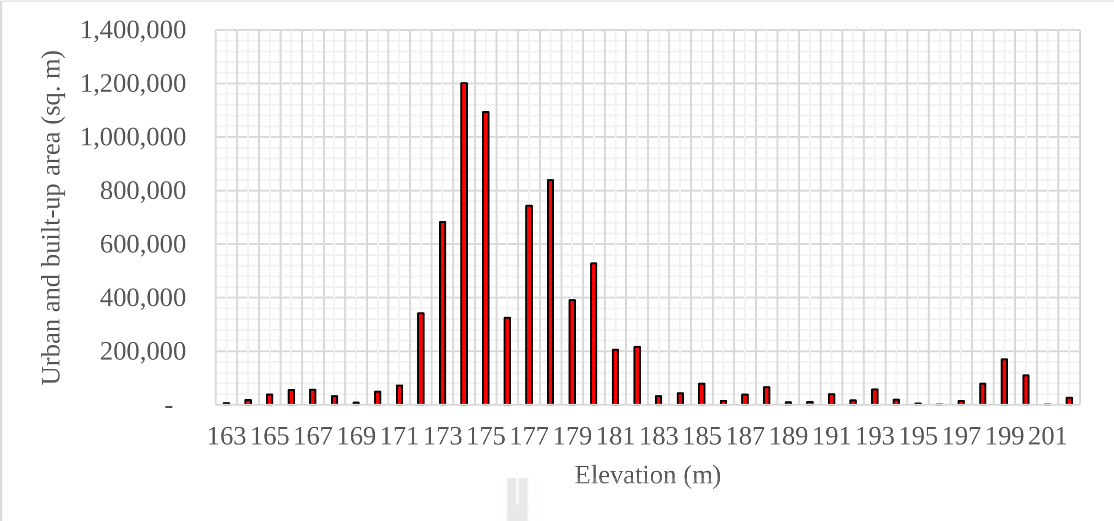

Figure 4.17 Distribution of urban and built-up area according to its elevation.

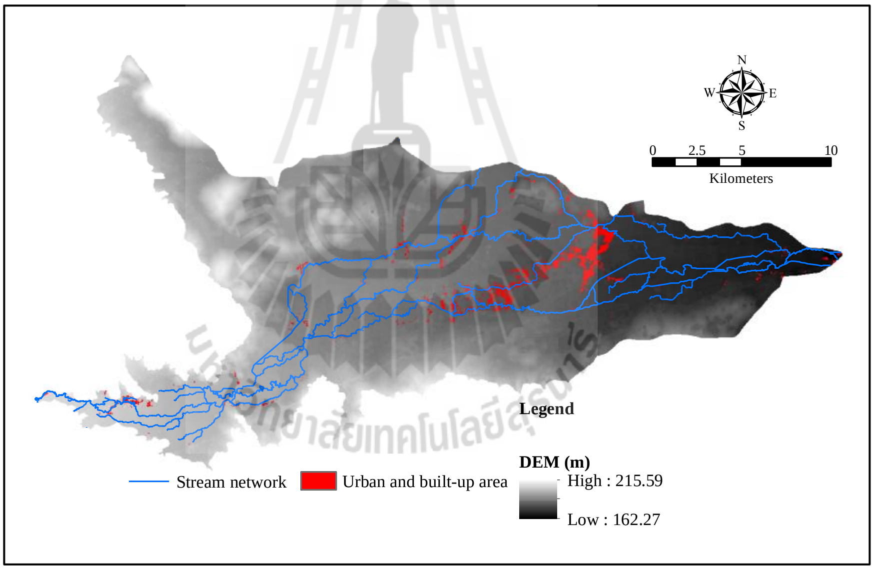

Figure 4.18 Distribution of flooded urban and built-up area and its elevation.

Under the urban and built-up area, the 3 urban and built-up area classes that affected from urban flood were concrete and wooden house (5.59 sq. km), house with 2 floors (0.80 sq. km), and large industrial (0.39 sq. km) whereas commercial buildings with 3 floors, large warehouse, railway station, and townhouse with 2 floors had no effected from urban flood (see Figure 4.19). These data were used to calculate the economic value loss for urban flood vulnerability analysis. The details of daily flood extent on land use type during 14 to 27 October 2010 was provided in Table 4.28.

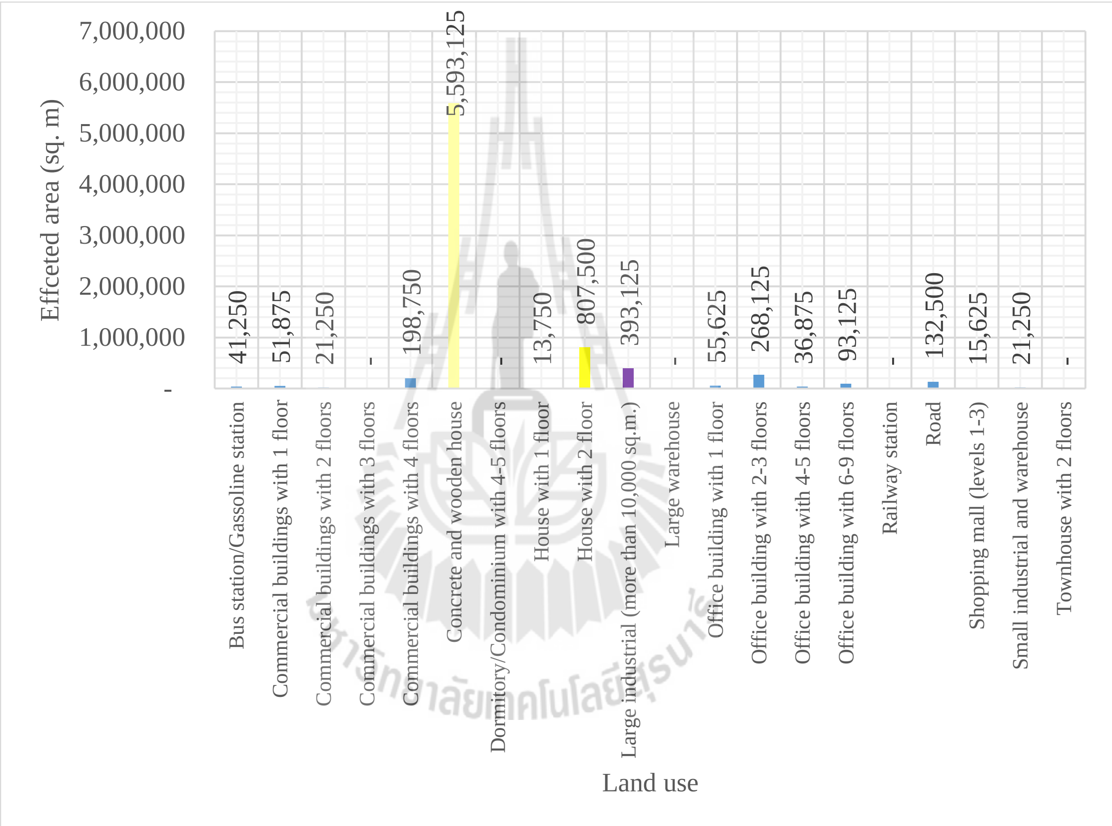

Figure 4.19 Urban and built-up area effecting urban flood on 24 October 2010.

Table 4.28 Daily flood extent affected on land use types during 14 to 27 October 2010.

Land use type		Daily effected area on urban and built-up area in sq. m													
Level 1	**Level II/III**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
U	Bus station/Gasoline station	0	0	0	0	0	0	625	1,875	36,250	41,875	41,250	46,875	40,000	39,375
U	Commercial buildings with 1 floor	0	0	0	21,250	26,250	48,750	51,875	51,875	51,875	51,875	51,875	51,875	51,875	51,250
U	Commercial buildings with 2 floors	0	0	0	0	0	19,375	19,375	21,250	20,000	21,250	21,250	20,000	20,000	19,375
U	Commercial buildings with 4 floors	0	0	0	0	0	19,375	26,250	67,500	192,500	199,375	198,750	199,375	193,125	185,000
U	Concrete and wooden house	295,625	373,750	529,375	1,020,625	1,221,250	3,783,125	4,066,875	4,672,500	5,172,500	5,511,250	5,593,125	5,542,500	5,410,000	5,263,750
U	House with 1 floor		13,125	13,750	13,750	13,750	13,750	13,750	13,750	13,750	13,750	13,750	13,750	13,750	13,750
U	House with 2 floor		75,000	86,875	95,625	95,000	95,625	513,750	715,625	784,375	810,000	807,500	793,750	760,000	731,875
U	Large industrial		6,250	8,750	105,625	209,375	354,375	354,375	390,000	389,375	392,500	393,125	376,875	373,750	365,625
U	Office building with 1 floor	3,750	3,750	3,750	7,500	23,750	49,375	51,875	51,875	51,875	51,875	55,625	55,625	53,750	53,125
U	Office building with 2-3 floors	0	0	8,125	27,500	48,125	236,875	243,125	268,125	266,875	270,000	268,125	258,125	255,625	251,250
U	Office building with 4-5 floors	0	0	0	0	0	0	21,250	28,750	33,125	36,875	36,875	33,750	33,125	31,875
U	Office building with 6-9 floors	0	0	0	0	0	0	0	0	92,500	93,125	93,125	93,125	93,125	93,125
U	Road	0	0	0	22,500	50,000	113,125	113,125	124,375	128,750	133,750	132,500	125,000	123,750	115,625
U	Shopping mall (1-3 floors)	0	0	0	0	0	0	0	0	14,375	15,625	15,625	15,625	15,000	13,750
U	Small industrial and warehouse	0	625	625	10,000	14,375	17,500	18,125	21,250	21,250	21,250	21,250	21,250	21,250	21,250
A	Abandoned paddy field	0	0	0	10,000	11,250	518,750	593,125	599,375	621,875	624,375	639,375	673,750	667,500	660,625
A	Animal farm house	0	15,000	16,875	40,000	41,250	47,500	50,000	49,375	48,750	49,375	47,500	45,625	45,000	43,750
A	Field crop	0	0	0	0	25,000	46,250	71,250	80,625	81,250	81,875	82,500	77,500	75,625	74,375
A	Horticulture	0	6,250	148,125	2,273,125	3,025,000	3,746,250	4,413,125	5,335,625	5,512,500	5,630,000	5,839,375	5,453,750	5,370,625	5,221,875
A	Orchard	121,250	355,625	437,500	564,375	832,500	1,007,500	1,161,250	1,199,375	1,233,125	1,240,625	1,233,750	1,180,625	1,169,375	1,129,375

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Table 4.28 Daily flood extent affected on land use types during 14 to 27 October 2010 (Continued).

Land use type		Daily effected area on urban and built-up area in sq. m													
Level 1	**Level II/III**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
A	Pasture	0	3,750	3,750	4,375	18,750	27,500	66,250	69,375	70,625	71,875	71,875	66,875	66,250	65,000
A	Perennial trees	0	39,375	42,500	83,125	91,250	88,125	90,625	94,375	94,375	96,250	93,750	89,375	89,375	86,875
A	Rice paddy	2,465,625	11,610,625	20,678,750	30,124,375	39,932,500	48,963,750	65,170,000	68,422,500	68,344,375	68,958,750	68,883,750	65,611,875	65,709,375	63,511,250
F	Disturbed deciduous forest	15,000	41,250	42,500	43,750	43,750	48,750	48,750	56,875	55,625	56,875	55,000	51,875	51,875	49,375
M	Grass	0	0	0	15,000	81,250	384,375	600,625	685,000	742,500	751,250	751,250	740,625	739,375	727,500
M	Landfill	0	4,375	9,375	205,000	281,875	322,500	340,625	383,125	385,625	385,000	386,250	368,750	369,375	359,375
M	Marsh and swamp	0	1,250	69,375	97,500	351,250	573,750	706,875	745,625	760,000	780,625	828,750	825,000	825,625	810,000
M	Recreation and green area	0	0	6,250	10,625	54,375	85,000	136,250	153,125	242,500	310,625	361,875	434,375	411,875	400,625
M	Shrub/Scrub	104,375	333,750	403,125	558,125	801,875	991,875	1,390,625	1,663,750	1,733,125	1,751,250	1,750,625	1,685,000	1,656,250	1,611,875
Total		**3,005,625**	**12,883,750**	**22,509,375**	**35,353,750**	**47,293,750**	**61,603,125**	**80,333,750**	**85,966,875**	**87,195,625**	**88,453,125**	**88,769,375**	**84,952,500**	**84,705,625**	**82,001,875**

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4.2.2.3 Physical urban flood depth.

The daily results of urban flood depth during 14 to 27 October 2010 had provided in Table 4.29, Figure 4.20, and Figure 4.21. It was illustrated the range of flood depth varies between 0.10 to 3.91 m. The minimum value of flood depth has been set at 0.10 m as a constant value to detect such flood occur as suggestion by local expert of the Royal Irrigation Department (Wachirasak Pakdee, Head of Khud Hin Watergate). It means that, if flood depth has value below 0.10 m, it would not be considered as a flood. Furthermore, the result of daily maximum value have shown flood depths between 3.14 to 3.91 m.

In general, the nature characteristic of Mueang Nakhon Ratchasima urban flood 2010 has flows in the same direction of the Lum Takhong River from the West at Kud Hin Watergates to the East at Gun Phom Watergate. It would be express that such flood event was caused by water overflowing from stream networks. Moreover, high urban flood depths are also located close to stream networks with nature characteristics of low land (low elevation). However, some parts of study area also have road networks which mostly construct with fills terrain higher than normal. It performs as man0made barriers to prevent flood flows and stored water volume in one side of road, i.e. road number 22 (Bypass Mitraphap Khon Kaen road). As results, it might lead to high flood depths near the road networks.

Table 4.29 Daily physical urban flood depths data.

	Flood depth (m)		
Day	**Minimum**	**Maximum**	**Mean**
14 October 2010	0.10	3.14	0.46
15 October 2010	0.10	3.81	0.39
16 October 2010	0.10	3.85	0.46
17 October 2010	0.10	3.90	0.50
18 October 2010	0.10	3.90	0.54
19 October 2010	0.10	3.88	0.54
20 October 2010	0.10	3.90	0.53
21 October 2010	0.10	3.91	0.53
22 October 2010	0.10	3.91	0.53
23 October 2010	0.10	3.90	0.53
24 October 2010	**0.10**	**3.89**	**0.53**
25 October 2010	0.10	3.88	0.54
26 October 2010	0.10	3.88	0.54
27 October 2010	0.10	3.86	0.55

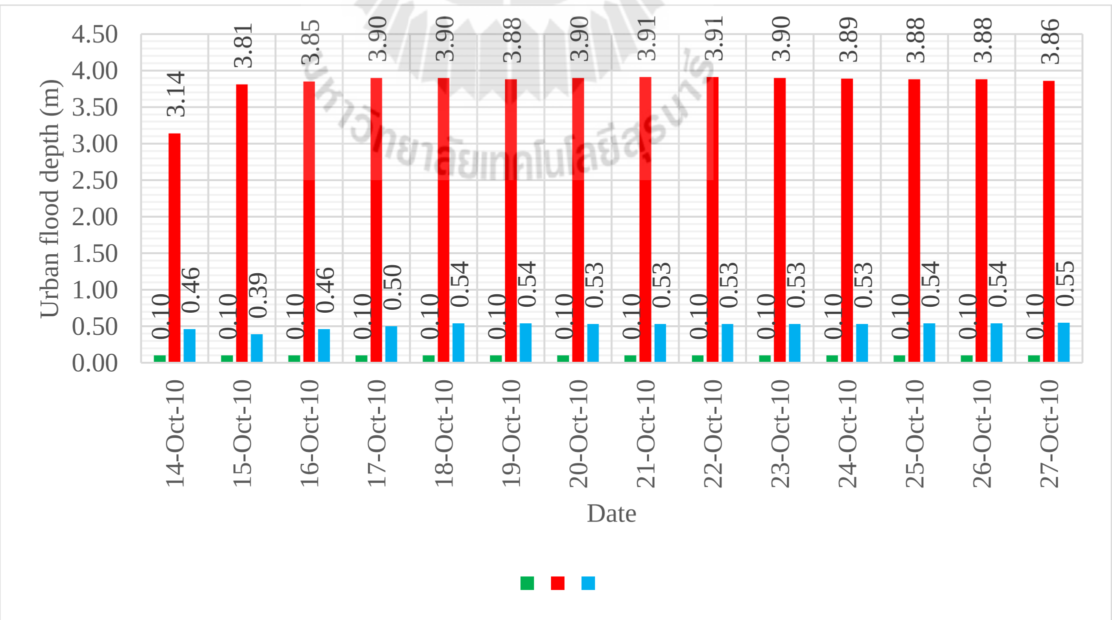

Figure 4.20 Daily physical urban flood depths data.

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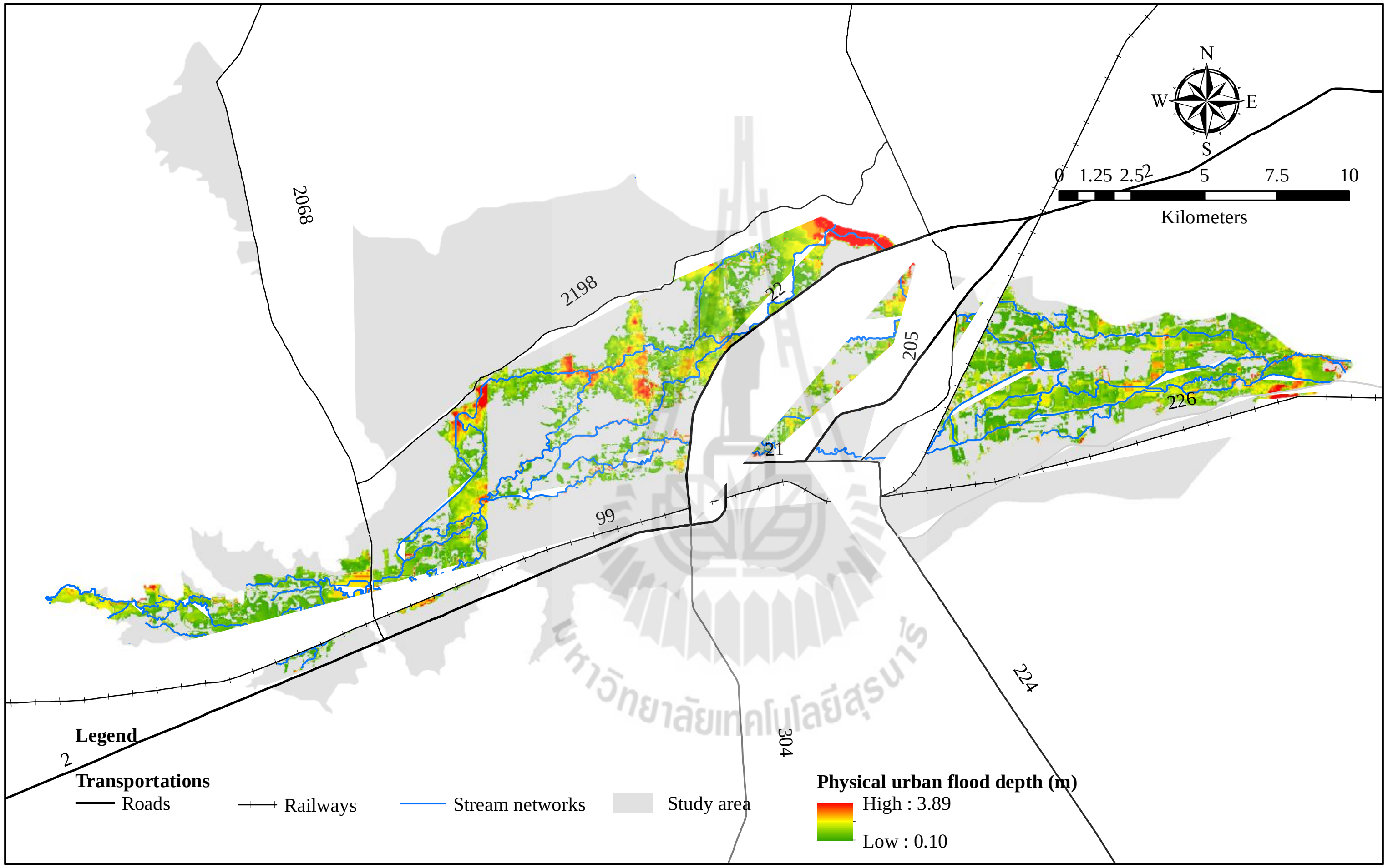

Figure 4.21 Distribution of physical urban flood depth on 24 October 2010.

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4.2.2.4 Physical urban flood velocity.

The results from hydrodynamic simulation indicated urban flood velocity was extremely increased from 0.00 m/s to 2.03 m/s on 19 October 2010, then gradually increased to the highest value on 22 and 23 October 2010 with 2.06 m/s before slightly decreased to 1.97 m/s on 27 October 2010. The spatial variability of maximum urban flood velocity are represented location close to stream network and very flat floodplain. For overland flows on the flat plain, the highest urban flood velocity was smaller than flows in the flood plain close to Lum Taklong River. Some extreme values could reached 2.00 m/s in the places where next to the stream networks. However, the mean of urban flood velocity have shown values in range between 0.22 m/s to 0.14 m/s which was very low in difference. These could cause by the nature flat characteristic of the study area. The daily results have provided in Table 4.30 and Figure 4.22, while the distribution of urban flood velocity have displayed in Figure 4.23.

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Table 4.30 Daily physical urban flood velocity.

Date	Velocity (m/s)		
	Min	**Max**	**Mean**
14 October 2010	0.00	0.88	0.22
15 October 2010	0.00	0.91	0.17
16 October 2010	0.00	1.23	0.17
17 October 2010	0.00	1.28	0.17
18 October 2010	0.00	1.29	0.16
19 October 2010	0.00	2.03	0.14
20 October 2010	0.00	1.99	0.14
21 October 2010	0.00	2.05	0.14
22 October 2010	0.00	2.06	0.14
23 October 2010	0.00	2.06	0.14
24 October 2010	**0.00**	**2.06**	**0.14**
25 October 2010	0.00	2.03	0.14
26 October 2010	0.00	2..00	0.14
27 October 2010	0.00	1.97	0.14

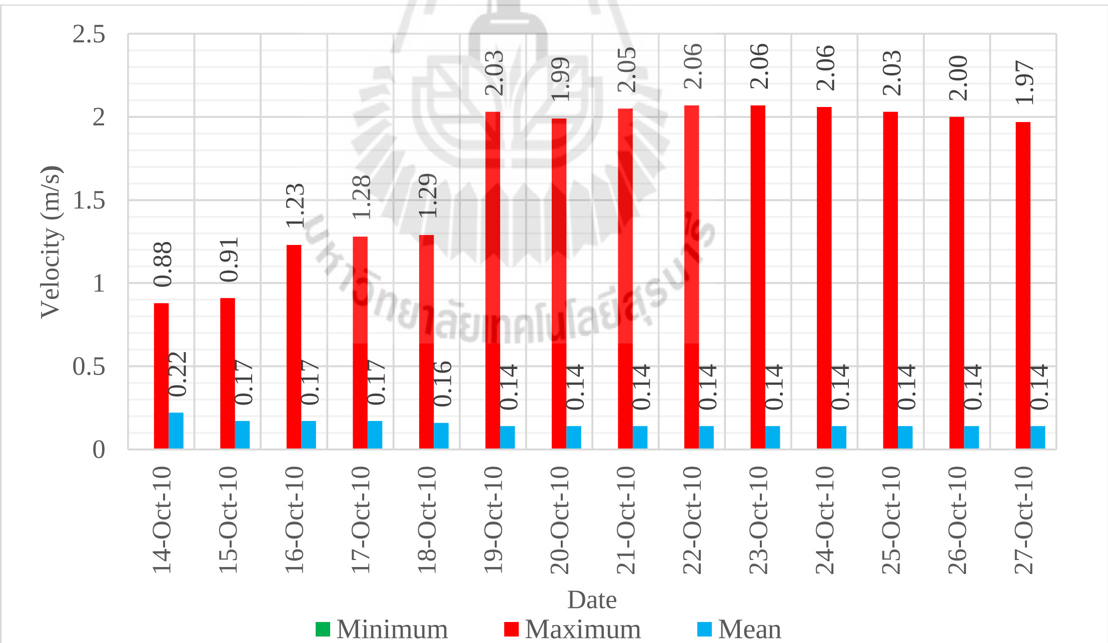

Figure 4.22 Daily movement of physical urban flood velocity.

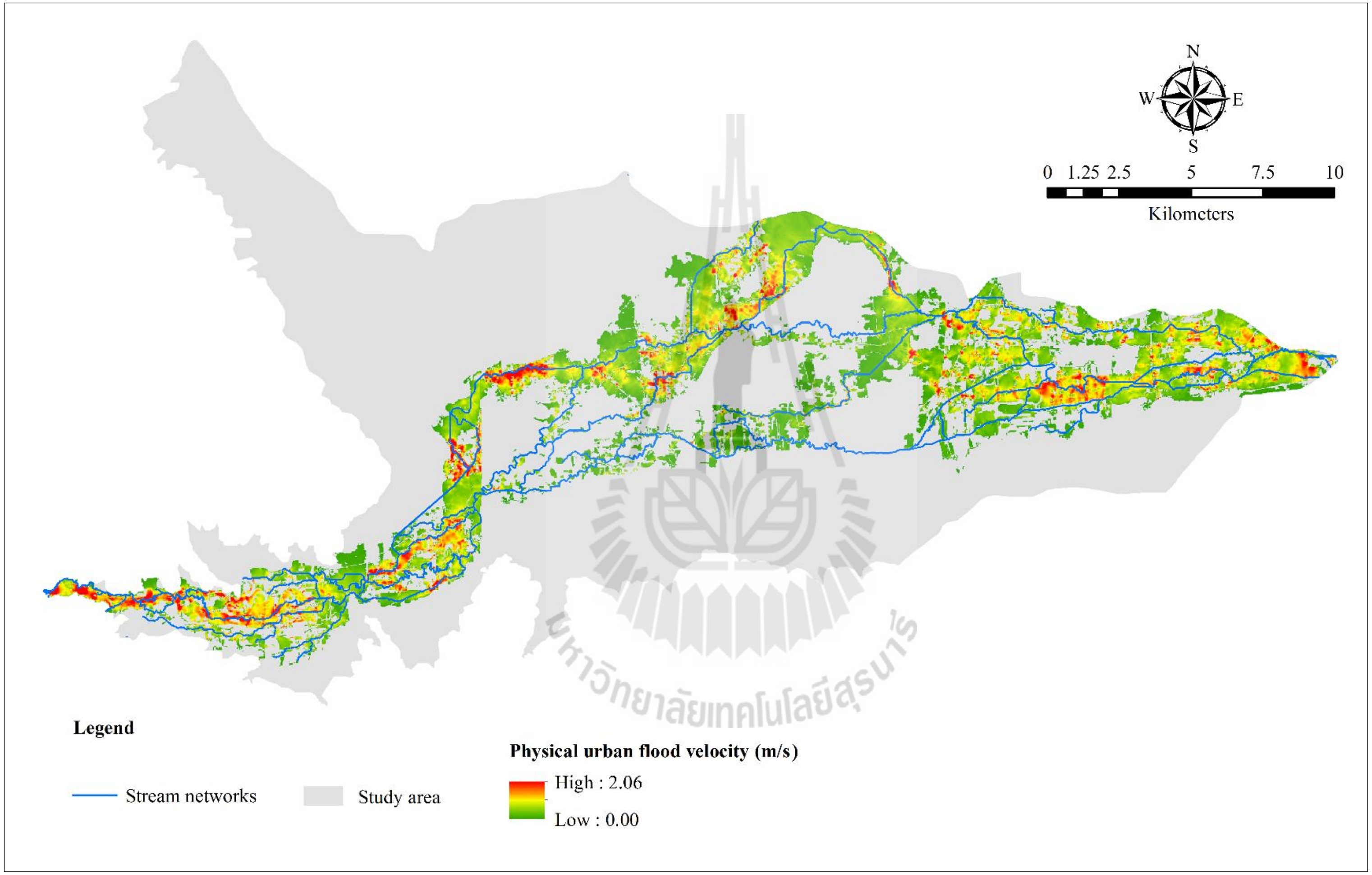

Figure 4.23 Distribution of physical urban flood velocity on 24 October 2010.

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4.2.2.5 Physical urban flood duration.

This section presents the results of physical urban flood duration analysis based on Mueang Nakhon Ratchasima flood 2010. According to the limitation of hydrological data (discharge) which was only available 14 days (14 to 27 October 2010), the flood duration. Therefore, it was considered under this time period. The basic concept of duration analysis was combined the daily flood extent during 14 to 27 October 2010 by raster calculation function to represent the repeated areas by number of days (1 to 14 days).

As results, 14 values of urban flood durations with urban flood area have presented in Figure 4.24. It can be seen that the trend of urban flood area have slowly increased as same as duration increased.

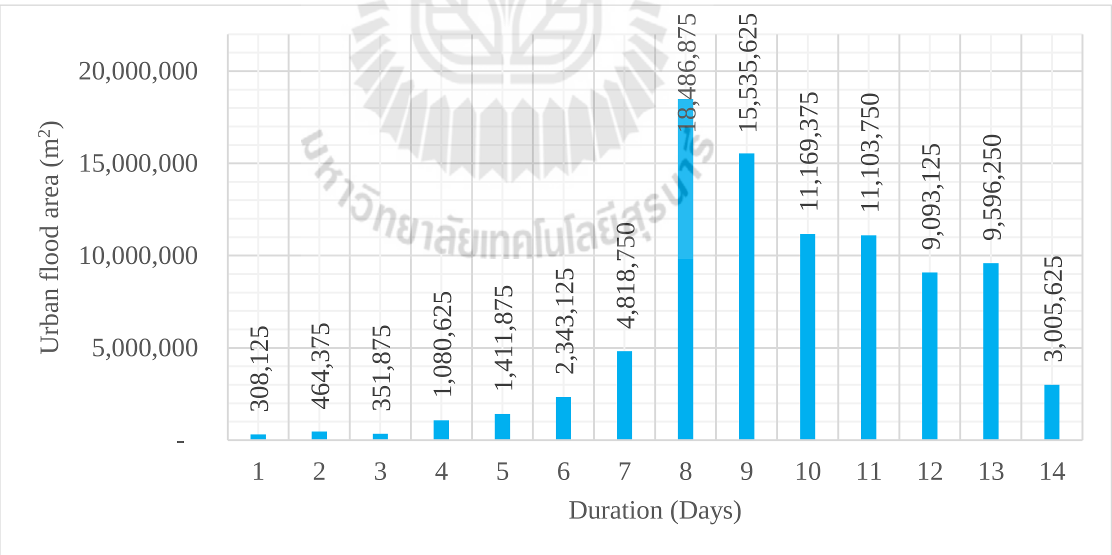

Figure 4.24 Physical urban flood duration.

Considered the urban flood area with urban flood periods, the highest urban flood area of 18.48 sq. km was represented 8 days of duration period followed by area of 15.53 sq. km with represented 9 days of duration period. Furthermore, under the duration period of 8 and 9 days, the concrete and wooden house was the most land use type that effected on flood duration as area of 0.28 sq. km and 2.57 sq. km. The spatial location of highest urban flood duration (14 days) were mostly located close to Kud Hin Watergate, and mainly situated in Sung Noen district whereas the minimum of urban flood duration was also located in Nong Krathum, and Muen Wai sub-district, Mueang Nakhon Ratchasima districts. The distribution of urban flood duration and its effect on land use were are provided in Figure 4.25 and Table 4.31.

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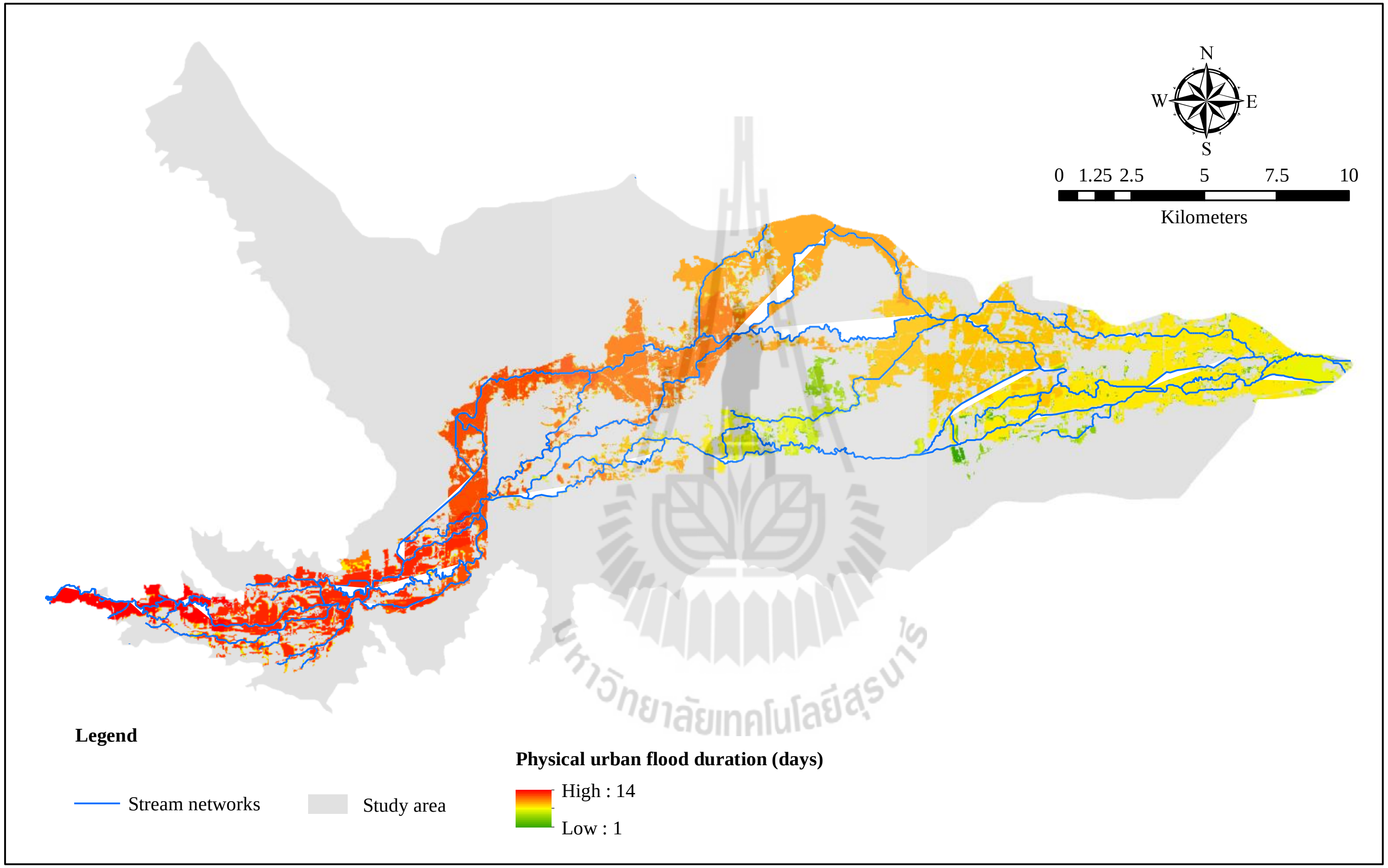

Figure 4.25 Distribution of urban flood duration.

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Table 4.31 The details of physical urban flood duration effected on land use (sq. m).

		Urban flood duration periods (day)													
Level 1	**Land use level II / III**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
U	Bus station/Gasoline station	0	0	3,125	625	1,250	34,375	1,250	625	0	0	0	0	0	0
U	Commercial buildings with 1 floor	0	0	0	0	0	0	0	3,750	21,875	5,000	21,250	0	0	0
U	Commercial buildings with 2 floors	0	0	1,250	0	0	625	0	0	19,375	0	0	0	0	0
U	Commercial buildings with 3 floors	0	0		0	0	0	0	0		0	0	0	0	0
U	Commercial buildings with 4 floors	0	1,250	2,500	3,750	2,500	123,750	41,250	7,500	16,250	0	0	0	0	0
U	Concrete and wooden house	5,625	32,500	66,875	160,000	264,375	538,750	536,875	281,875	2,573,125	158,750	462,500	140,000	76,250	295,625
U	Dormitory/Condominium with 45 floors	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U	House with 1 floor	0	0	0	0	0	0	0	0	0	0	0	625	13,125	0
U	House with 2 floor	625	2,500	12,500	16,250	27,500	78,125	185,000	389,375	4,375	1,250	2,500	13,125	74,375	0
U	Large industrial (more than 10,000 sq. m.)		1,250	1,250	1,250	5,000	1,250	38,750	5,000	145,625	91,875	93,125	2,500	6,250	0
U	Large warehouse	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U	Office building with 1 floor	0	0	0	4,375	0	625	1,250	1,250	25,000	15,625	3,750	0	0	3,750
U	Office building with 2-3 floors	0	2,500	1,875	1,250	0	1,250	23,750	6,250	191,250	16,250	15,625	8,125	0	0
U	Office building with 4-5 floors	0	625	2,500	625	0	8,750	3,125	1,250	20,000	0	0	0	0	0
U	Office building with 6-9 floors	0	0	0	0	625	92,500	0	0	0	0	0	0	0	0

Table 4.31 The details of physical urban flood duration effected on land use (sq. m) (Continued).

		Urban flood duration periods (day)													
Level 1	**Land use level II / III**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
U	Railway station	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U	Road	0	1,250	1,250	3,125	2,500	9,375	3,750	3,750	63,125	21,875	22,500	0	0	0
U	Shopping mall (levels 1-3)	0	0	0	1,875	0	0	0	0	0	0	0	0	0	0
U	Small industrial and warehouse	0	0	0	0	0	0	3,125	625	3,125	4,375	9,375	0	0	0
U	Townhouse with 2 floors	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A	Abandoned aquaculture	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A	Abandoned field crop	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A	Abandoned paddy field	1,250	625	1,875	14,375	1,250	29,375	625	73,125	506,875	0	10,000	0	0	0
A	Animal farm house	0	0	0	625	0	0	1,875	625	6,250	625	20,625	1,875	15,000	0
A	Field crop	625	0	625	1,250	2,500	625	8,125	28,125	15,625	25,000	0	0	0	0
A	Horticulture	174,375	18,750	48,125	104,375	136,250	235,625	823,750	686,250	827,500	540,625	2,096,250	141,250	6,250	0
A	Orchard	0	2,500	11,875	16,250	11,250	43,750	50,000	136,875	181,250	255,000	108,750	64,375	230,625	121,250
A	Pasture	0	1,250	0	1,875	625	2,500	1,250	39,375	6,875	14,375	0	0	3,750	0
A	Perennial trees	0	625	0	0	2,500	625	3,750	0	1,875	3,750	38,125	3,125	39,375	0
A	Rice paddy	118,125	381,250	173,125	606,875	841,875	883,750	2,675,000	15,983,125	10,116,250	9,374,375	7,817,500	8,570,000	8,876,875	2,465,625
F	Dense forest Plantation	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	Disturbed deciduous forest	0	0	0	3,125	0	1,250	1,875	0	5,000	0	1,250	2,500	25,000	15,000
M	Cemetery	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	Garbage dump	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	Golf course	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.31 The details of physical urban flood duration effected on land use (sq. m) (Continued).

		Urban flood duration periods (day)													
Level 1	**Land use level II / III**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
M	Grass	0	2,500	5,000	8,125	6,875	66,875	65,625	213,125	302,500	65,625	15,000	0	0	0
M	Landfill			2,500	8,125	3,125	2,500	37,500	18,750	45,625	69,375	192,500	3,125	3,125	0
M	Marsh and swamp	1,875	5,625	1,875	50,000	16,250	18,125	30,625	140,000	217,500	252,500	25,000	68,125	1,250	0
M	Pit														0
M	Recreation and green area	2,500	1,875	2,500	50,625	61,875	89,375	16,875	52,500	30,000	43,750	3,750	6,250	0	0
M	Shrub/Scrub	3,125	7,500	11,250	21,875	23,750	65,625	263,750	413,750	189,375	209,375	144,375	68,125	224,375	104,375
W	Water body	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total		**308,125**	**464,375**	**351,875**	**1,080,625**	**1,411,875**	**2,343,125**	**4,818,750**	**18,486,875**	**15,535,625**	**11,169,375**	**11,103,750**	**9,093,125**	**9,596,250**	**3,005,625**

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4.3 Urban flood severity analysis

In this part, flood depth and velocity on 24 October 2010 were used to classify urban flood severity maps based on Chen (2007), while as duration have classified by manual classification method. Herein, physical urban flood severity according to flood depth, velocity, and duration have been here individually displayed and described. Later, the depth and velocity have normalized by benefit criterion normalization method and combined together using raster calculation extension with additive method. The physical urban flood severity according to combination of depth and velocity had classified by six classification methods (equal interval, defined interval, quantile, natural break, geometrical interval and standard deviation) under spatial analysis tools of ArcGIS 9.3 and examine the consistency test with the affected population by flood (PAPF) for an optimum methods of classification. In the end, physical urban flood severity have classified in to five classes as very low, low, moderate, high, and very high.

4.3.1 Physical urban flood severity classification by flood depth

The results were showed that the major physical urban flood severity class was moderate with covered area of 35.32 sq. km or 39.80% of flood area and it followed by low class with area of 26.42 sq. km or 29.77% of flood area. In addition, the very high class of urban flood severity was covered only area of 3.36 sq. km or 3.79% of flooded area (Table 4.32).

Table 4.32 Area and percent of physical urban flood severity classification by flood depth.

Classification	Depth (m)	Area (sq. m)	% of area
Very low	0.10 - 0.20	16,550,625	18.64%
Low	0.20 - 0.40	26,423,125	29.77%
Moderate	0.40 - 1.00	35,327,500	39.80%
High	1.00 - 1.50	7,103,125	8.00%
Very high	1.50 - 3.89	3,365,000	3.79%
Total		**88,769,375**	**100.00%**

Furthermore, when this classification was combined with land use at level I, it was shown that 2 main land use types included urban and built-up area and agricultural land were suffered from urban flood and mostly situated in the moderate class of flood severity as shown in Table 4.33.

Table 4.33 Physical urban flood severity classification by flood depth with major land use types (sq. m).

Level I	Very low	Low	Moderate	High	Very high	Total
Urban and built-up area	1,307,500	2,291,875	2,879,375	862,500	402,500	7,743,750
Agricultural land	14,706,875	23,245,000	30,741,875	5,686,875	2,511,250	76,891,875
Forest land	10,625	16,875	18,125	5,000	4,375	55,000
Miscellaneous land	525,625	869,375	1,688,125	548,750	446,875	4,078,750
Water body	0	0	0	0	0	0
Total	**16,550,625**	**26,423,125**	**35,327,500**	**7,103,125**	**3,365,000**	**88,769,375**

Under the urban and built-up area, concrete and wooden house, and house with 2 floors were the main urban and built-up area types that suffered with urban flood depth. The moderate urban flood depth was also covered area of 2.02 sq. km of concrete and wooden house or 36.15% whereas the very high urban flood depth was covered area of 0.26 sq. km or 4.69%. The details of physical urban flood severity classification by flood depth with land use was summarized in Table 4.34 and Figure 4.26 displayed urban flood severity classification by flood depth.

Table 4.34 Details of physical urban flood severity classification by flood depth with land use type (sq. m).

Level I	Land use level II/III	Very low	Low	Moderate	High	Very high	Total
U	Bus station/Gasoline station	9,375	15,000	13,125	3,750	0	41,250
U	Commercial buildings with 1 floor	2,500	13,750	28,125	7,500	3,125	55,000
U	Commercial buildings with 2 floors	3,125	3,750	8,125	3,125	0	18,125
U	Commercial buildings with 4 floors	38,750	69,375	65,000	6,250	19,375	198,750
U	Concrete and wooden house	**946,875**	**1,650,000**	**2,021,875**	**711,875**	**262,500**	**5,593,125**
U	House with 1 floor	1,875	8,750	3,125	0	0	13,750
U	House with 2 floor	**176,250**	**257,500**	**299,375**	**36,875**	**37,500**	**807,500**
U	Large industrial (more than 10,000 sq. m.)	55,625	88,750	167,500	45,625	35,625	393,125
U	Office building with 1 floor	10,625	18,125	15,000	5,625	6,250	55,625
U	Office building with 2-3 floors	26,875	68,750	136,250	10,625	25,625	268,125
U	Office building with 4-5 floors	6,250	6,875	16,875	6,875	0	36,875
U	Office building with 6-9 floors	1,875	26,875	64,375	0	0	93,125
U	Road	25,000	53,125	33,125	14,375	6,875	132,500
U	Shopping mall (levels 1-3)	1,875	5,000	2,500	625	5,625	15,625
U	Small industrial and warehouse	625	6,250	5,000	9,375	0	21,250
A	Abandoned paddy field	32,500	70,625	323,125	181,875	31,250	639,375
A	Animal farm house	11,875	14,375	15,625	3,125	2,500	47,500
A	Field crop	10,625	16,875	43,750	6,250	5,000	82,500
A	Horticulture	**1,142,500**	**1,615,000**	**2,683,125**	**350,625**	**48,125**	**5,839,375**
A	Orchard	247,500	381,250	471,250	99,375	34,375	1,233,750
A	Pasture	9,375	26,875	26,875	6,250	2,500	71,875
A	Perennial trees	10,625	15,625	51,875	13,750	1875	93,750
A	Rice paddy	**13,241,875**	**21,104,375**	**27,126,250**	**5,025,625**	**2,385,625**	**68,883,750**
F	Disturbed deciduous forest	10,625	16,875	18,125	5,000	4375	55,000
M	Grass	95,625	170,625	271,875	106,875	106,250	751,250
M	Landfill	51,875	67,500	199,375	34,375	33,125	386,250
M	Marsh and swamp	81,875	134,375	473,125	120,000	19,375	828,750
M	Recreation and green area	36,250	83,125	146,250	64,375	31,875	361,875
M	Shrub/Scrub	260,000	413,750	597,500	223,125	256,250	1,750,625
Total		**16,550,625**	**26,423,125**	**35,327,500**	**7,103,125**	**3,365,000**	**88,769,375**

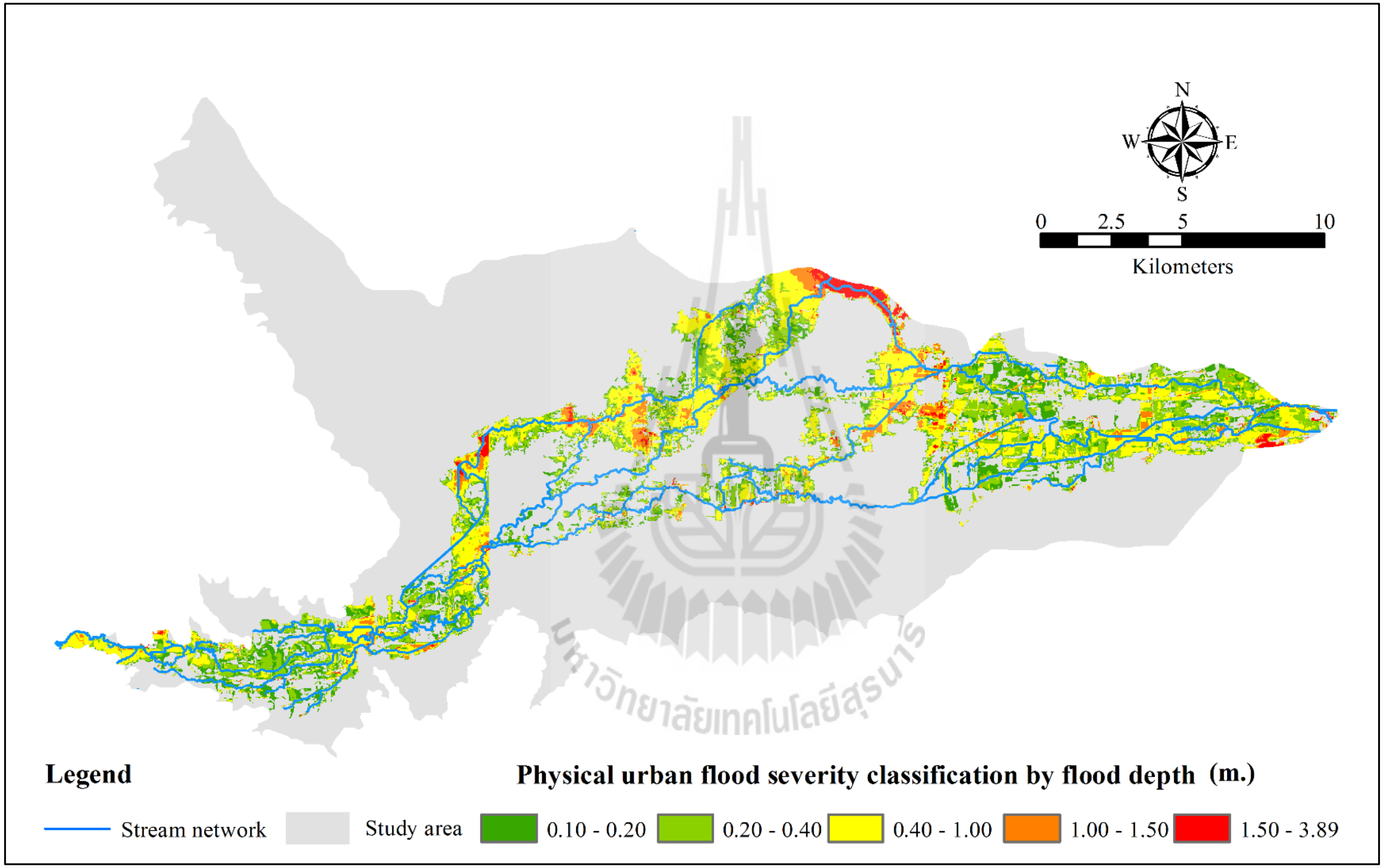

Figure 4.26 Physical urban flood severity classification by flood depth on 24 October 2010.

4.3.2 Physical urban flood severity classification by flood velocity

The results were shown that most of physical urban flood severity class by flood velocity was very low and covered area of 72.97 sq. km or 82.21% of flood area. It was followed by low urban flood severity class with area of 14.21 sq. km or 16.01% of flood area. The very high class covered only 625 sq. m or 0.001% of flooded area as shown in Table 4.35.

Table 4.35 Area and percent of physical urban flood severity classification by flood velocity.

Classification	Velocity (m/s)	Area (sq. m)	% of area
Very low	0.00 - 0.25	72,979,375	82.21%
Low	0.25 - 0.50	14,211,875	16.01%
Moderate	0.50 - 1.00	1,540,000	1.73%
High	1.00 - 2.00	37,500	0.04%
Very high	2.00 - 2.06	625	0.001%
Total		**88,769,375**	**100.00%**

In addition, when this classification was combined with land use at level I, it was found that 2 main land uses types: urban and built-up area and agricultural land affected to urban flood velocity. However, most of flood area only affected with the very low velocity as shown in Table 4.36.

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Table 4.36 Physical urban flood severity classification by flood velocity with major land use type (sq. m).

Level I	Very low	Low	Moderate	High	Very high	Total
Urban and built-up area	6,828,750	752,500	149,375	13,125	0	7,743,750
Agricultural land	62,136,250	13,346,875	1,383,750	24,375	625	76,891,875
Forest land	53,125	1875	0	0	0	55,000
Miscellaneous land	3,961,250	110,625	6,875	0	0	4,078,750
Water body	0	0	0	0	0	0
Total	**72,979,375**	**14,211,875**	**1,540,000**	**37,500**	**625**	**88,769,375**

Under the urban and built-up area, concrete and wooden house was the main land use type that affected by urban flood severity based on velocity (5.59 sq. km). Here, the very low class of it was covered area of 4.90 sq. km or 87.72% of urban and built-up area. The details of physical urban flood velocity classification with land use was summarized in Table 4.37 and distribution of physical urban flood severity map by flood depth was displayed in Figure 4.27.

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Table 4.37 Details of physical urban flood severity classification by flood velocity with land use types (sq. m).

Level I	Land use level II/III	Very low	Low	Moderate	High	Very high	Total
U	Bus station/Gasoline station	36,875	3,125	1,250	0	0	41,250
U	Commercial buildings with 1 floor	47,500	4,375	0	0	0	51,875
U	Commercial buildings with 2 floors	11,250	8,125	1,875	0	0	21,250
U	Commercial buildings with 4 floors	197,500	1,250	0	0	0	198,750
U	Concrete and wooden house	**4,906,250**	**580,000**	**101,875**	**5,000**	**0**	**5,593,125**
U	House with 1 floor	13,750	0	0	0	0	13,750
U	House with 2 floor	773,125	24,375	8,750	1,250	0	807,500
U	Large industrial (more than 10,000 sq. m)	296,250	77,500	19,375	0	0	393,125
U	Office building with 1 floor	40,625	15,000	0	0	0	55,625
U	Office building with 2-3 floors	254,375	13,125	625	0	0	268,125
U	Office building with 4-5 floors	36,875	0	0	0	0	36,875
U	Office building with 6-9 floors	93,125	0	0	0	0	93,125
U	Road	91,250	20,000	14,375	6,875	0	132,500
U	Shopping mall (levels 103)	14,375	1,250	0	0	0	15,625
U	Small industrial and warehouse	15,625	4,375	1,250	0	0	21,250
A	Abandoned paddy field	624,375	15,000	0	0	0	639,375
A	Animal farm house	46,875	625	0	0	0	47,500
A	Field crop	80,625	1,875	0	0	0	82,500
A	Horticulture	5,023,125	743,750	71,875	625	0	5,839,375
A	Orchard	1,040,000	155,625	38,125	0	0	1,233,750
A	Pasture	71,875	0	0	0	0	71,875
A	Perennial trees	93,125	625	0	0	0	93,750
A	Rice paddy	**55,156,250**	**12,429,375**	**1,273,750**	**23,750**	**625**	**68,883,750**
F	Disturbed deciduous forest	53,125	1,875	0	0	0	55,000
M	Grass	743,750	7,500	0	0	0	751,250
M	Landfill	360,625	24,375	1,250	0	0	386,250
M	Marsh and swamp	798,125	29,375	1,250	0	0	828,750
M	Recreation and green area	338,125	21,250	2,500	0	0	361,875
M	Shrub/Scrub	1,720,625	28,125	1,875	0	0	1,750,625
Total		**72,979,375**	**14,211,875**	**1,540,000**	**37,500**	**625**	**88,769,375**

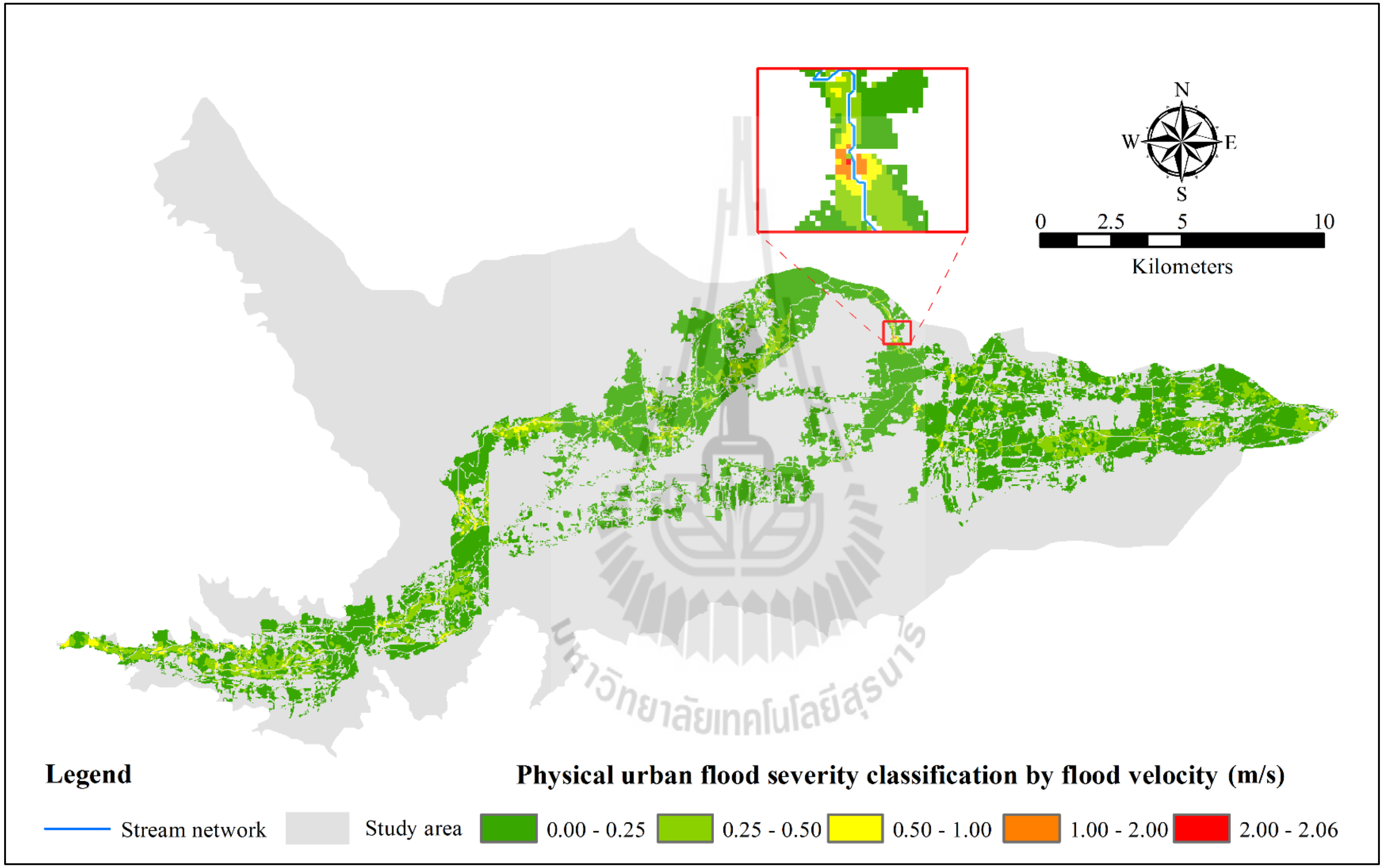

Figure 4.27 Physical urban flood severity classification by flood velocity on 24 October 2010.

4.3.3 Physical urban flood severity classification by flood duration.

According to physical urban flood severity classification by flood duration, it was found that the major severity class was moderate and it covered area of 34.02 sq. km or 38.33% while very low class covered area only area of 1.12 sq. km or only 1.27% of urban flood duration area as shown in Table 4.38. It can be seen that the movement of flood direction can be used to indicate urban flood duration classification. Very high flood duration was mainly represented close to Kud Hin Watergate and located on the West and the North while very low flood duration area was situated on the South of study area.

Table 4.38 Area and percent of physical urban flood severity classification by flood duration.

Classification	Duration (day)	Area (sq. m)	% of area
Very low	1 to 3	1,124,375	1.27%
Low	4 to 6	9,654,375	10.88%
Moderate	7 to 9	34,022,500	38.33%
High	10 to 12	22,273,125	25.09%
Very high	13 to 14	21,695,000	24.44%
Total		**88,769,375**	**100.00%**

In addition, when this classification was combined with land use at level I, it was found that 2 main land use types included urban and built-up area and agricultural land suffered from urban flood duration. Most of urban flood severity by flood duration situated in moderate class as shown in Table 4.39.

Table 4.39 Physical urban flood severity classification by flood duration with major land use type (sq. m).

Land use types	Very low	Low	Moderate	High	Very high	Total
Urban and built-up area	141,250	2,238,125	3,784,375	945,625	634,375	7,743,750
Agricultural land	935,000	6,502,500	28,610,000	20,305,000	20,539,375	76,891,875
Forest land	0	6,250	5,000	1,250	42,500	55,000
Miscellaneous land	48,125	907,500	1,623,125	1,021,250	478,750	4,078,750
Water body	0	0	0	0	0	0
Total	**1,124,375**	**9,654,375**	**34,022,500**	**22,273,125**	**21,695,000**	**88,769,375**

In case of urban and built-up area, concrete and wooden house, and house with 2 floors were the main types that suffered from urban flood by its duration. Herein, moderate urban flood severity class covered area of 2.85 sq. km of concrete and wooden house or 49.61%. The details of physical urban flood severity classification by flood duration with land use was summarized in Table 4.40 and distribution of physical urban flood severity classification by flood duration was presented in Figure 4.28.

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Table 4.40 Details of physical urban flood severity classification by flood duration with land use types (sq. m).

Level I	Land use level II/III	Very low	Low	Moderate	High	Very high	Total
U	Bus station/Gasoline station	3,125	37,500	625	0	0	41,250
U	Commercial buildings with 1 floor	0	0	25,625	26,250	0	51,875
U	Commercial buildings with 2 floors	1,250	625	19,375	0	0	21,250
U	Commercial buildings with 4 floors	3,750	171,250	23,750	0	0	198,750
U	Concrete and wooden house	105,000	1,500,000	2,855,000	621,250	511,875	5,593,125
U	House with 1 floor	0	0	0	0	13,750	13,750
U	House with 2 floor	15,625	306,875	393,750	3,750	87,500	807,500
U	Large industrial (more than 10,000 sq. m.)	2,500	46,250	150,625	185,000	8,750	393,125
U	Office building with 1 floor	0	6,250	26,250	19,375	3,750	55,625
U	Office building with 2-3 floors	4,375	26,250	197,500	31,875	8,125	268,125
U	Office building with 4-5 floors	3,125	12,500	21,250	0	0	36,875
U	Office building with 6-9 floors	0	93,125	0	0	0	93,125
U	Road	2,500	18,750	66,875	44,375	0	132,500
U	Shopping mall (levels 1-3)	0	15,625	3,750	13,750	0	33,125
U	Small industrial and warehouse	0	3,125	0	0	625	3,750
A	Abandoned paddy field	3,750	45,625	580,000	10,000	0	639,375
A	Animal farm house	0	2,500	6,875	21,250	16,875	47,500
A	Field crop	1,250	12,500	43,750	25,000	0	82,500
A	Horticulture	241,250	1,300,000	1,513,750	2,636,875	147,500	5,839,375
A	Orchard	14,375	121,250	318,125	363,750	416,250	1,233,750
A	Pasture	1,250	6,250	46,250	14,375	3,750	71,875
A	Perennial trees	625	6,875	1,875	41,875	42,500	93,750
A	Rice paddy	672,500	5,007,500	26,099,375	17,191,875	19,912,500	68,883,750
F	Disturbed deciduous forest	0	6,250	5,000	1,250	42,500	55,000
M	Grass	7,500	147,500	515,625	80,625	0	751,250
M	Landfill	2,500	51,250	64,375	261,875	6,250	386,250
M	Marsh and swamp	9,375	115,000	357,500	277,500	69,375	828,750
M	Recreation and green area	6,875	218,750	82,500	47,500	6,250	361,875
M	Shrub/Scrub	21,875	375,000	603,125	353,750	396,875	1,750,625
Total		**1,124,375**	**9,654,375**	**34,022,500**	**22,273,125**	**21,695,000**	**88,769,375**

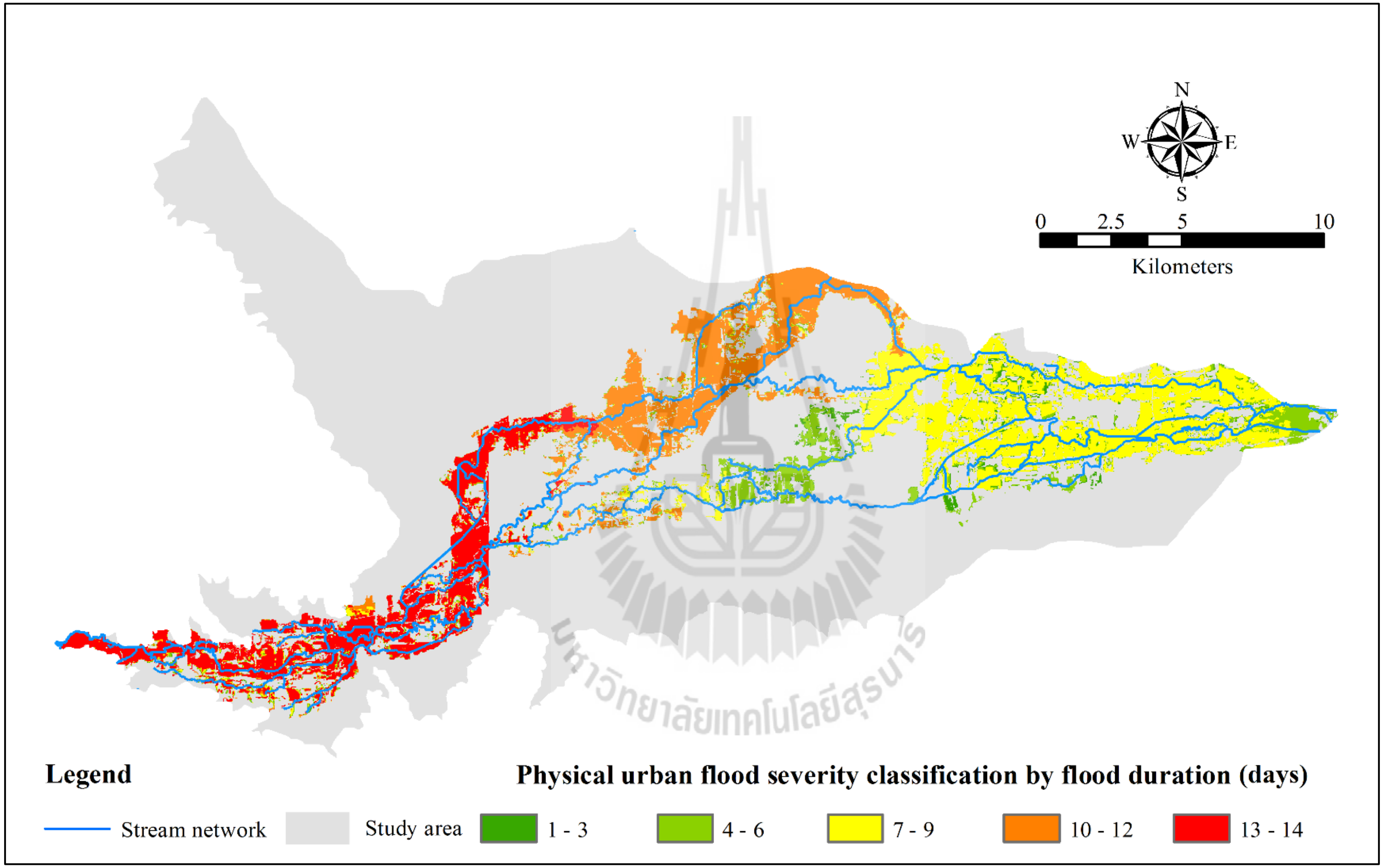

Figure 4.28 Physical urban flood severity classification by flood duration.

4.3.4 Physical urban flood severity classification by combination of flood depth and velocity

Under this part, the values of physical urban flood depth and physical urban flood velocity have normalized by benefit criterion normalization method, showing the maximum of value as 1.274004459 and the minimum of value as 0.000052816. Hence, a set of physical urban flood severity value have classified by (1) equal interval, (2) defined interval, (3) quantile, (4) natural break, (5) geometrical interval, and (6) standard deviation. Range value of urban flood severity class of six classification methods was summarized in Table 4.41 while comparison area of urban flood severity class by percent was displayed in Figure 4.29. The derived results are then used to examine the consistency with percentage of affected population by flood (PAPF) by overlay analysis to identify an optimum methods of classification (Tables 4.42 - 4.47). The summary of consistency test comparison from six classification method with PAPF was shown in Table 4.48.

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Table 4.41 Range value of physical urban flood severity class by six classification methods.

Classification method	Range value of physical urban flood severity class				
	Very low	**Low**	**Moderate**	**High**	**Very high**
Equal interval	0.0000 - 0.2548	0.2548 - 0.5096	0.5096 - 0.7644	0.7644 - 1.0192	1.0192 - 1.2740
Defined interval	0.0000 - 0.2548	0.2548 - 0.5096	0.5096 - 0.7644	0.7644 - 1.0192	1.0192 - 1.2740
Quantile	0.0000 - 0.0799	0.0799 - 0.1399	0.1399 - 0.1948	0.1948 - 0.2698	0.2698 - 1.2740
Natural break	0.0000 - 0.1049	0.1049 - 0.1998	0.1998 - 0.3097	0.3097 - 0.4896	0.4896 - 1.2740
Geometrical interval	0.0000 - 0.0974	0.0974 - 0.1320	0.1320 - 0.2294	0.2294 - 0.5033	0.5033 - 1.27400
Standard deviation	0.0000 - 0.1203	0.1203 - 0.2406	0.2406 - 0.3609	0.3609 - 0.4812	0.4812 - 1.2740

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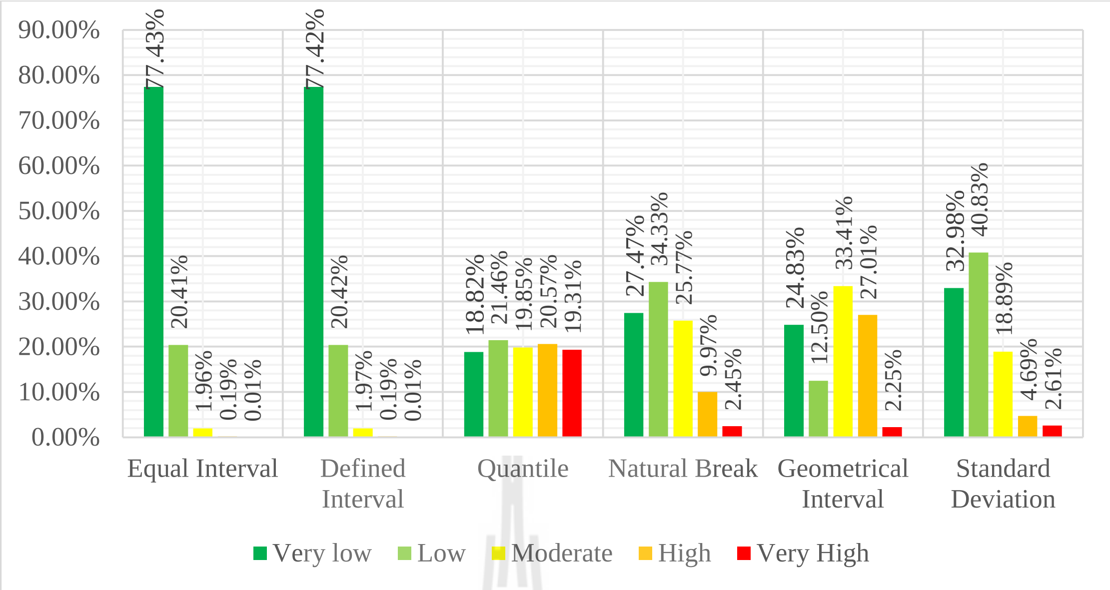

Figure 4.29 Comparison area of urban flood severity class in percent from six classification methods.

Table 4.42 The consistency test between physical urban flood severity classification with equal interval method and PAPF (Pixels).

Equal interval	**Normalize PAPF Equal Interval**						**Consistency**
	Very low	**Low**	**Moderate**	**High**	**Very high**	**Total**	
Very low	80,576	14,299	6,317	4,451	4,328	109,971	73.27%
Low	20,406	3,141	3,899	1,078	466	28,990	10.83%
Moderate	953	55	1,677	92	12	2,789	60.13%
High	183	6	68	14	0	271	5.17%
Very high	7	0	3	0	0	10	0.00%
Total	**102,125**	**17,501**	**11,964**	**5,635**	**4,806**	**142,031**	

Table 4.43 The consistency test between physical urban flood severity classification with defined interval method and PAPF (Pixels).

Defined interval	Normalize PAPF Equal Interval						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	80,568	14,299	6,316	4,451	4,327	109,961	73.27%
Low	20,413	3,141	3,899	1,078	467	28,998	10.83%
Moderate	954	55	1,678	92	12	2,791	60.12%
High	183	6	68	14	0	271	5.17%
Very high	7		3		0	10	0.00%
Total	**102,125**	**17,501**	**11,964**	**5,635**	**4,806**	**142,031**	

Table 4.44 The consistency test between physical urban flood severity classification with quantile method and PAPF (Pixels).

Quantile	Normalize PAPF Equal Interval						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	18,290	4,242	1,004	1,364	1,826	26,726	68.44%
Low	22,795	3,840	1,473	1,357	1,011	30,476	12.60%
Moderate	21,667	3,069	1,684	962	807	28,189	5.97%
High	21,156	3,670	2,610	943	830	29,209	3.23%
Very high	18,217	2,680	5,193	1,009	332	27,431	1.21%
Total	**102,125**	**17,501**	**11,964**	**5,635**	**4,806**	**142,031**	

Table 4.45 The consistency test between physical urban flood severity classification with natural break method and PAPF (Pixels).

Natural break	Normalize PAPF Equal Interval						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	27,380	5,886	1,527	1,946	2,281	39,020	70.17%
Low	37,171	5,531	2,818	1,814	1,421	48,755	11.34%
Moderate	26,492	4,709	3,263	1,197	946	36,607	8.91%
High	9,693	1,298	2,471	557	145	14,164	3.93%
Very high	1,389	77	1,885	121	13	3,485	0.37%
Total	**102,125**	**17,501**	**11,964**	**5,635**	**4,806**	**142,031**	

Table 4.46 The consistency test between physical urban flood severity classification with geometrical interval method and PAPF (Pixels).

Geometrical interval	Normalize PAPF Equal Interval						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	27,380	5,886	1,527	1,946	2,281	39,020	70.17%
Low	37,171	5,531	2,818	1,814	1,421	48,755	11.34%
Moderate	26,492	4,709	3,263	1,197	946	36,607	8.91%
High	9,693	1,298	2,471	557	145	14,164	3.93%
Very high	1,389	77	1,885	121	13	3,485	0.37%
Total	**102,125**	**17,501**	**11,964**	**5,635**	**4,806**	**142,031**	

Table 4.47 The consistency test between physical urban flood severity classification with standard deviation method and PAPF (Pixels).

Standard deviation	Normalize PAPF Equal Interval						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	33,227	6,864	1,941	2,301	2,509	46,842	70.93%
Low	43,885	6,718	3,778	1,984	1,624	57,989	11.58%
Moderate	19,036	3,489	2,755	925	622	26,827	10.27%
High	4,467	349	1,516	294	37	6,663	4.41%
Very high	1,510	81	1,974	131	14	3,710	0.38%
Total	**102,125**	**17,501**	**11,964**	**5,635**	**4,806**	**142,031**	

Table 4.48 Comparison result between consistency test of six classification methods and PAPF.

	Percentage of consistency					
PUFS*	**Equal interval**	**Defined interval**	**Quantile**	**Natural break**	**Geometrical interval**	**Standard deviation**
Very low	73.27%	73.27%	68.44%	70.17%	69.64%	70.93%
Low	10.83%	10.83%	12.60%	11.34%	12.62%	11.58%
Moderate	60.13%	60.12%	5.97%	8.91%	6.44%	10.27%
High	5.17%	5.17%	3.23%	3.93%	3.54%	4.41%
Very high	0.00%	0.00%	1.21%	0.37%	0.38%	0.38%

*Notification PUFS is physical urban flood severity.

The result illustrated that equal interval and defined interval classification methods presented the highest consistency value in very low, moderate, and high classes whereas the consistency value in low class have slightly difference with others. However, it presented inconsistency result in very high physical urban flood severity classification. Quantile classification method also presented the lowest consistency value in very low class with 68.44%, but it indicated the highest consistency value in very high class with 1.21%. Natural break classification method indicated the consistency value in very low class higher than quantile method with 70.17%, but lower in very high class with 0.37%. Geometrical interval classification method presented the highest consistency value of low class, but lower consistency value in high and very high classes. Standard deviation classification method provided the high consistency value of very low (70.93%), moderate (10.27%), and high classes (4.41%) and it was followed by equal interval and defined interval methods. In addition. It provided a high consistency value in low classes with 11.58% and it was followed by geometrical interval method. It was also high consistency value in very high class with 0.38%.

Therefore, the standard deviation classification method was here considered as the optimum method for physical urban flood severity classification with capability to represent all five urban flood severity classification in high consistency when it was compared with others, and advantaged to see which features are above or below and average value. The final result of physical urban flood severity and its distribution have presented in Table 4.49 and Figure 4.30.

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Table 4.49 Physical urban flood severity by combination of flood depth and velocity using standard deviation classification method.

Classification	Values	Area (sq. m)	% of flooded area
Very low	0.0000 - 0.1203	29,276,250	32.98%
Low	0.1203 - 0.2406	36,243,125	40.83%
Moderate	0.24064- 0.3609	16,766,875	18.89%
High	0.36093- 0.4812	4,164,375	4.69%
Very high	0.4812 - 1.2740	2,318,750	2.61%
Total		**88,769,375**	**100.00%**

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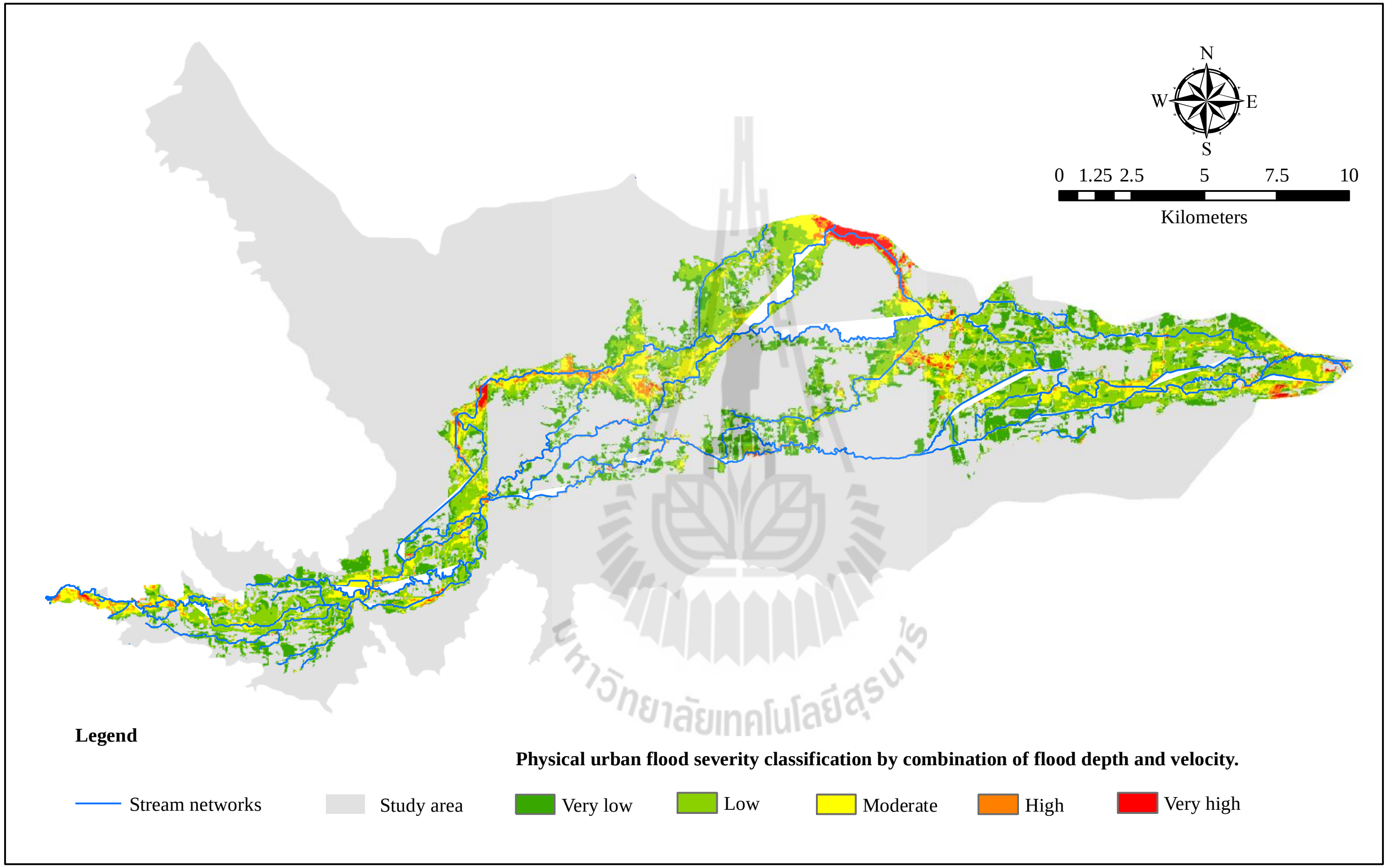

Figure 4.30 Distribution of physical urban flood severity classification by combination of flood depth and velocity.

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In addition, when this physical urban flood severity classification was combined with land use at level I, it showed that 2 main classes included urban and built-up area and agricultural land were mostly effect by urban flood. Most of urban and built-up area was located in very low class while agricultural land was located in low class as shown in Table 4.50.

Table 4.50 The summary of physical urban flood severity with land use level I in sq. m.

Level I	Very low	Low	Moderate	High	Very high	Total
Urban and built-up area	3,136,250	2,631,875	1,313,125	425,000	237,500	7,743,750
Agricultural land	24,490,000	32,368,125	14,825,625	3,385,000	1,823,125	76,891,875
Forest land	32,500	8,750	6,875	4,375	2,500	55,000
Miscellaneous land	1,617,500	1,234,375	621,250	350,000	255,625	4,078,750
Water body	0	0	0	0	0	0
Total	**29,276,250**	**36,243,125**	**16,766,875**	**4,164,375**	**2,318,750**	**88,769,375**

For urban and built-up area, concrete and wooden house and house with 2 floors are the main types that suffered from urban flood severity. Most of them were located in very low severity class and covered area of 2.13 sq. km and 0.46 sq. km. The detail of this physical urban flood severity classification with land use was summarized in Table 4.51.

Table 4.51 Details of physical urban flood severity classification by combing of flood depth and velocity with land use types.

Level I	**Land use level II/III**	**Very low**	**Low**	**Moderate**	**High**	**Very high**	**Total**
U	Bus station/Gasoline station	21,250	13,125	6,250	625	0	41,250
U	Commercial buildings with 1 floor	11,875	25,625	14,375	0	0	51,875
U	Commercial buildings with 2 floors	3,125	4,375	6,875	3,750	3,125	21,250
U	Commercial buildings with 4 floors	128,750	43,750	6,250	5,000	15,000	198,750
U	Concrete and wooden house	**2,134,375**	1,955,000	1,054,375	310,625	138,750	5,593,125
U	House with 1 floor	9,375	4,375	0	0	0	13,750
U	House with 2 floor	**461,875**	235,000	58,750	25,625	26,250	807,500
U	Large industrial (more than 10,000 sq. m)	90,625	138,750	93,125	39,375	31,250	393,125
U	Office building with 1 floor	14,375	28,125	5,625	3,125	4,375	55,625
U	Office building with 203 floors	96,250	131,875	13,125	26,875	0	268,125
U	Office building with 405 floors	23,125	6,875	6,875	0	0	36,875
U	Office building with 609 floors	88,750	4,375	0	0	0	93,125
U	Road	46,250	30,625	33,125	9,375	13,125	132,500
U	Shopping mall (levels 103)	4,375	3,750	1,875	0	5,625	15,625
U	Small industrial and warehouse	1,875	6,250	12,500	625	0	21,250
A	Abandoned paddy field	122,500	222,500	253,750	28,125	12,500	639,375
A	Animal farm house	30,000	7,500	7,500	0	2,500	47,500
A	Field crop	33,125	35,000	6,875	3,750	3,750	82,500
A	Horticulture	2,265,000	2,353,125	1,090,625	108,750	21,875	5,839,375
A	Orchard	545,000	401,875	213,750	59,375	13,750	1,233,750
A	Pasture	41,250	21,250	6,250	625	2,500	71,875
A	Perennial trees	35,000	41,250	14,375	3,125	0	93,750
A	Rice paddy	21,418,125	29,285,625	13,232,500	3,181,250	1,766,250	68,883,750
F	Disturbed deciduous forest	32,500	8,750	6,875	4,375	2,500	55,000
M	Grass	309,375	190,625	113,125	81,875	56,250	751,250
M	Landfill	120,625	137,500	82,500	40,000	5,625	386,250
M	Marsh and swamp	251,875	391,875	115,000	65,625	4,375	828,750
M	Recreation and green area	134,375	111,875	62,500	36,250	16,875	361,875
M	Shrub/Scrub	801,250	402,500	248,125	126,250	172,500	1,750,625
Total		**29,276,250**	**36,243,125**	**16,766,875**	**4,164,375**	**2,318,750**	**88,769,375**

4.4 Urban flood vulnerability analysis

Urban flood vulnerability means the degree of loss of a given element at risk resulting from the occurrence of a natural phenomenon of a given magnitude and expresses on a scale. This research attempted to develop urban flood vulnerability index or classification based on literature review which was focused on physical, social, and economic, and environmental factors (or criteria). These factors are individually prepared and normalized with benefit criterion normalization method (Malczewski, 1999), and used as score under multiplication method. The details of each factor are described in the following section.

4.4.1 Physical factor

The physical urban flood severity, which was combined between flood depth and velocity, represents the most important effect of flood on urban flood vulnerability as mentioned in Section 4.3.4 (Figure 4.30). Meanwhile the normalized physical criteria map was displayed in Figure 4.31.

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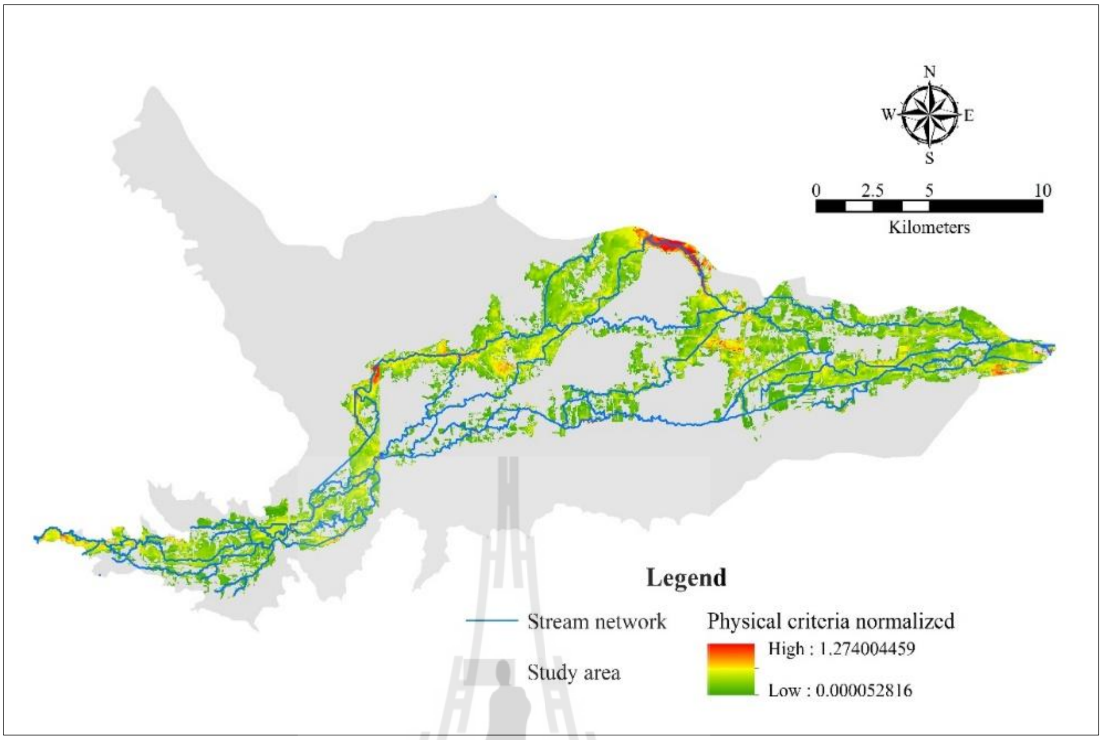

Figure 4.31 Physical criteria map based on additive normalize of depth and velocity.

4.4.2 Social factor

Information about social condition needs to be included in urban flood vulnerability analysis as percentage of affected population by flood (PAPF) in sub districts according to flood report in 2010 of Nakhon Ratchasima City Municipality. Herein, percentages of affected population by flood (PAPF) were calculated according to number of actual flood sufferer and actual flooded area in 2010 for each district (Table 4.52). The distribution of original and normalized social criteria maps are displayed in Figure 4.32 - 4.33.

Table 4.52 Percentage of affected persons by flood in each sub-district.

District	Sub-district	Flooded area (sq. m)	Affected persons by flood	PAPF (%)
Sung Noen	Bung Khilek	1,336,875	120	0.0089
Sung Noen	Non Kha	1,088,125	72	0.0066
Sung Noen	Na Klang	260,625	238	0.0913
Sung Noen	Khong Yang	5,292,500	480	0.00907
Kham Thale So	Pong Daeng	2,105,000	30	0.0014
Kham Thale So	Kham Tale So	7,495,625	450	0.0060
Mueang Nakhon Ratchasima	Khok Sung	1,250	0	0.0000
Mueang Nakhon Ratchasima	Nong Rawiang	1,271,875	7,668	0.6028
Mueang Nakhon Ratchasima	Maroeng	378,750	500	0.1320
Mueang Nakhon Ratchasima	Phanoa	1,196,875	150	0.0125
Mueang Nakhon Ratchasima	Nong Krathum	2,809,375	5,900	0.2100
Mueang Nakhon Ratchasima	Talat	6,474,375	1	0.0000
Mueang Nakhon Ratchasima	Paru Yai	2,956,875	6,015	0.2034
Mueang Nakhon Ratchasima	Muen Wai	4,793,125	6,000	0.1251
Mueang Nakhon Ratchasima	Cho Ho	5,567,500	16,148	0.2900
Mueang Nakhon Ratchasima	Hua Thale	1,731,875	9,450	0.5456
Mueang Nakhon Ratchasima	Ban Pho	8,456,875	8,900	0.1052
Mueang Nakhon Ratchasima	Phon Krang	1,910,000	5,080	0.2659
Mueang Nakhon Ratchasima	Suranaree and Ban Mai	777,500	3,436	0.4419
Mueang Nakhon Ratchasima	Khok Kruat	2,744,375	11,000	0.4008
Mueang Nakhon Ratchasima	Si Mum	4,878,125	1,700	0.0348
Mueang Nakhon Ratchasima	Putsa	9,980,000	1,025	0.0102
Mueang Nakhon Ratchasima	Nai Mueang and Ban Koh	7,823,125	5,859	0.0748
Chaleom Pra Kiat	Nong Yang	408,125	200	0.0490
Chaleom Pra Kiat	Tha Chang	4,031,875	500	0.0124
Chaleom Pra Kiat	Pha Put	2,998,750	500	0.0166
Total		**88,769,375**	**91,422.00**	-

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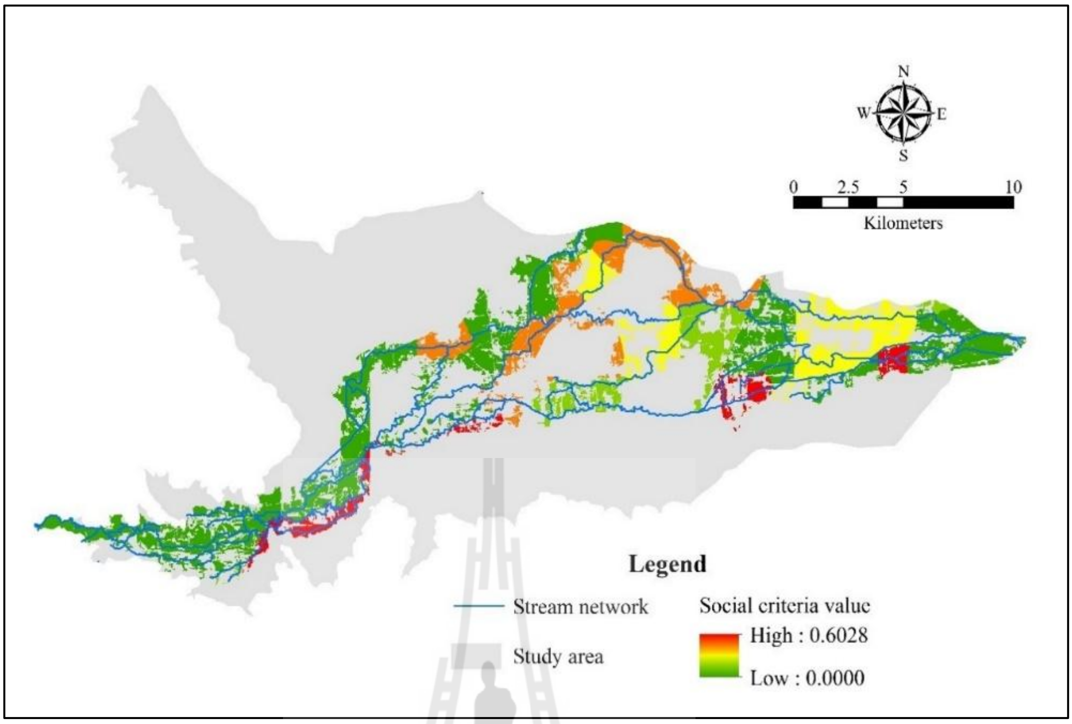

Figure 4.32 Distribution of percentage of affected population by flood (PAPF).

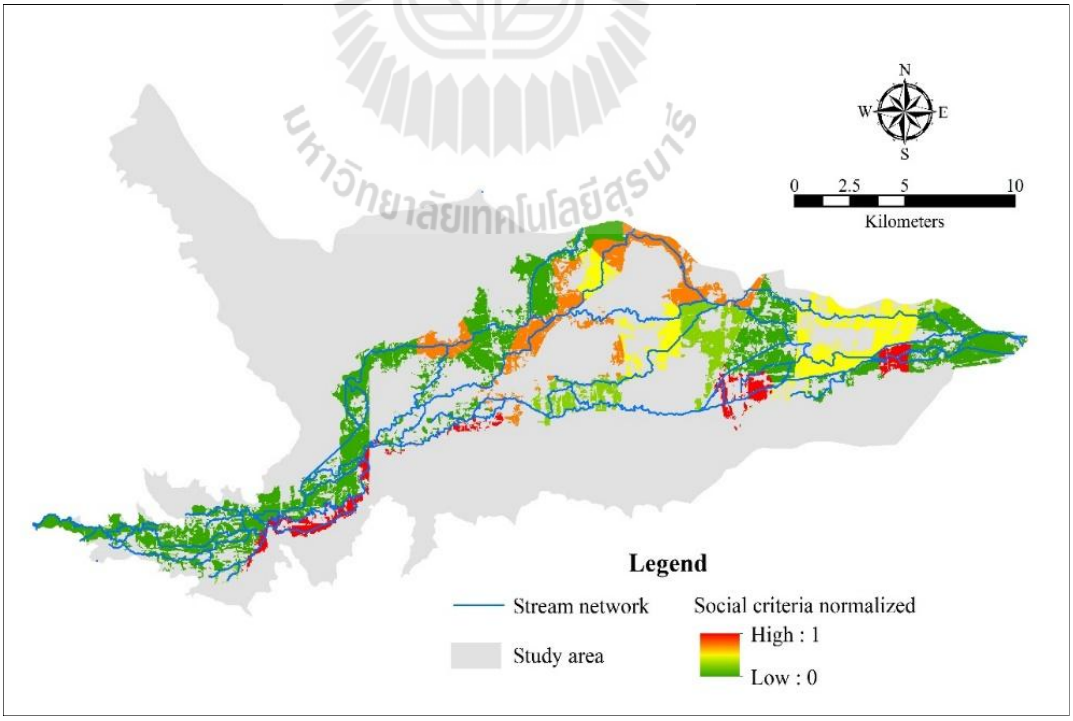

Figure 4.33 Normalized social criteria map.

4.4.3 Economic factor

Economic factor has created and represented as economic value loss based on compensation rate. The compensate rate for urban and built-up area classes at Level III and agricultural land at Level II are calculated according to standard payment from Office of Insurance Commission (OIC) and Cabinet Resolutions on August 25, 2011 as shown in Table 4.53. The distribution of economic value loss based on compensate rate and normalized economic criteria maps are displayed in Figure 4.34 - 4.35.

Table 4.53 Economic value loss based on compensation rate.

Level I	**Land use**	**Flood extent** (Pixels)	**Compensate rate (Baht/ Pixels)**	**Normalized**
U	Bus station/Gasoline station	66	4,300,625.00	0.5896
U	Commercial buildings with 1 floor	83	2,288,125.00	0.3137
U	Commercial buildings with 2 floors	34	3,923,750.00	0.5380
U	Commercial buildings with 4 floors	318	3,695,000.00	0.5066
U	Concrete and wooden house	8,949	5,985,625.00	0.8207
U	House with 1 floor	22	5,831,250.00	0.7995
U	House with 2 floors	1,292	6,637,500.00	0.9100
U	Large industrial (more than 10,000 sq. m)	629	5,541,250.00	0.7597
U	Office building with 1 floor	89	5,831,250.00	0.7995
U	Office building with 2-3 floors	429	6,242,500.00	0.8559
U	Office building with 4-5 floors	59	6,176,875.00	0.8469
U	Office building with 6-9 floors	149	5,932,500.00	0.8134
U	Road	212	4,300,625.00	0.5896
U	Shopping mall (levels 1-3)	25	7,293,750.00	1.0000
U	Small industrial and warehouse	34	4,361,250.00	0.5979
A	Abandoned paddy field	1,023	2,288,125.00	0.0000
A	Animal farm house	76	1,230.47	0.3137
A	Field crop	132	1,991.41	0.0002
A	Horticulture	9,343	1,991.41	0.0003
A	Orchard	1,974	1,230.47	0.0003
A	Pasture	115	1,991.41	0.0002
A	Perennial trees	150	867.97	0.0003
A	Rice paddy	110,214	2,288,125.00	0.0001

Table 4.53 Economic value loss based on compensation rate (Continued).

Level I	Land use	Flood extent (Pixels)	Compensate rate (Baht/ Pixels)	Normalized
F	Disturbed deciduous forest	88	0.0000	0.0000
M	Grass	1,202	0.0000	0.0000
M	Landfill	618	0.0000	0.0000
M	Marsh and swamp	1,326	0.0000	0.0000
M	Recreation and green area	579	0.0000	0.0000
M	Shrub/Scrub	2,801	0.0000	0.0000
Total		**142,031**		

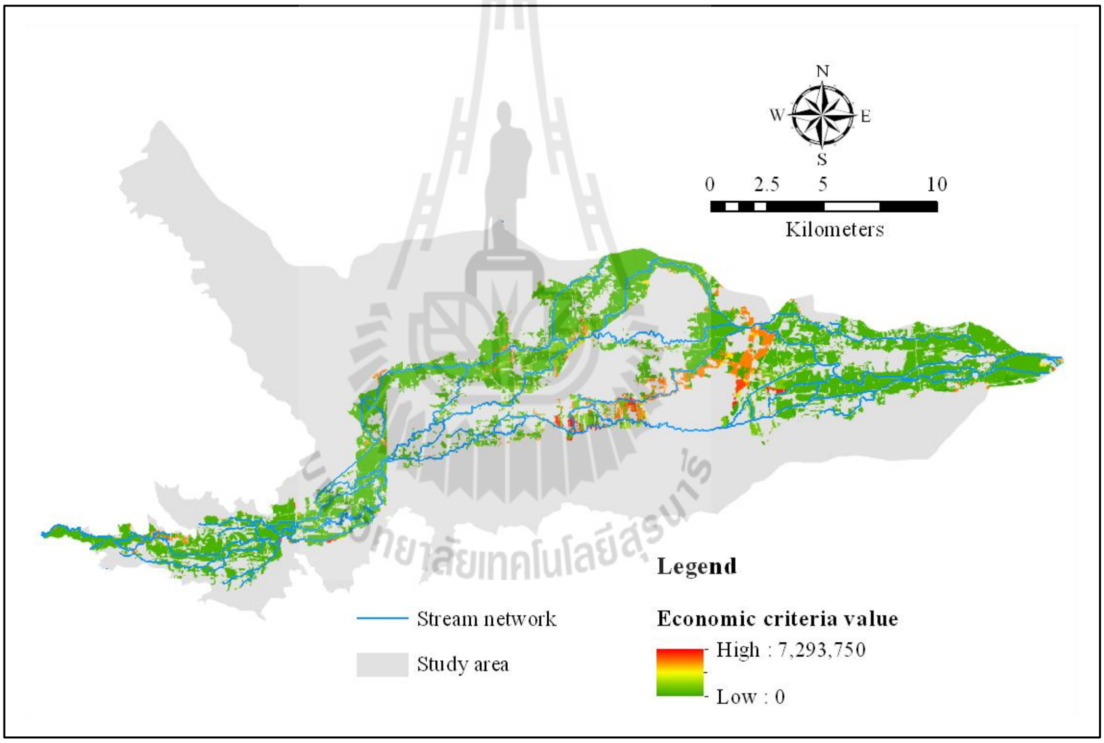

Figure 4.34 The distribution of economic value loss based on compensate rate.

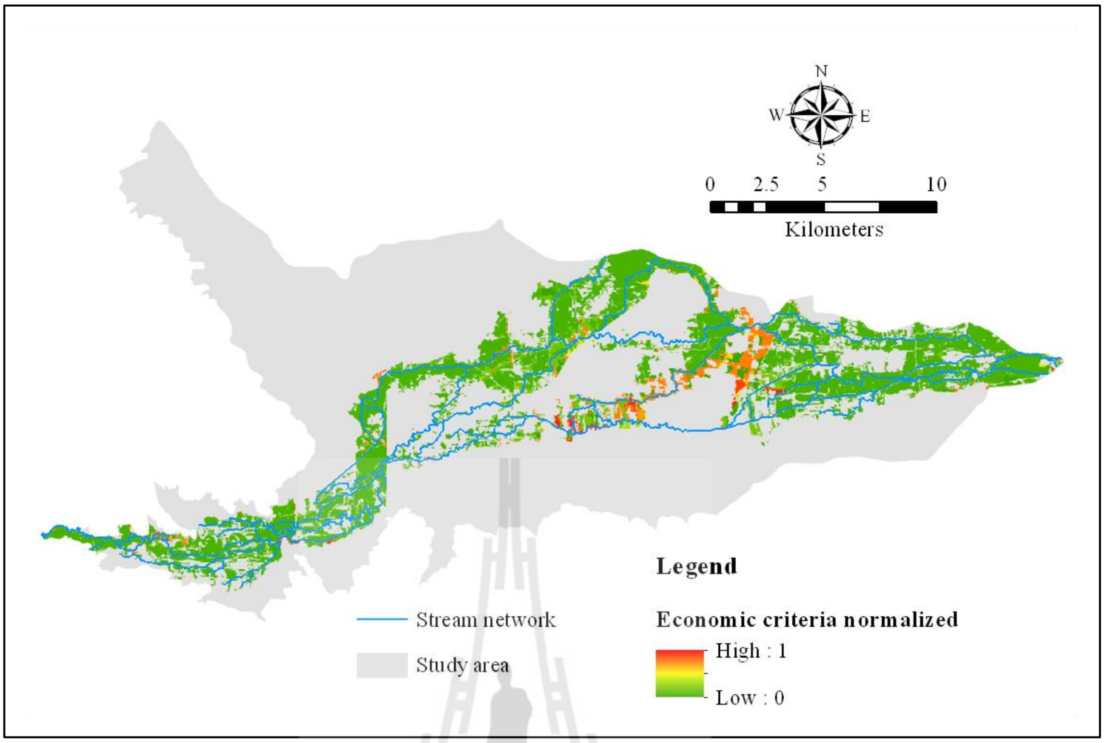

Figure 4.35 Normalized economic criteria map.

4.4.4 Environmental factor

Environmental factor consists of positive and negative environmental impact on human during flooding. Natural areas included agricultural land, forest land, miscellaneous land, and water body were used as positive environment impact while the urban and built-up area was used as negative environmental impact. The positive and negative environmental impacts were assigned as significant environmental impact with value of 0 and 1 (Table 4.54). The distribution of environmental criteria map with no require normalization was displayed in Figure 4.36.

Table 4.54 Environmental classification.

Classification	Value	Area (sq. m)
Positive environmental impact	0	81,025,625
Negative environmental impact	1	7,743,750
Total		**88,769,375**

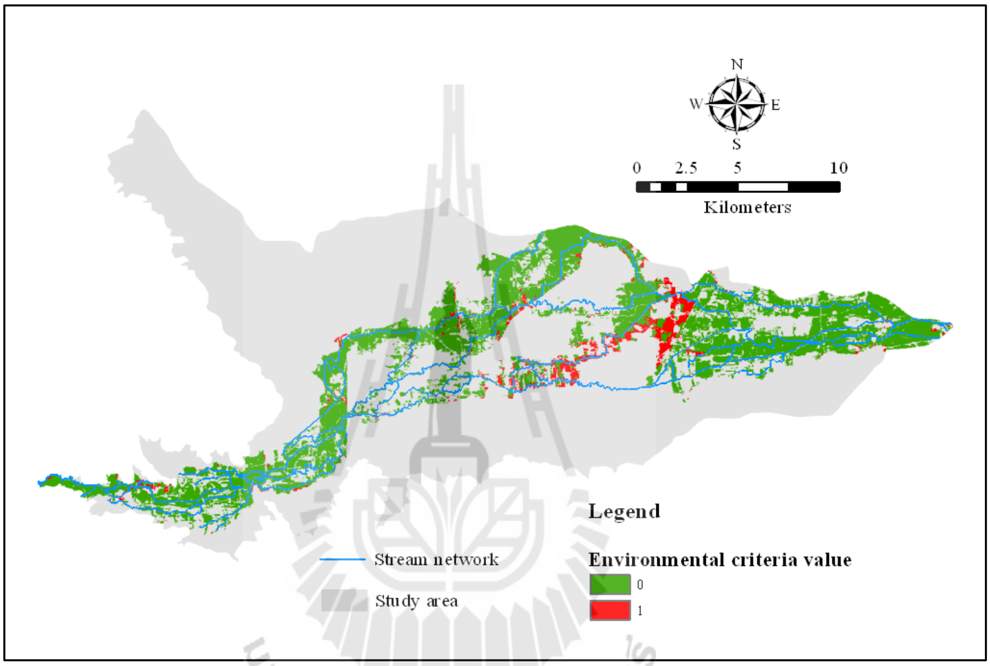

Figure 4.36 Distribution of environmental criteria data as positive and negative impact.

4.4.5 Urban flood vulnerability classification

In brief, four normalized score from each criterion for urban flood vulnerability analysis was here firstly combined with multiplication method to create urban flood vulnerability index (UFVI), showing the maximum of value was 0.3584 and the minimum of value was integer 0 as shown in Figure 4.37. After that the UFVI was further reclassified into five classes: very low, low, moderate, high, and very high vulnerability by six classification method including (1) equal interval, (2) defined interval, (3) quantile, (4) natural break, (5) geometrical interval, and (6) standard deviation. The optimal classification method was examined consistency test by comparison with physical urban flood duration classification (in pixels) (see Section 4.2.2.4) as coincident matrix. The classification method which provides the highest consistency was then used to generate the final urban flood vulnerability map.

Range value of urban flood vulnerability classification of six classification methods was summarized in Table 4.55 meanwhile comparison area of urban flood vulnerability class by percent was displayed in Figure 4.38. The details result of consistency test between physical urban flood duration classes and urban flood vulnerability classes from six classification methods are provided in Table 4.56 - 4.61. In addition, the comparison result of all consistency test was summarized in Table 4.62.

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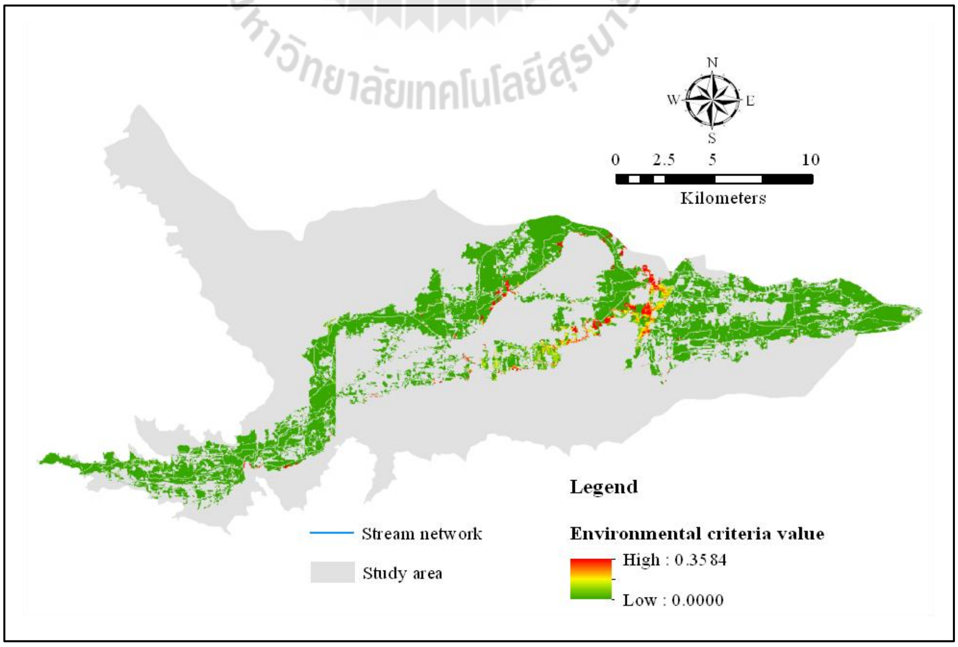

Figure 4.37 Urban flood vulnerability index.

Table 4.55 Range value of urban flood vulnerability classes from six classification methods.

	Range values of urban flood vulnerability class				
Classification methods	**Very low**	**Low**	**Moderate**	**High**	**Very high**
Equal Interval	0.0000 - 0.0716	0.0716 - 0.1433	0.1433 - 0.2150	0.2150 - 0.2867	0.2867 - 0.3584
Defined Interval	0.0000 - 0.0716	0.0716 - 0.1433	0.1433 - 0.2150	0.2150 - 0.2867	0.2867 - 0.3584
Quantile	0.0000 – 0.0000	0.0000 - 0.0070	0.0070 - 0.0168	0.0168 - 0.0351	0.0351 - 0.3584
Natural break	0.0000 - 0.0098	0.0098 - 0.0379	0.0379 - 0.0885	0.0885 - 0.1715	0.1715 - 0.3584
Geometrical Interval	0.0000 - 0.0012	0.0012 - 0.0058	0.0058 - 0.0237	0.0237 - 0.0927	0.0927 - 0.3584

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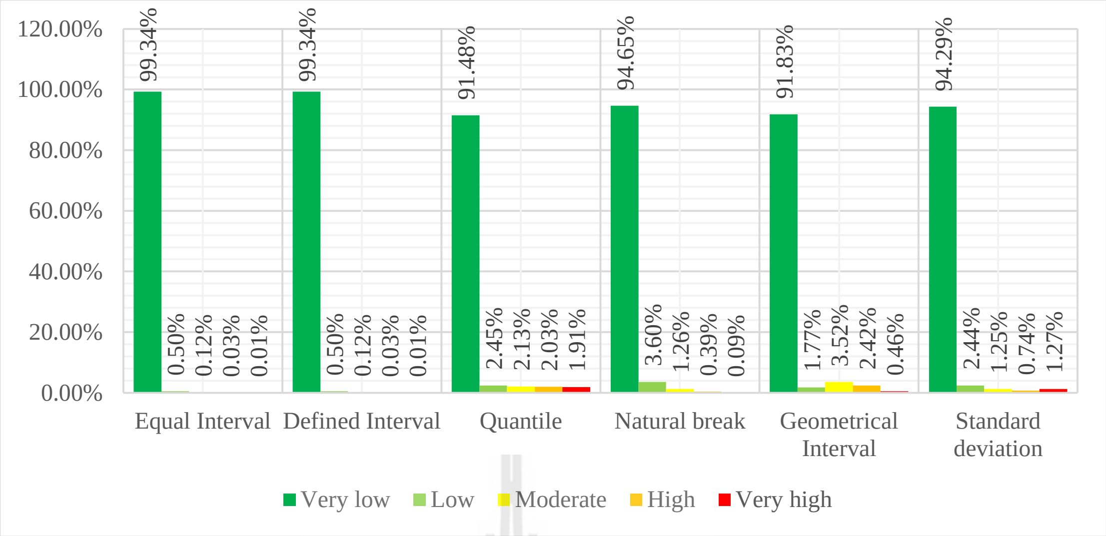

Figure 4.38 Comparison area of urban flood vulnerability class in percent from six classification methods.

Table 4.56 The consistency test between physical urban flood duration classes and urban flood vulnerability classes from equal interval classification method.

UFVI classes (Pixels)	Physical urban flood duration class (Pixels)						Consistency
	Very low	**Low**	**Moderate**	**High**	**Very high**	**Total**	
Very low	1,798	15,380	54,013	35,324	34,582	141,097	1.27%
Low	0	66	335	236	69	706	9.35%
Moderate	0	1	85	51	40	177	48.02%
High	1	0	1	20	15	37	54.05%
Very high	0	0	2	6	6	14	42.86%
Total	**1,799**	**15,447**	**54,436**	**35,637**	**34,712**	**142,031**	

Table 4.57 The consistency test between physical urban flood duration classes and urban flood vulnerability classes from defined interval classification method.

UFVI classes (Pixels)	Physical urban flood duration class (Pixels)						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	1,798	15,380	54,013	35,324	34,582	141,097	1.27%
Low	0	66	335	236	69	706	9.35%
Moderate	0	1	85	51	40	177	48.02%
High	1	0	1	20	15	37	54.05%
Very high	0	0	2	6	6	14	42.86%
Total	**1,799**	**15,447**	**54,436**	**35,637**	**34,712**	**142,031**	

Table 4.58 The consistency test between physical urban flood duration classes and urban flood vulnerability classes from quantile classification method.

UFVI classes (Pixels)	Physical urban flood duration class (Pixels)						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	1,576	11,882	48,633	34,125	33,716	129,932	1.21%
Low	168	1,350	743	478	739	3,478	38.82%
Moderate	36	1,258	1,562	97	70	3,023	51.67%
High	16	613	2,032	199	22	2,882	6.90%
Very high	3	344	1466	738	165	2,716	6.08%
Total	**1,799**	**15,447**	**54,436**	**35,637**	**34,712**	**142,031**	

Table 4.59 The consistency test between physical urban flood duration classes and urban flood vulnerability classes from natural break classification method.

UFVI classes (Pixels)	Physical urban flood duration class (Pixels)						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	1,756	13,774	49,775	34,646	34,477	134,428	1.31%
Low	40	1,367	3,353	284	75	5,119	26.70%
Moderate	2	267	986	492	44	1,791	55.05%
High	0	38	274	165	83	560	29.46%
Very high	1	1	48	50	33	133	24.81%
Total	**1,799**	**15,447**	**54,436**	**35,637**	**34,712**	**142,031**	

Table 4.60 The consistency test between physical urban flood duration classes and urban flood vulnerability classes from geometrical interval classification method.

UFVI classes (Pixels)	Physical urban flood duration class (Pixels)						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	1,661	12,019	48,675	34,202	33,877	130,434	1.27%
Low	76	950	547	383	555	2,511	37.83%
Moderate	52	1,884	2,757	198	107	4,998	55.16%
High	9	566	2,149	658	58	3,440	19.13%
Very high	1	28	308	196	115	648	17.75%
Total	**1,799**	**15,447**	**54,436**	**35,637**	**34,712**	**142,031**	

Table 4.61 The consistency test between physical urban flood duration classes and urban flood vulnerability classes from standard deviation classification method.

UFVI classes (Pixels)	Physical urban flood duration class (Pixels)						Consistency
	Very low	Low	Moderate	High	Very high	Total	
Very low	1,750	13,514	49,567	34,626	34,468	133,925	1.31%
Low	34	1,210	2,037	121	67	3,469	34.88%
Moderate	12	360	1,261	133	12	1,778	70.92%
High	2	132	765	139	17	1,055	13.18%
Very high	1	231	806	618	148	1,804	8.20%
Total	**1,799**	**15,447**	**54,436**	**35,637**	**34,712**	**142,031**	

Table 4.62 Comparison result of six consistency test from six classification methods.

UFVI classes	Consistency value (%)					
	Equal interval	Defined interval	Quantile	Natural break	Geometrical interval	Standard deviation
Very low	1.27%	1.27%	1.21%	1.31%	1.27%	1.31%
Low	9.35%	9.35%	**38.82%**	26.70%	37.83%	34.88%
Moderate	48.02%	48.02%	51.67%	55.05%	55.16%	70.92%
High	**54.05%**	**54.05%**	6.90%	29.46%	19.13%	13.18%
Very high	**42.86%**	**42.86%**	6.08%	24.81%	17.75%	8.20%

The consistency test was shown that quantile classification method was provided highest consistency only in low class (38.82%) which was considered as unsuitable method to present the result of UFVI in all 5 classes as well as natural break and geometrical classification which were provided with no highest consistency in all 5 classes. Here, equal and defined interval classification methods were provided with highest consistency in 2 class (high class with 54.05% and very high with 42.86% of UFVI) as well as standard deviation classification method which was provided with highest consistency in 2 classes (very low class with 1.31% and moderate class with 70.92% of UFVI). However, when considered with the consistency value in low class, the standard deviation classification method was shown the better consistency value (34.88%) than equal and defined interval (9.35%) classification methods. Therefore, the standard deviation classification method was considered as the optimum method for urban flood vulnerability classification as summary in Table 4.63. The distribution of urban flood vulnerability classification was presented in Figure 4.39.

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Table 4.63 Urban flood vulnerability based on standard deviation classification method.

Classification	Values	Area (sq. m)	% of flooded area
Very low	0.0000 - 0.0084	83,703,125	94.29%
Low	0.0084 - 0.0210	2,168,125	2.44%
Moderate	0.0210 - 0.0335	1,111,250	1.25%
High	0.0335 - 0.0460	659,375	0.74%
Very high	0.0460 - 0.3584	1,127,500	1.27%
Total		**88,769,375**	**100.00%**

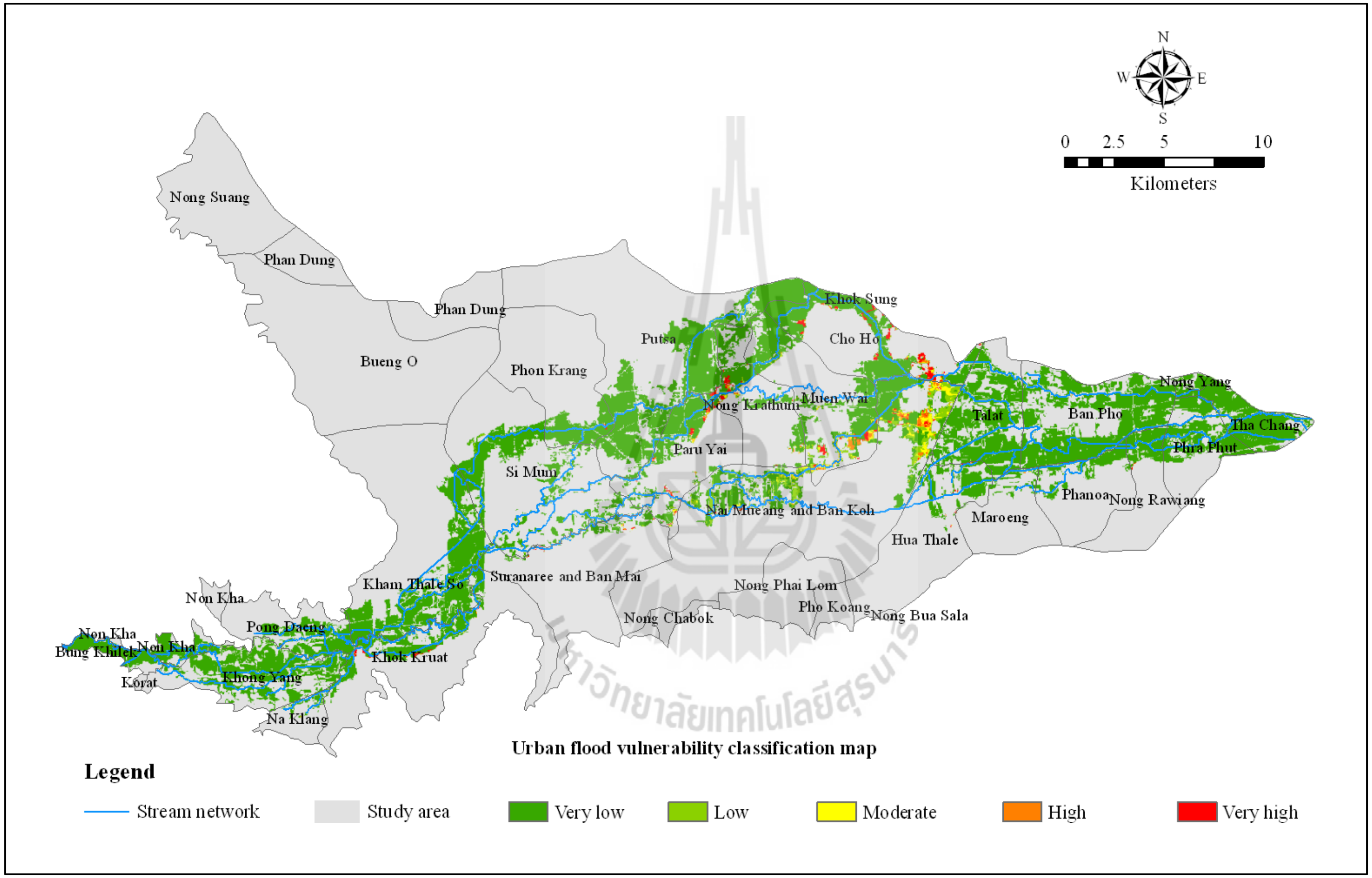

Figure 4.39 Urban flood vulnerability classification map based on standard deviation classification method.

In addition, sensitivity analysis by leave-one-out approach (Malczewski, 1999) had examined with four different Scenarios as shown in Table 4.64. The derived urban flood vulnerability (UFVI) of four Scenarios with standard deviation classification method provided different consistency values when they compared with the physical flood duration. The comparison of consistency values between UFVI by four factors and UFVI of four scenarios was summarized in Table 4.65. The difference of consistency values in Scenario 1, 2, 3, and 4 had shown priorities of factors. Here, Scenario 2 was shown a highest change of consistency value with 33.94% followed by Scenario 1, and Scenario 3 with 21.65% and 1.80%. While, Scenario 4 was provided no change of consistency value. Therefore, it can be summarized that the range of important UFVI's factors were social, physical, and economic respectively while as environmental factor was considered as unimportant factor.

Table 4.64 Defining of four different scenarios for sensitivity analysis by leave-one-out approach.

Factors	UFVI	Scenario1	Scenario2	Scenario3	Scenario4
Physical	Yes	No	Yes	Yes	Yes
Social	Yes	Yes	No	Yes	Yes
Economic	Yes	Yes	Yes	No	Yes
Environmental	Yes	Yes	Yes	Yes	No

Table 4.65 Comparison of consistency value of UFVI with 4 factors and UFVI of 4 scenarios based on leave-one-out approach.

Physical urban flood duration classification	**Consistency value (%)**								
	UFVI	**S 1**	**C 1**	**S 2**	**C 2**	**S 3**	**C 3**	**S 4**	**C 4**
Very low	1.31%	1.21%	0.10%	1.32%	0.10%	1.31%	0.00%	1.31%	0.00%
Low	34.88%	41.34%	6.46%	47.45%	6.11%	35.11%	0.23%	34.88%	0.00%
Moderate	70.92%	63.37%	7.55%	51.44%	11.93%	71.95%	1.03%	70.92%	0.00%
High	13.18%	5.69%	7.49%	17.53%	11.84%	13.15%	0.03%	13.18%	0.00%
Very high	8.20%	8.14%	0.06%	12.10%	3.96%	7.70%	0.50%	8.20%	0.00%
Total of Change (%)			**21.65%**		**33.94%**		**1.80%**		**0.00%**
Rang of Important			**2**		**1**		**3**		**4**

*Notification

S 1 = Scenario 1, C 1 = Change in Scenario 1

S 2 = Scenario 2, C 2 = Change in Scenario 2

S 3 = Scenario 3, C 3 = Change in Scenario 3

S 4 = Scenario 4, C 4 = Change in Scenario 4

4.4.6 Urban flood vulnerability with land use

According to urban flood vulnerability classification, agricultural land was the dominant main land use type that affected by flood with area of 76.89 sq. km (Table 4.66) followed by urban and built-up area, miscellaneous land, and forest land with 7.74, 4.07, and 0.05 sq. km respectively.

Interestingly, very low urban flood vulnerability class was distributed in 4 main land use classes included agricultural land (91.86%), miscellaneous land (4.87%), urban and built-up area (3.20%), and forest land (0.07%). While as low, moderate, high, and very high urban flood vulnerability classes were distributed only in urban and built-up area (Table 4.67).

Table 4.66 The summary of urban flood vulnerability classification area (sq. m) with land use level I.

Land use level I	Very low	Low	Moderate	High	Very high	Total
Urban and built-up area	2,677,500	2,168,125	1,111,250	659,375	1,127,500	7,743,750
Agricultural land	76,891,875	0	0	0	0	76,891,875
Forest land	55,000	0	0	0	0	55,000
Miscellaneous land	4,078,750	0	0	0	0	4,078,750
Water body	0	0	0	0	0	0
Total	**83,703,125**	**2,168,125**	**1,111,250**	**659,375**	**1,127,500**	**88,769,375**

Table 4.67 Distribution of UFVI in 5 main land use classes.

Land use level I	Very low	Low	Moderate	High	Very high
Urban and built-up area	3.20%	100.00%	100.00%	100.00%	100.00%
Agricultural land	91.86%	0.00%	0.00%	0.00%	0.00%
Forest land	0.07%	0.00%	0.00%	0.00%	0.00%
Miscellaneous land	4.87%	0.00%	0.00%	0.00%	0.00%
Water body	0.00%	0.00%	0.00%	0.00%	0.00%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Furthermore, concrete and wooden house was the main type that was affected from urban flood with area of 5.59 sq. km and allocated in very low (1.88 sq. km), low (1.54 sq. km), moderate (0.89 sq. km), high (0.52 sq. km), and very high (0.76 sq. km). House with 2 floors was affected from urban flood with area of 0.80 sq. km and it distributed in very low (0.39 sq. km), low (0.24 sq. km), moderate (0.04 sq. km), high (0.02 sq. km), and very high (0.11 sq. km). While, house with 1 floor was only distributed in very low urban flood classification (0.01 sq. km). The details of urban flood vulnerability classification with detail land use type was presented in Table 4.68.

Table 4.68 The details of urban flood vulnerability classification and its area (sq. m) with land use type.

Level I	Land use level II/III	Very low	Low	Moderate	High	Very high	Total
U	Bus station/Gasoline station	21,875	17,500	1,875	0	0	41,250
U	Commercial buildings with 1 floor	8,125	15,625	25,000	3,125	0	51,875
U	Commercial buildings with 2 floors	3,125	7,500	7,500	1,250	1,875	21,250
U	Commercial buildings with 4 floors	144,375	34,375	6,250	13,750	0	198,750
U	Concrete and wooden house	1,884,375	1,543,750	889,375	516,875	758,750	5,593,125
U	House with 1 floor	13,750	0	0	0	0	13,750
U	House with 2 floor	391,250	240,625	44,375	17,500	113,750	807,500
U	Large industrial (more than 10,000 sq. m)	48,125	60,625	76,250	60,625	147,500	393,125
U	Office building with 1 floor	4,375	18,750	7,500	5,625	19,375	55,625
U	Office building with 2-3 floors	89,375	111,875	25,625	21,875	19,375	268,125
U	Office building with 4-5 floors	8,750	15,000	3,750	1,875	7,500	36,875
U	Office building with 6-9 floors	23,750	68,750	625	0	0	93,125
U	Road	30,000	30,625	18,125	13,125	40,625	132,500
U	Shopping mall (levels 1-3)	1,875	2,500	2,500	1,875	6,875	15,625
U	Small industrial and warehouse	4,375	625	2,500	1,875	11,875	21,250
A	Abandoned paddy field	639,375	0	0	0	0	639,375
A	Animal farm house	47,500	0	0	0	0	47,500
A	Field crop	82,500	0	0	0	0	82,500
A	Horticulture	5,839,375	0	0	0	0	5,839,375

Table 4.68 The details of urban flood vulnerability classification and its area (sq. m) with land use type (Continued).

Level I	Land use level II/III	Very low	Low	Moderate	High	Very high	Total
A	Orchard	1,233,750	0	0	0	0	1,233,750
A	Pasture	71,875	0	0	0	0	71,875
A	Perennial trees	93,750	0	0	0	0	93,750
A	Rice paddy	68,883,750	0	0	0	0	68,883,750
F	Disturbed deciduous forest	55,000	0	0	0	0	55,000
M	Grass	751,250	0	0	0	0	751,250
M	Landfill	386,250	0	0	0	0	386,250
M	Marsh and swamp	828,750	0	0	0	0	828,750
M	Recreation and Green Area	361,875	0	0	0	0	361,875
M	Shrub/Scrub	1,750,625	0	0	0	0	1,750,625
Total		**83,703,125**	**2,168,125**	**1,111,250**	**659,375**	**1,127,500**	**88,769,375**

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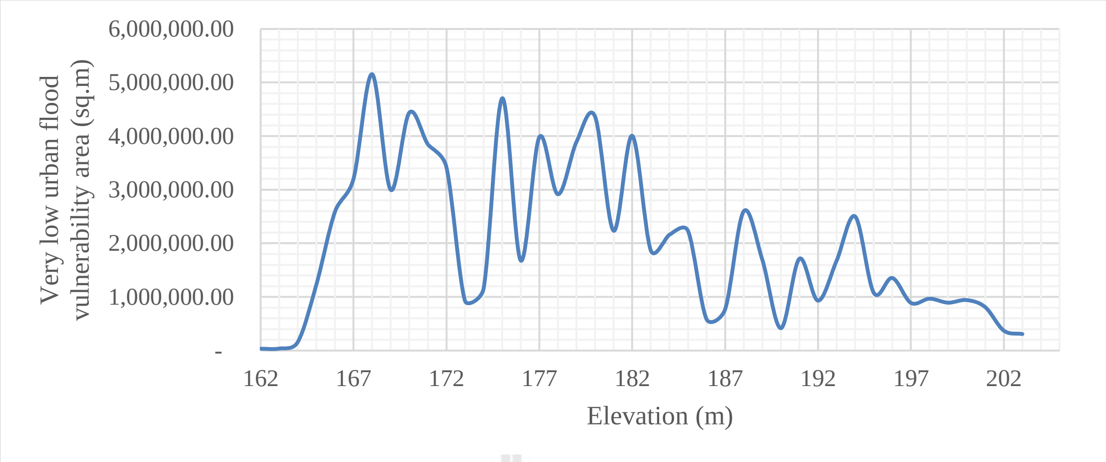
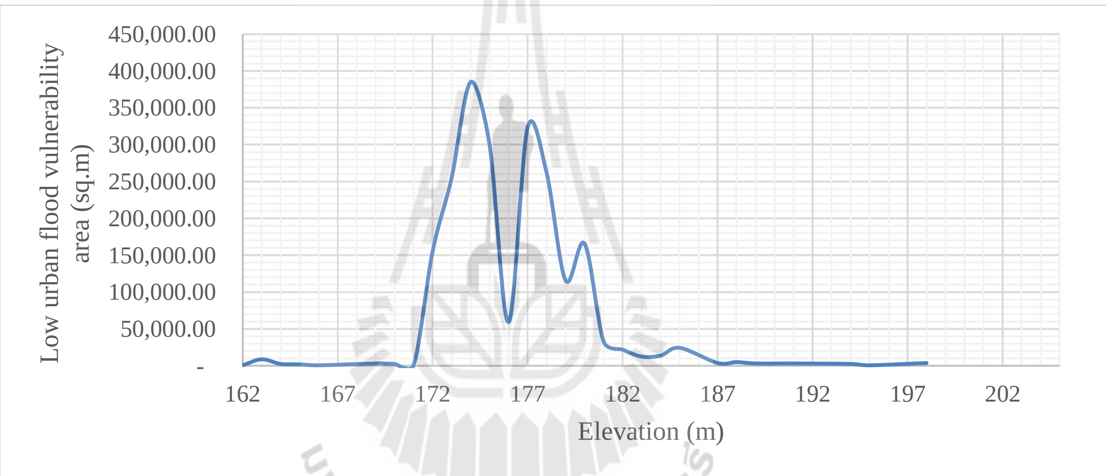
4.4.7 Urban flood vulnerability with elevation

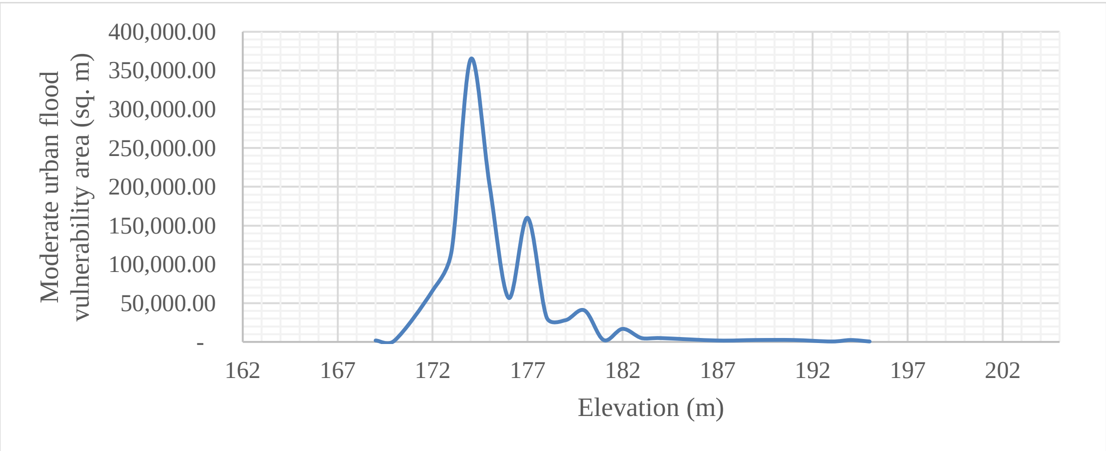
This part was attempted to identify the relation between urban flood vulnerability class and its elevation. The results showed that all urban flood vulnerability classes had distributed between at 162.27 to 203 m. above mean sea level (amsl). The major distribution of very low class of UFVI with area of 83.70 sq. km was allocated between 162.27 to 203 m (amsl) while the major distributed areas were significant at 168, 170, 175, 180, and 182 m (amsl). The distribution of low class of UFVI with area of 2.17 sq. km was located between 162.27 to 198 m (amsl) while the main distributed areas were significant at 173, 174, 175, 177, and 178 m (amsl). The distribution of moderate class of UFVI with area of 1.11 sq. km was situated between 169 to 195 m (amsl) while the major distributed areas were significantly located at 174 and 175 m (amsl). The distribution of high class of UFVI with area of 0.66 sq. km was distributed between 168 to 195 m (amsl) while the main distributed areas were significant at 174 m (amsl). At the same time, the distribution of very high class of UFVI with area of 1.13 sq. km was allocated between 168 to 194 m (amsl) while the main distributed areas were significant at 175 m (amsl) (Figure 4.40 and Table 4.69).



(a) Very low urban flood vulnerability

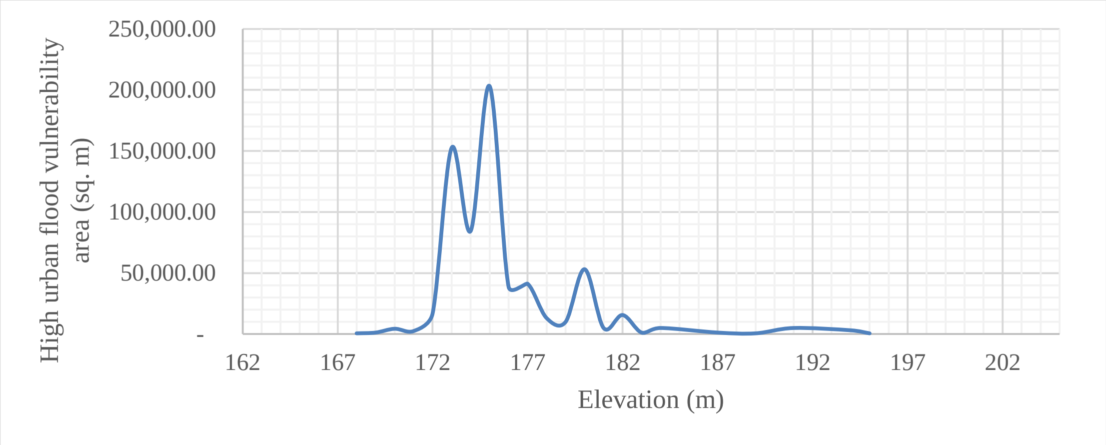


(b) Low urban flood vulnerability

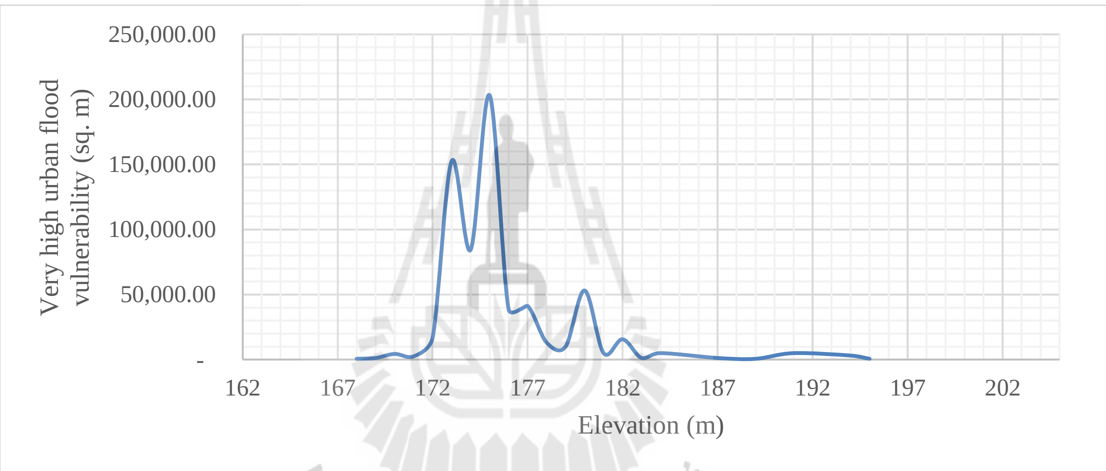


(c) Moderate urban flood vulnerability

Figure 4.40 Distribution of urban flood vulnerability classes and its elevation.



(d) High urban flood vulnerability



(e) Very high urban flood vulnerability

Figure 4.40 Distribution of urban flood vulnerability classes and its elevation (Continued).

Table 4.69 The relation between urban flood vulnerability class and its elevation.

Classification	Total area (sq. m)	Main distribution based on elevation (m)	Area of main Distribution (sq. m)	% distribution
Very low	83,703,125.00	168, 170, 175, 180, and 182	22,661,875	27.07%
Low	2,168,125.00	173, 174, 175, 177, and 178	1,524,375	70.31%
Moderate	1,111,250.00	174 and 175	566,250	50.96%
High	659,375.00	174	203,125	30.81%
Very high	1,127,500.00	175	215,625	19.12%

4.4.8 Urban flood vulnerability with economic value loss

This part was attempted to find out the connection between urban flood vulnerability classification and economic value loss based on actual cash values. Herein economic loss of urban and built-up areas, and agricultural lands were evaluated according to standard compensate rates from Office of Insurance Commission (OIC) and Cabinet Resolutions on August 25, 2011. The results had shown that the total economic value loss in 2010 was 7,351.54 million Baht. The very low urban flood vulnerability class was represented with the highest economic value loss with 25,605.81 million Baht or 34.83% of total economic value loss.

The low, moderate, high, and very high urban flood vulnerability classes were illustrated EVL as 20,647.36 million Baht (or 28.09% of total EVL), 10,397.00 million Baht (or 14.14% of total EVL), 6,188.36 million Baht (or 8.42% of total EVL, and 10,678.00 million Baht (or 14.52% of total EVL) respectively. The summary of economic value loss in 2010 in each urban flood vulnerability classes was provided in Table 4.70.

Under urban and built-up areas, concrete and wooden house was the major type that described the highest economic value loss with 5,356.36 million Baht or 72.86% of total economic value loss in 2010.

The detail of economic value loss (million Baht) in each land use type with urban flood vulnerability classification was provided in Table 4.70.

Table 4.70 The summary of economic value loss (million Baht) in 2010.

Land use level I	Very low	Low	Moderate	High	Very high	Total
Urban and built-up area	25,313.11	20,647.36	10,397.00	6,188.36	10,678.00	73,223.84
Agricultural land	292.70	0.00	0.00	0.00	0.00	292.70
Total	**25,605.81**	**20,647.36**	**10,397.00**	**6,188.36**	**10,678.00**	**73,516.54**
Percent	**34.83%**	**28.09%**	**14.14%**	**8.42%**	**14.52%**	**100.00%**

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Table 4.71 The details of economic value loss (million Baht) in 2010 with urban flood vulnerability classification.

		Urban flood vulnerability classification						
Level I	**Land use level II/III**	**Very low**	**Low**	**Moderate**	**High**	**Very high**	**Total**	**Percent**
U	Bus station/Gasoline station	150.52	120.42	12.90	0.00	0.00	283.84	0.39%
U	Commercial buildings with 1 floor	29.75	57.20	91.53	11.44	0.00	189.91	0.26%
U	Commercial buildings with 2 floors	21.81	52.34	52.34	8.72	13.08	148.28	0.20%
U	Commercial buildings with 4 floors	853.55	203.23	36.95	81.29	0.00	1,175.01	1.60%
U	Concrete and wooden house	18,046.66	14,784.49	8,517.54	4,950.11	7,266.55	53,565.36	72.86%
U	House with 1 floor	128.29	0.00	0.00	0.00	0.00	128.29	0.17%
U	House with 2 floor	4,154.68	2,555.20	471.22	185.83	1,207.91	8,574.84	11.66%
U	Large industrial (more than 10,000 sq. m)	426.68	537.50	676.03	537.50	1,307.74	3,485.45	4.74%
U	Office building with 1 floor	40.82	174.94	69.98	52.48	180.77	518.98	0.71%
U	Office building with 2-3 floors	892.68	1,117.41	255.94	218.49	193.52	2,678.03	3.64%
U	Office building with 4-5 floors	86.48	148.25	37.06	18.53	74.12	364.44	0.50%
U	Office building with 6-9 floors	225.44	652.58	5.93	0.00	0.00	883.94	1.20%
U	Road	206.43	210.73	124.72	90.31	279.54	911.73	1.24%
U	Shopping mall (levels 1-3)	21.88	29.17	29.17	21.88	80.22	182.33	0.25%
U	Small industrial and warehouse	27.47	3.92	15.70	11.77	74.55	133.41	0.18%

Table 4.71 The details of economic value loss (million Baht) in 2010 with urban flood vulnerability classification (Continued).

		Urban flood vulnerability classification						
Level I	**Land use level II/III**	**Very low**	**Low**	**Moderate**	**High**	**Very high**	**Total**	**Percent**
A	Animal farm house	173.90	0.00	0.00	0.00	0.00	173.90	0.24%
A	Field crop	0.16	0.00	0.00	0.00	0.00	0.16	Very close to 0.00%
A	Horticulture	18.61	0.00	0.00	0.00	0.00	18.61	0.03%
A	Orchard	3.93	0.00	0.00	0.00	0.00	3.93	0.01%
A	Pasture	0.14	0.00	0.00	0.00	0.00	0.14	Very close to 0.00%
A	Perennial trees	0.30	0.00	0.00	0.00	0.00	0.30	Very close to 0.00%
A	Rice paddy	95.66	0.00	0.00	0.00	0.00	95.66	0.13%
Total		**25,605.81**	**20,647.36**	**10,397.00**	**6,188.36**	**10,678.00**	**73,516.54**	**100.00%**

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4.5 Urban flood simulation for flood mitigation and prevention

This part was focused on reduce the historical discharge in 2010 by each 10% and reprocessed by DHI MIKE 21 in order to create simulated urban flood extent and to extract total economic value loss (EVL) based on the compensate payment for urban and built-up area, and agricultural land. In practice, the reduced historical discharge of 2010 of 15 days by each 10% (Refer to Table 4.4) were here used to simulate urban flood scenarios and then extract urban flood extent and economic value loss on the peak day. Herein, summary of discharge and its mean, flood extent, total EVL, and peak day was shown in Table 4.72 and distribution of urban flood extent was displayed in Figure 4.41. Details of simulated urban flood extent, and total EVL in different scenarios are provided in Tables 4.73 - 4.74.

As results, major findings can be further elaborated in two parts: (1) basic statistics of urban flood simulation and (2) minimal discharge for minimal urban flood extent and economic value loss identification.

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Table 4.72 The summary of simulated flood scenario by reduced 10 % of historical discharge in 2010.

Scenario	**Reduced discharge (%)**	**Urban flood Extent (sq. km)**	**Initial discharge at Kud Hin Watergate**	**Total EVL (Million Baht)**	**Day**	**Remark**
Historical	0	88.77	44.54	73,516.54	11 th day	24 Oct. 2010
Scenario 1	10%	86.64	40.09	71,280.60	11 th day	-
Scenario 2	20%	84.68	35.63	69,942.88	11 th day	-
Scenario 3	30%	83.50	31.18	66,724.22	11 th day	-
Scenario 4	40%	82.37	26.72	64,739.96	11 th day	-
Scenario 5	50%	51.76	22.27	27,252.91	12 th day	-
Scenario 6	60%	31.12	17.82	14,380.24	12 th day	-
Scenario 7	62%	30.42	16.93	14,014.61	12 th day	-
Scenario 8	64%	29.79	16.04	12,157.44	13 th day	-
Scenario 9	66%	28.87	15.15	11,297.42	13 th day	-
Scenario 10	**67%**	**-**	**14.70**	**-**	**-**	**-**

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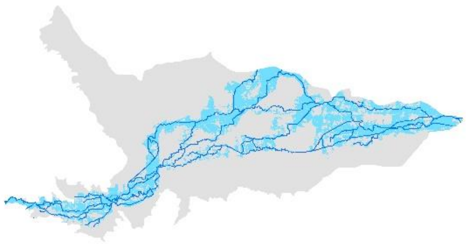
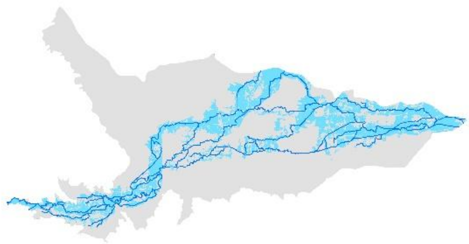
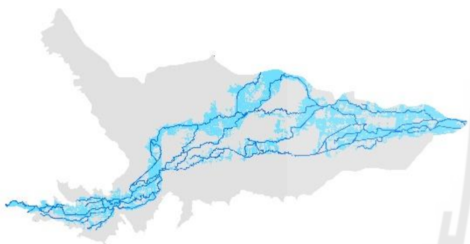


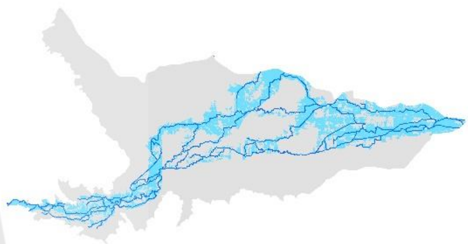
(a) Historical



(b) Scenario 1



(c) Scenario 2



(d) Scenario 3

(e) Scenario 4

(f) Scenario 5

(g) Scenario 6

(h) Scenario 7

Figure 4.41 Simulated urban flood extent of various scenarios.

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(i) Scenario 8

(j) Scenario 9

(k) Scenario 10

Figure 4.41 Simulated urban flood extent of various scenarios (Continued).

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Table 4.73 The details of simulated urban flood extent in different scenarios (sq. m).

Class	Land use	Historical	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
U	Bus station/Gasoline station	41,250	40,625	40,000	34,375	33,125	8,750	5,000	5,000	0	0
U	Commercial buildings with 1 floor	51,875	50,000	49,375	37,500	33,125	22,500	15,625	15,625	15,625	15,625
U	Commercial buildings with 2 floors	21,250	21,250	20,000	19,375	19,375	18,125	13,125	13,125	1,250	1,250
U	Commercial buildings with 4 floors	198,750	198,125	198,125	181,250	179,375	11,875	1,875	1,250	1,250	0
U	Concrete and wooden house	5,593,125	5,412,500	5,316,250	5,081,250	4,922,500	2,248,750	1,176,875	1,145,625	1,005,625	930,000
U	House with 1 floor	13,750	13,750	13,750	13,125	13,125	2,500	0	0	0	0
U	House with 2 floor	807,500	799,375	794,375	731,875	711,875	168,750	70,000	68,750	68,750	63,750
U	Large industrial (more than 10,000 sq. m)	393,125	376,250	371,875	375,000	363,750	228,750	154,375	151,250	123,750	119,375
U	Office building with 1 floor	55,625	51,250	47,500	43,750	43,125	23,750	18,125	17,500	17,500	16,875
U	Office building with 2-3 floors	268,125	256,250	235,000	235,000	233,750	51,875	18,750	18,125	18,125	15,625
U	Office building with 4-5 floors	36,875	36,250	33,125	32,500	30,000	2,500	625	625	0	0
U	Office building with 6-9 floors	93,125	93,125	93,125	91,250	91,250	5,625	1,875	1,875	0	0
U	Road	132,500	125,000	122,500	116,250	113,750	65,625	44,375	43,125	26,250	25,625
U	Shopping mall (levels 1-3)	15,625	15,625	15,625	12,500	8,750	5,000	1,250	1,250	0	0
U	Small industrial and warehouse	21,250	20,000	19,375	21,250	20,625	16,250	7,500	7,500	7,500	7,500

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Table 4.73 The details of simulated urban flood extent in different scenarios (sq. m) (Continued).

Class	Land use	Historical	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
A	Abandoned paddy field	639,375	631,875	630,000	626,250	609,375	211,250	60,625	60,000	59,375	58,750
A	Animal farm house	47,500	40,000	38,125	35,000	33,125	8,750	3,125	3,125	3,125	3,125
A	Field crop	82,500	80,625	75,625	76,250	76,250	29,375	10,000	10,000	10,000	9,375
A	Horticulture	5,839,375	5,693,125	5,576,875	5,155,625	5,063,750	2,796,875	1,714,375	1,680,625	1,640,000	1,525,625
A	Orchard	1,233,750	1,166,875	1,131,875	1,093,125	1,078,750	543,125	329,375	320,000	319,375	302,500
A	Pasture	71,875	67,500	64,375	66,250	61,875	17,500	8,750	8,750	8,750	8,750
A	Perennial trees	93,750	80,000	77,500	81,875	73,125	26,250	1,250	1,250	1,250	1,250
A	Rice paddy	68,883,750	67,378,125	65,844,375	65,560,625	64,886,875	44,211,875	27,104,375	26,490,000	26,125,625	25,434,375
F	Disturbed deciduous forest	55,000	43,750	40,625	39,375	38,750	16,250	8,750	8,125	8,125	8,125
M	Grass	751,250	744,375	740,625	748,125	747,500	241,875	49,375	49,375	44,375	44,375
M	Landfill	386,250	371,875	362,500	363,750	343,125	150,000	78,125	75,625	75,625	75,000
M	Marsh and swamp	828,750	803,750	791,250	768,750	755,625	228,125	92,500	90,000	81,250	75,625
M	Recreation and green area	361,875	343,125	323,125	238,750	229,375	50,000	28,750	28,750	26,875	25,625
M	Shrub/Scrub	1,750,625	1,686,250	1,616,250	1,620,625	1,553,750	348,125	103,125	102,500	101,875	99,375
Total		**88,769,375**	**86,640,625**	**84,683,125**	**83,500,625**	**82,368,750**	**51,760,000**	**31,121,875**	**30,418,750**	**29,791,250**	**28,867,500**

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Table 4.74 The details of simulated EVL in difference scenarios (million Baht).

Class	Land use	Historical	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
U	Bus station/Gasoline station	283.84	279.54	275.24	236.53	227.93	60.21	34.41	34.41	-	-
U	Commercial buildings with 1 floor	189.91	183.05	180.76	137.29	121.27	82.37	57.20	57.20	57.20	57.20
U	Commercial buildings with 2 floors	148.28	148.28	139.56	135.20	135.20	126.48	91.59	91.59	8.72	8.72
U	Commercial buildings with 4 floors	1,175.01	1,171.32	1,171.32	1,071.55	1,060.47	70.21	11.09	7.39	7.39	-
U	Concrete and wooden house	53,565.36	51,835.51	50,913.73	48,663.13	47,142.78	21,536.28	11,270.93	10,971.65	9,630.87	8,906.61
U	House with 1 floor	128.29	128.29	128.29	122.46	122.46	23.33	-	-	-	-
U	House with 2 floor	8,574.84	8,488.56	8,435.47	7,771.78	7,559.40	1,791.96	743.33	730.06	730.06	676.96
U	Large industrial (more than 10,000 sq. m.)	3,485.45	3,335.83	3,297.04	3,324.75	3,225.01	2,028.10	1,368.69	1,340.98	1,097.17	1,058.38
U	Large warehouse	518.98	478.16	443.18	408.19	402.36	221.59	169.11	163.28	163.28	157.44
U	Office building with 1 floor	2,678.03	2,559.43	2,347.18	2,347.18	2,334.70	518.13	187.28	181.03	181.03	156.06
U	Office building with 2-3 floors	364.44	358.26	327.37	321.20	296.49	24.71	6.18	6.18	-	-
U	Office building with 4-5 floors	883.94	883.94	883.94	866.15	866.15	53.39	17.80	17.80	-	-
U	Office building with 6-9 floors	911.73	860.13	842.92	799.92	782.71	451.57	305.34	296.74	180.63	176.33
U	Road	182.33	182.33	182.33	145.86	102.10	58.35	14.59	14.59	-	-
U	Shopping mall (levels 1-3)	133.41	125.56	121.64	133.41	129.48	102.02	47.09	47.09	47.09	47.09
U	Small industrial and warehouse	283.84	279.54	275.24	236.53	227.93	60.21	34.41	34.41	-	-

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Table 4.74 The details of simulated EVL in difference scenarios (million Baht) (Continued).

Class	Land use	Historical	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
A	Animal farm house	173.90	146.44	139.58	128.14	121.27	32.03	11.44	11.44	11.44	11.44
A	Field crop	0.16	0.16	0.15	0.15	0.15	0.06	0.02	0.02	0.02	0.02
A	Horticulture	18.61	18.14	17.77	16.43	16.13	8.91	5.46	5.35	5.23	4.86
A	Orchard	3.93	3.72	3.61	3.48	3.44	1.73	1.05	1.02	1.02	0.96
A	Pasture	0.14	0.13	0.13	0.13	0.12	0.03	0.02	0.02	0.02	0.02
A	Perennial trees	0.30	0.25	0.25	0.26	0.23	0.08	0.00	0.00	0.00	0.00
A	Rice paddy	95.66	93.57	91.44	91.05	90.11	61.40	37.64	36.79	36.28	35.32
Total		**73,516.54**	**71,280.60**	**69,942.88**	**66,724.22**	**64,739.96**	**27,252.91**	**14,380.24**	**14,014.61**	**12,157.44**	**11,297.42**

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4.5.1 Basic statistics of urban flood simulation

Refer to Table 4.70, the relationship between historical discharge reduction (%) and simulated urban flood extent and total EVL can be presented as scatter plot with smooth line in Figure 4.42 and Figure 4.43, respectively. As results, it can be observed that urban flood extent slightly decreases when historical discharge in 2010 reduces between 10 to 40%. However, urban flood extent dramatically decreases with accelerate rate when historical discharge in 2010 reduces between 40 to 60%. After that its extent slightly decreases when historical discharge in 2010 reduces between 60 to 66%. Similarly, total EVL change occurs when discharge is reduced. The pattern of total EVL change is the same as urban flood extent change (Figure 4.44).

In addition, the relationship between simulated urban flood extent and total EVL can be presented as shown in Figure 4.45. Herein the simple linear equation between simulated urban flood extent and total EVL showed positive relationship with R^2 at 99.16% as:

$$y = -19{,}128 + 1031.2x \qquad (4.1)$$

Where,

y is total EVL in million Baht and,

x is simulated urban flood extent in sq. km.

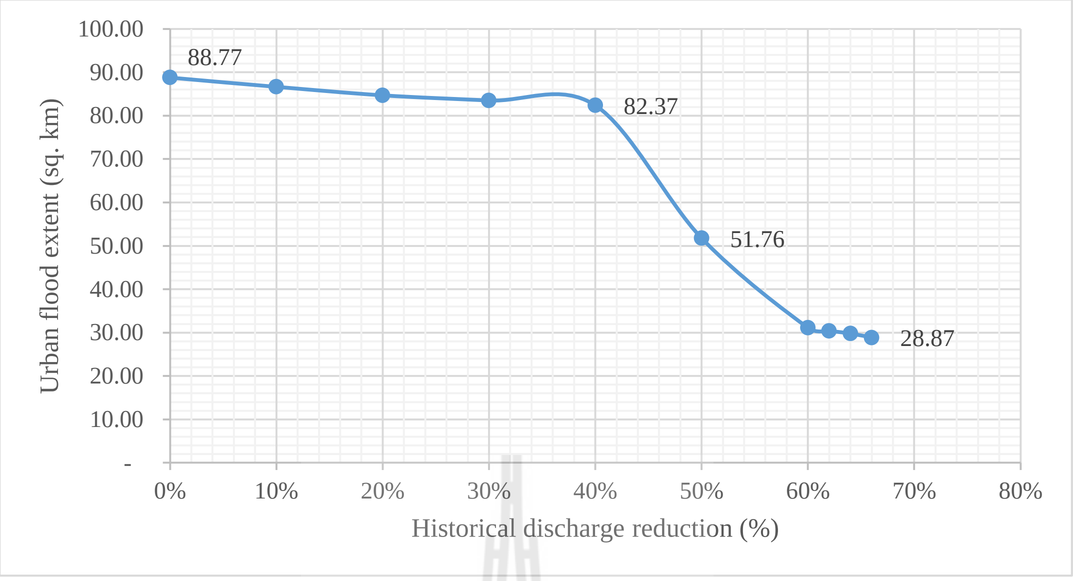

Figure 4.42 The relationship between simulated historical discharge reduction (%) and urban flood extent.

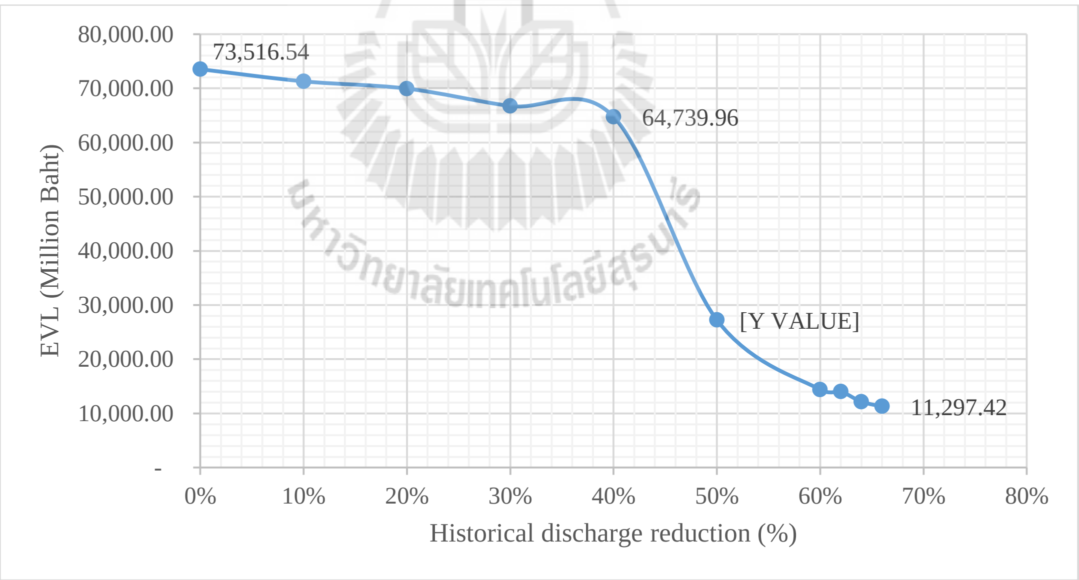

Figure 4.43 The relationship between simulated historical discharge reduction (%) and EVL.

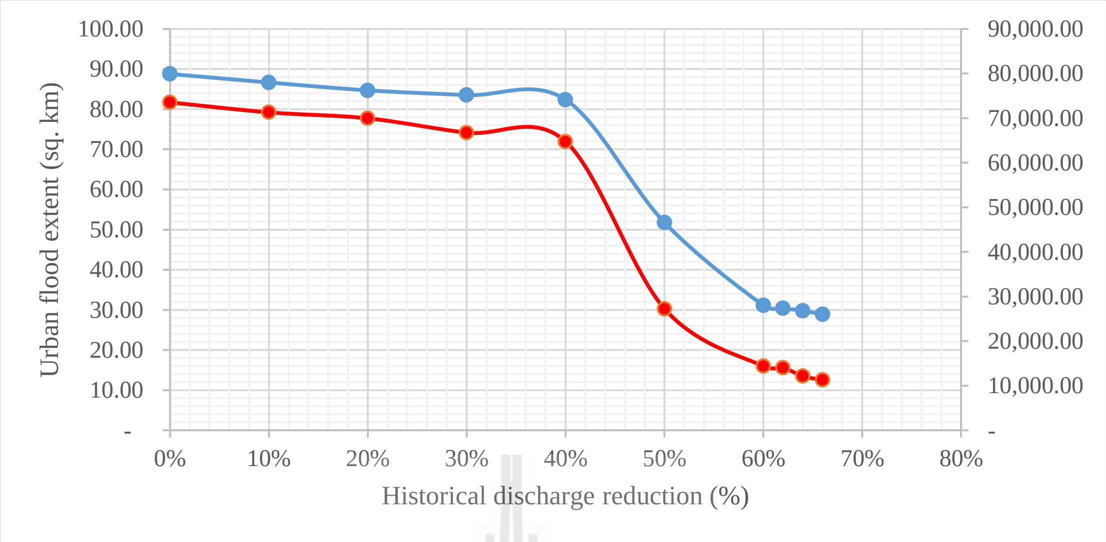

Figure 4.44 Pattern of simulated urban flood extent and total EVL change according to discharge reduction (%).

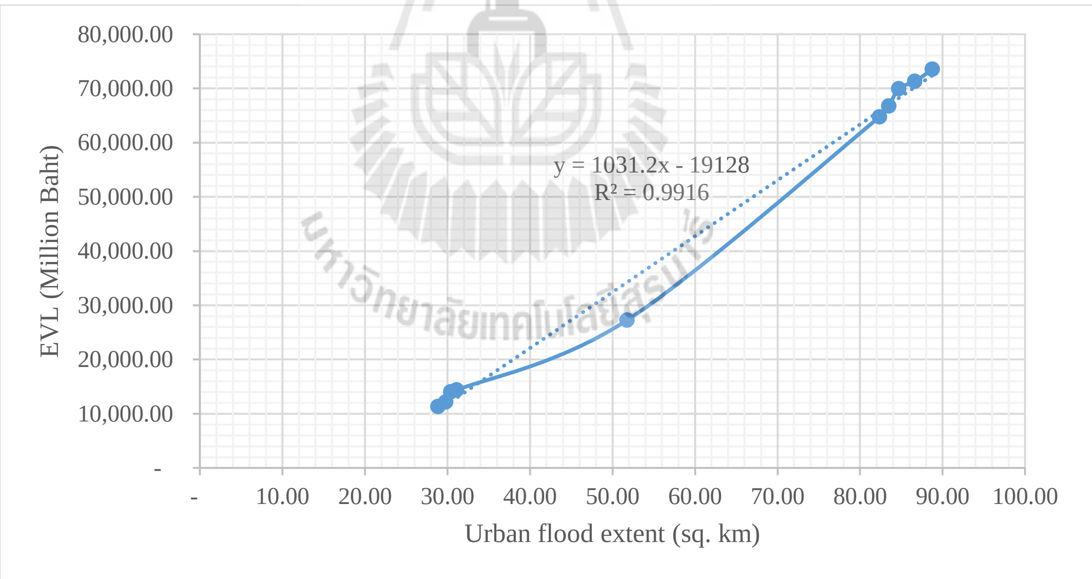

Figure 4.45 The relationship between simulated urban flood extent and total EVL.

4.5.2 Minimal discharge for minimal urban flood extent and economic value loss identification

As results presented in Table 4.70 and Figure 4.44, it was found that urban flood extent and total EVL was abruptly decrease from historical urban flood record in 2010 at Scenario 5 and Scenario 6 and peak day was extended one day. Herein, the urban flood extent was reduced from 88.77 sq. km to be 51. 76 sq. km at Scenario 5 and 31.12 sq. km at Scenario 6. Similarly, the total EVL of historical scenario was dropped from 73,516.54 million Baht to be 27,252.91 million Baht at Scenario 5 and 14,380.24 million Baht at Scenario 6.

After Scenario 6, reduction of discharge by each 2% from 60% for Scenario 7 to Scenario 9 showed slightly decreasing of flood extent and Total EVL. Herein, urban flood extent was reduced from 31.12 sq. km. at Scenario 6 to be 28. 87 sq. km at Scenario 9 and the total EVL was dropped from 14,380.24 million Baht at Scenario 6 to be 11,297.42 million Baht at Scenario 9. It shows non-significant change occurring during Scenario 6 to Scenario 9 when it is compared with Scenario 4 to Scenario 6. Lastly, Scenario 10 with discharge reduction at 67%, it was found that no flood occurred in the study area. The change of flood extent and total EVL due to discharge reduction between two scenarios can be displayed in Figure 4.46.

Furthermore, it was found that rate of change for flood extent and total EVL by percent of discharge reduction among scenarios as shown in Figure 4.47 was similar pattern as change of flood extent and total EVL. Summary of change of flood extent and total EVL and their rate due to discharge reduction by percent was presented in Table 4.75.

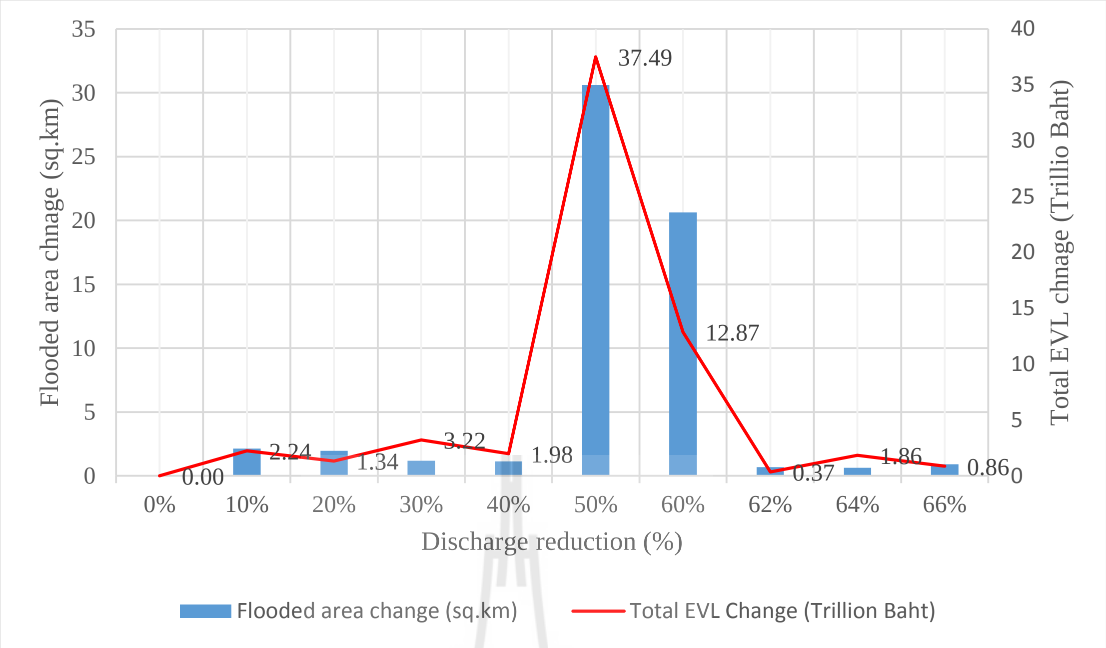

Figure 4.46 Change of flooded area and total EVL due to discharge reduction between two scenarios.

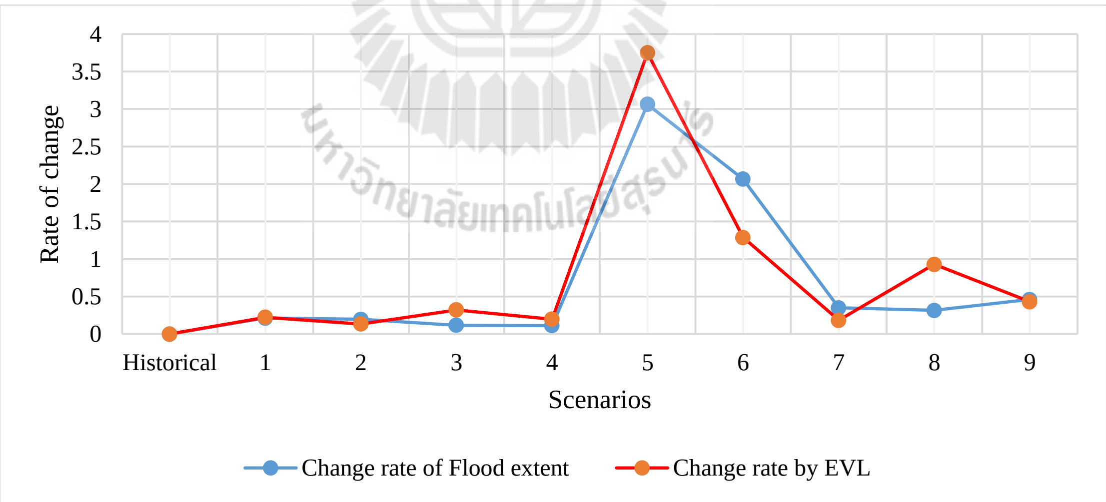

Figure 4.47 Rate of change for flood extent and total EVL by percent of discharge reduction.

Table 4.75 Summary of change of flood extent and total EVL and their rate due to discharge reduction by percent.

		Flood extent (sq. km)		Total EVL (trillion Baht)	
Scenarios	**Discharge reduction (%)**	**Change area**	**Change rate**	**Change Value**	**Change rate**
Historical	0.00	0.00	0.00	0.00	0.00
Scenario 1	10.00	2.13	0.21	2.23	0.22
Scenario 2	20.00	1.96	0.19	1.33	0.13
Scenario 3	30.00	1.18	0.11	3.21	0.32
Scenario 4	40.00	1.13	0.11	1.98	0.19
Scenario 5	50.00	30.61	3.06	37.48	3.74
Scenario 6	60.00	20.64	2.06	12.87	1.28
Scenario 7	62.00	0.70	0.35	0.36	0.18
Scenario 8	64.00	0.63	0.31	1.85	0.92
Scenario 9	66.00	0.92	0.46	0.86	0.43

As results mentioned earlier, the optimum reduction discharge from historical record in 2010 for flood mitigation should be 60%, this will be reduced flood extent about 57.65 sq. km or 64.94% of flood extent in 2010. In addition, reduction discharge from historical record in 2010 for flood prevention should be 67%, this will be protect urban flood in Mueang Nakhon Ratchasima district as occurring in 2010. To achieve flood mitigation, discharge at Kud Hin Watergate should be controlled and less than 17.82 m^3/s. Meanwhile when discharge at to Kud Hin Watergate is equal or less than 14.70 m^3/s, it will protect urban flood in Mueang Nakhon Ratchasima district.

CHAPTER V

CONCLUSION AND RECOMMENDATION

This chapter provides the conclusion according to objectives, that include (1) to characterize urban flood severity (2) to develop urban flood vulnerability index (UFVI) map (3) to simulate urban flood information (cut off inflow volume) for urban flood impact reduction, and recommendation for future research and development.

5.1 Conclusion

5.1.1 Urban flood simulation by DHI MIKE 21 model and urban flood severity classification

The normal Manning's M number is demonstrated as an optimum Manning's M number parameters for urban flood simulation in 2010 through calibration of simulated urban flood extent and historical urban flood record in 2010. The urban flood simulation in 2010 by DHI MIKE 21 model have illustrated urban flood extent during the flood occurred on 14 to 27 October 2010 with the maximum extent on 24 October 2010 which covers area of 88.36 sq. km. While, Putsa, Ban Pho, and Nai Mueang and Ban Kho sub-districts, Mueang Nakhon Ratchasima district are the main area that was affected by urban flood. The main land use types that effect on simulated urban flood extent in 2010 are agricultural land, and urban and built-up area. Herein, concrete and wooden house is the main land use type that affected on urban flood with the highest EVL in 2010. The characteristic of simulated urban flood in 2010 has flows with the same direction of the Lum Takhong River from the West at Kud Hin Watergates to the East at Gun Phom Watergate. While, the bypass Mitraphap Khon Kean road plays an important role as flood barrier to prevent the flood flow from west to east. In contrast, Mitraphap road through the city of Mueang Nakhon Ratchasima to bypass Mitraphap Khon Kean road cannot prevent the flood.

For urban flood severity analysis based on 24 October 2010, the physical urban flood depth severity have illustrate in rank between 0.10 to 3.89 m. The physical urban flood velocity severity have illustrate in rank between 0.00 to 2.06 m/s. The physical urban flood duration severity have provide between 1 – 14 days due to limitation of historical discharge data. The final product of this part is the physical urban flood severity according to flood depth and velocity which is here classified into 5 classes: very low, low, moderate, high, and very high by optimum classification method (standard deviation). The dominant urban flood severity classes are very low and low which cover area of 29.27 and 36.24 sq. km or 32.98 and 40.83% of flooded area.

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5.1.2 Urban flood vulnerability analysis

Urban flood vulnerability analysis determines the likelihood and scale of damage from urban flood resulting from physical, social, economic, and environment using index model with multiplication method. UFVI values which range between 0.0000 - 0.3584 are classified into 5 urban flood vulnerability classes: very low, low, moderate, high, and very high by optimum classification method (Standard deviation) according to consistency test with physical urban flood duration. Herein, the dominant urban flood vulnerability classes is very low which cover area of

83.70 sq. km and it is provides the highest economic value loss with value of 25605.81 million Baht in 2010.

5.1.3 Urban flood simulation for flood mitigation and prevention

An optimum reduction discharge from historical record in 2010 for flood mitigation should be 60%, this will be reduced flood extent about 57.65 sq. km or 64.94% of flood extent in 2010. Meanwhile, the reduction discharge from historical record in 2010 for flood prevention should be 67%, this will be protect urban flood in Mueang Nakhon Ratchasima district as occurring in 2010.

To achieve flood mitigation, discharge at Kud Hin Watergate should be less than 17.82 m^3/s and when discharge at to Kud Hin Watergate is less than 14.70 m^3/s, it will protect urban flood in Mueang Nakhon Ratchasima district.

5.2 Recommendation

The recommendation of this study have divided into three parts includes (1) urban flood simulation by hydrodynamic model of DHI MIKE 21, (2) urban flood severity and vulnerability study, and (3) Mueang Nakhon Ratchasima urban flood mitigation and prevention.

5.2.1 Urban flood simulation by hydrodynamic model of DHI MIKE 21

The data preparation is the first important step of urban flood severity and vulnerability, the hydrodynamic data for example historical discharge per day is an important data that should provide as much as possible during urban flood occurs. Moreover, the discharge data is need to be as continuous data series in order to create simulated urban flood results. Secondly, DEM is another important data that need to verify error and fix pixel by pixel. Thirdly, the optimum Manning' M number have to be verify before running the DHI MIKE 21 model. Fourthly, actual flood map of GISTDA or other sources that provide urban flood extent, and historical flood record data such as pictures, and flood scares are need for validating with simulated urban flood extent. Finally, the further study of urban flood simulation should be include pipe system with integration of DHI MIKE flood.

5.2.2 Urban flood severity and vulnerability study

The further study on urban flood severity and vulnerability in different study areas might find a way to combine physical urban flood severity according to flood depth, velocity and duration, resulting in different physical urban flood severity index and different urban flood vulnerability index. However, the physical urban flood duration is also need the historical discharge per day cover the start and stop urban flood events.

5.2.3 Mueang Nakhon Ratchasima urban flood mitigation and prevention

The safety point for urban flood with discharge less than 14.70 m^3/s at Kud Hin Watergate is could be used to reference a signal pole securities of urban flood occurs in Mueang Nakhon Ratchasima. Moreover, it could be used to find a way to control discharge of Kud Hin such as install the pushing water machine including other Watergates, repair all UNIDATA of Lam Takhong stream network in order to report the real-time discharge data, and searching the stream network and pipe system to increase ability to obtain water volume and reduce the friction of the water, resulting in smoothly flood flows.

Furthermore, an interesting area which is giving a good potentiality of constructing a new drainage area is here suggest at Bung Khilek district, Sung Noen district as descript in two reasons.

(1) Bung Khilek sub-district is situate close to Kud Hin Watergate, the area is confluence of the stream network and it would be easy to drain water into the area.

(2) The main land use type of the district is provide with paddy field and if a new drainage has introduce here, paddy field will have the direct benefit to agriculture activities such as agriculturists and increasing of economic value of sub-district.

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