ASSESSMENT OF FLOOD RISK AND FLOOD DAMAGE USING GEOSPATIAL TECHNIQUES: A CASE STUDY OF SUKHOTHAI PROVINCE, THAILAND.

KAMONCHAT SEEJATA

A Thesis Submitted to the Graduate School of Naresuan University
in Partial Fulfillment of the Requirements
for the Master of Science in Disaster Management - (Plan A Type A2) International Program
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Thesis entitled "Assessment of flood risk and flood damage using Geospatial techniques: A case study of Sukhothai Province, Thailand. "

By KAMONCHAT SEEJATA

has been approved by the Graduate School as partial fulfillment of the requirements for the Master of Science in Disaster Management - (Plan A Type A2) International Program of Naresuan University

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Title ASSESSMENT OF FLOOD RISK AND FLOOD DAMAGE USING GEOSPATIAL TECHNIQUES: A CASE STUDY OF SUKHOTHAI PROVINCE, THAILAND.

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ABSTRACT

Floods are the most severe and frequent disaster in Thailand which cause enormous damages during the monsoon season almost every year. Sukhothai Province is one of the flood-prone areas that annually experience a considerable effect of the flood on both agriculture and residential areas. Therefore, the primary purpose of this study is to conduct a flood risk assessment in Sukhothai Province, Thailand, using Geographical Information Systems (GIS) which is a handy tool for disaster management and flood damage assessment. The study had applied the Frequency Ratio (FR) method to generate a flood hazard map with nine influencing factors of historical flood area, average annual rainfall, elevation, slope degree, land use, soil drainage, drainage density, road density, and the distance from drainage. Whereas, the Analytic Hierarchy Process (AHP) method was applied to create a flood vulnerability map with seven factors of historical flood area, average annual rainfall, elevation, slope degree, land use, soil drainage, drainage density, road density, and the distance from drainage. Then, the integration of hazard and vulnerability was done using GIS to assess flood risk over the study area. Lastly, flood depth-duration damage curve was created using data collected from questionnaires in the highest-risk areas of year 2011, 2017, and 2018.

The result showed that the flood prone area of high and very high floods hazards are 23.12% and 35.64% of the total area, respectively. These areas located in Si Samrong, Mueang Sukhothai, Kong Krailat, and Khiri Mat Districts. By validating the obtained flood hazard map with the Area Under Curve (AUC) method, it showed high accuracy with the success rate and the prediction rate of 95.05% and 94.77%, respectively. The obtained flood vulnerability map revealed high and very high vulnerability areas distributed over the study area. The area of flood vulnerability mainly found in two classes of the high-level and very high level of 25.98% and 16.40%, respectively. The results also showed that the very low, low, moderate, high, and very high risk area cover 26.15%, 11.07%, 21%, 13.59%, and 28.22% of the total area, respectively. Most of high and very high-risk area located along the main river and tributaries, including flat area. The obtained flood depth-duration damage curve can be a guide for government agency to estimate the cost of damage according to the depth of flood for the studied area.

In addition, the results of physical and social information at the Sub-District level and information on flood hazards, vulnerability, and damage can be used to manage as a valuable tool in applying risk management, flood mitigation, measures, planning, and management in Sukhothai Province.

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ABBREVIATIONS

ADPC	=	Asian Disaster Preparedness Center
AHP	=	Analytic Hierarchy Process
AUC	=	Area Under Curve
DDPM	=	Department of Disaster Prevention and Mitigation
FR	=	Frequency Ratio
FVI	=	Flood Vulnerability Index
GIS	=	Geographic Information System
GISTDA	=	Geo-Informatics and Space Technology Development Agency
HAII	=	Hydro and Agro Informatics Institute
IDW	=	Inverse Distance Weighting
LDD	=	Land Development Department
NSO	=	National Statistical Office
RID	=	Royal Irrigation Department
TMD	=	Thai Meteorological Department
UNISDR	=	United Nations Office for Disaster Risk Reduction
USGS	=	United States Geological Survey
FSI	=	Flood Susceptibility Index
CR	=	Consistency Ratio

CHAPTER I
INTRODUCTION

1.1 Background

According to the United Nations Office for Disaster Risk Reduction (UNISDR), a disaster occurs when a community or society is disrupted by a hazardous event of any magnitude, leading to loss and impact on lives, the economy, and the environment, etc. (UN, 2016). There are two main factors caused disasters. The first is the natural hazards themselves including floods, droughts, tropical storms, earthquakes, volcanoes, and landslides. The second set includes the vulnerabilities of elements at risk such as populations, infrastructure, and economic activities that are more or less susceptible to damage by a hazard event (Dilley et al., 2005). Climate-related disasters like floods, droughts, landslides, and storms cause loss of lives and economic damage. Floods are one of the most common natural hazards responsible for the human, economic and environmental losses across the globe, leading to increased vulnerability of the society to flooding (EEA, 2008; Schmidt-Thome, 2006). During three decades (1998 to 2017), there have been 3,148 flood occurrences affected approximately two billions of people (CRED, EM-DAT, & UNISDR, 2018).

The majority of disasters in Thailand are associated with water due to the country's geographical and climatic characteristics. Floods, droughts, and landslides are the common disasters in Thailand. Floods are considered as the most severe and frequent disaster in Thailand. Every part of the country have been struggled with a flood during the monsoon season and causes maximum damages annually (CFE-DM, 2018). The leading causes of floods are the influence of climate phenomena. These are the southwest monsoon from May to September, the northeastern monsoon from October to December, monsoon through northern, northeastern, central regions, as well as a tropical cyclone such as tropical storm, a tropical depression, and typhoon (DDPM, 2015). The floods have exacerbated and more severe and devastating, as well as causing severe losses, as shown in **Figure 1**. For example, the 2011 flood was Thailand's most catastrophic flood. There were 64 of 77 provinces including Bangkok were affected. 5,247,125 households or 16,224,304 people were affected by flood, and the death toll was 1,026. Likewise, the total economic damage and losses amounted to 1.44 billion Baht (DDPM, 2015).

Sukhothai Province is located in one of the flood-prone areas of the Yom River Basin. It experiences a considerable impact of the flood on both agriculture and residential areas annually. The upstream basin in North of Sukhothai receives heavy rainfall, where water flows through a narrowed path leading to lower valleys. The amount of water flowing into Sukhothai province, therefore, has a large volume that can cause an overflow of the water. This large volume of water can damage the riverbanks, erosion, damages (RID4, 2009). Furthermore, the canal's ineffectiveness to drain water and deforestation are known to exacerbate the incidences of flooding. In 1995, 2002, 2006, and 2011, there was severe flooding in the Yom River Basin area, including Sukhothai Province, which caused severe damage to the houses and rice fields.

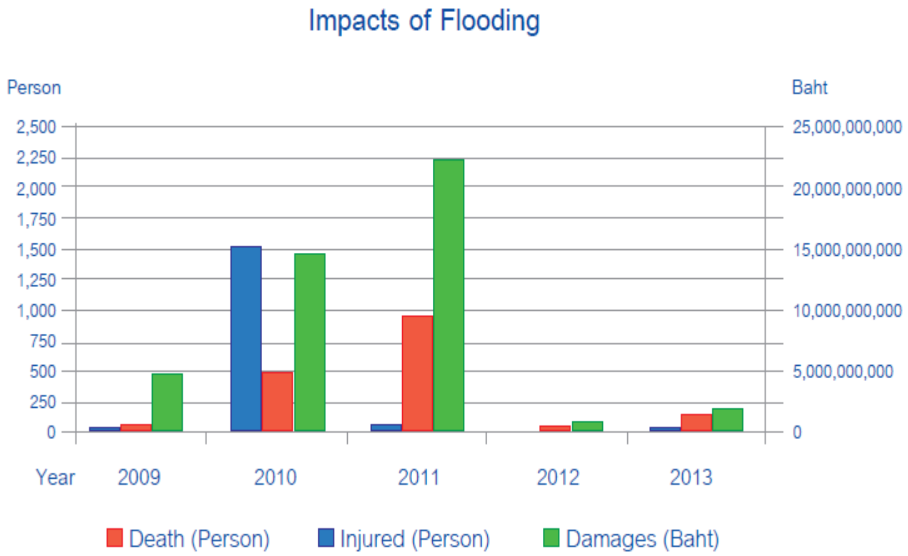


Figure 1 Statistical data on impacts of floods during 2009 – 2013

Source: DDPM (2015)

Assessing flood hazard, vulnerability, and risk along with the damage is very essential to understand the effects of floods. Flood hazard assessment can help to evaluate the flood situation by combining with Geographic Information System (GIS) for presenting flood-prone areas as map (OAS, 1991). Vulnerability assessment can identify the degree of vulnerability that an area, physical structure, and economic loss or damage caused by floods (Dandapat & Panda, 2017). Flood risk determines the extent of risk by analyzing hazards and vulnerability together (UNDP, 2010).

Therefore, the main objective of this study is to conduct a flood risk assessment in Sukhothai Province, Thailand, using GIS. In flood hazard analysis, the Frequency Ratio (FR) method is used to estimate flood probability and generate flood hazard maps with the GIS techniques (Anucharn & Iamchuen, 2017; Duangpiboon, Suteerasak, Rattanakom, & Towanlong, 2018; Samanta, Pal, & Palsamanta, 2018; Youssef, Pradhan, & Sefry, 2015). For flood vulnerability, Analytic Hierarchy Process (AHP) will be used to calculate the weighting value with vulnerability indexes to generate a flood vulnerability map (Dandapat & Panda, 2017; L. A. Hadi, W. M. Naim, N. A. Adnan, & A. Nisa, 2017; Rimba, Setiawati, Sambah, & Miura, 2017; Vishwanath & Tomaszewski, 2018). The overlay process is used to generate the flood risk map from hazard and vulnerability. Overall, this outcome of the study will help the local authorities, planners, government and related organizations to make their decisions based on analytical results of flood risk and to improve response plans for flooding in the future.

1.2 Statement of Problem

Sukhothai is one of the most affected provinces by floods in Thailand because of the narrowing width of the Yom River at the lower part of Sukhothai compared to the northern region of the basin (**Figure 2**). The occurrence of heavy rainfall in Payao and Phrae Provinces occurring in the upstream of the basin causes floods in the lower part of Sukhothai Province. This phenomenon occurs when the amount of water flowing into Sukhothai Province has a large volume, causing an overflow of the banks, erosion, and damage from high and severe flooding in residential and agricultural areas annually (RID4, 2009).

In June 2012, for example, the Yom River's water in Phrae Province overflowed and affected 3 districts, 12 sub-districts, 69 villages, 2,564 households, 6,480 people, and one death. Approximately 17.63 km^2 of paddy fields were also damaged (ThaiWater, 2012). In July 2017, Sukhothai was affected by the Talus depression impact, causing heavy rainfall. The agricultural area was reported to be affected 155.10 km^2 (ThaiWater, 2017).

There have been many studies conducted in Sukhothai Province and the Yom River Basin to deal with the flood problems. The past researches focused on the flood problem and climate change. There are several studies on flood analysis and response under climate change (Hanittinan, Sriariyawat, & Koontanakulvong, 2011), flood damage estimate using flood simulation (Sriariyawat, Pakoksung, Sayama, Tanaka, & Koontanakulvong, 2013), and the response of the flood peak to the spatial distribution of rainfall (Klongvessa, Lu, & Chotpantarat, 2018).

It is however still not addressing the spatial flood problems to our knowledge. This research, therefore, aims to find the flood risk area and analyze the damage due to floods by using GIS to understand physical characteristics and generate the flood stage-damage curve, particularly in residential and agriculture areas. It can help us to understand the problem and the damage caused by the floods.

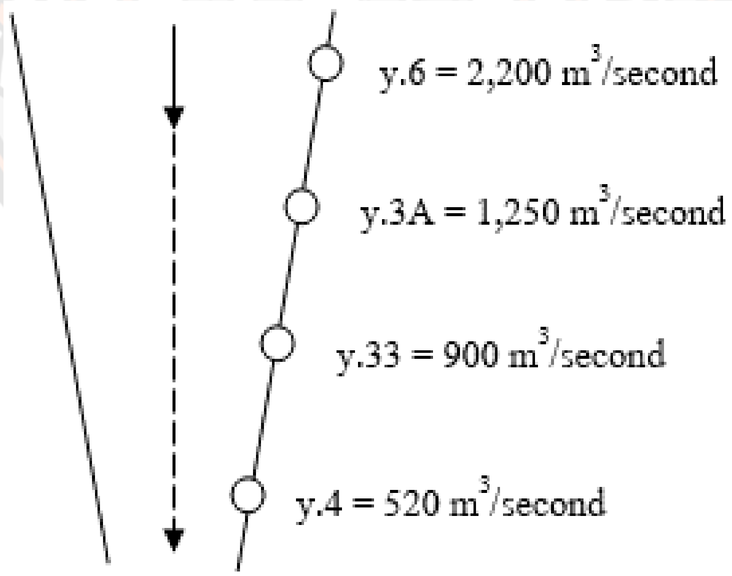


Figure 2 River structure from upper Yom River Basin to Sukhothai Province

Source: RID4 (2009)

1.3 Research Question

1.3.1 How much are the accuracy and efficiency of Frequency Ratio Method generate flood hazard map?

1.3.2 Where and how much is the most risk area over Sukhothai Province?

1.3.3 How much are the residential and agriculture area damage from floods?

1.4 Research Objective

The main objective of this study is to conduct a flood risk assessment using the FR, AHP, and GIS by identifying flood risk areas and assessing flood damage based on the highest-risk area in Sukhothai Province, Thailand.

1.4.1 The main research objectives are as follows:

1. To assess flood risk in Sukhothai Province.
2. To assess the residential damage and agriculture by focusing on house and paddy field damage areas affected by floods in Sukhothai Province.

1.4.2 The specific objectives are as follows:

1. To create a flood hazard map by applying the FR method and GIS.
2. To create flood vulnerability map by applying the AHP and GIS.
3. To generate flood risk map from flood hazard and vulnerability map.
4. To assess the house and paddy field damage from floods.
5. To generate flood damage map, and
6. To generate the flood depth duration-damage curve.

1.5 Research Scope

The research scopes of the study are presented as follows:

1.5.1 Study Area

This research is conducted in Sukhothai Province. It is located in the Yom River Basin and one of Thailand's upper central or lower Northern Provinces. The questionnaire survey is also conducted in the highest-risk areas. It consists of five districts: Mueang Sukhothai, Kong Krailat, Khiri Mat, Si Samrong, and Sawankhalok Districts for flood damage assessment.

1.5.2 Methodology

1. The FR method is used to generate a flood hazard map with influencing factors from secondary data (i.e. average annual rainfall obtained from TMD).
2. The AUC is used to validate flood hazard map.
3. The AHP method is used to prioritize the influent factors that influence flood vulnerability. The weight or priority given for each factor in the AHP is depended on the literature review.
4. The GIS is applied to generate the hazard, vulnerability, and risk maps in the study area.
5. Flood damage assessment is applied by using data collected from questionnaires in the highest-risk area. The questionnaires are collected for information on the paddy fields and houses damage in years of 2011, 2017 (The Bang Rakam Model 1st phase), and 2018. Including general information and flooding experienced.

1.6 Expected Outcome

This study has the expected outcome as follows:

1) Flood hazard map
2) Flood vulnerability map
3) Flood risk map
4) Flood damage map
5) Flood damage curve.

1.7 Key Words

Geographic Information System (GIS), Hazard, Vulnerability, Flood Risk, Frequency Ratio (FR), Damage Assessment.

CHAPTER II

LITERATURE REVIEW

This chapter provides a review of the relevant literatures and researches related to flood definition, flood situation in Sukhothai Province and Thailand. The definition of flood hazard, vulnerability, risk, and flood damage assessment, the FR and AHP methods, GIS, and spatial modeling are also provided.

2.1 Flood Definition

According to the Office of Disaster Preparedness and Management (ODPM, 2013), a flood is an accumulation or an overflow of floods and an expanse of water covered or inundated on dry land. A flood can occur anywhere in the world. Floods can cause loss of life, property and often cause disruption of life such as roads can be blocked and cause economic and environmental damage. It can be divided according to speed, geography, or cause of floods (FloodSite, 2008). Therefore, there are four different types of floods: coastal flood, river flood, flash flood, and urban flood as **Figure 3**.

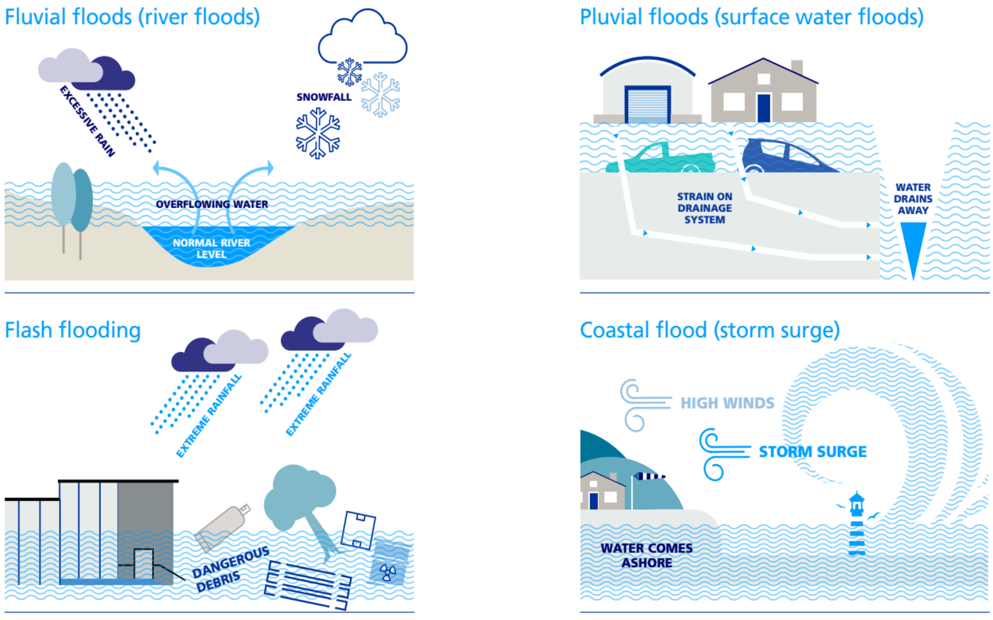


Figure 3 the common types of flood

Source: Zurich Company (2020)

1. Coastal flooding is caused by a surge and high waves from a severe storm. In this type, water overwhelms low land and impacts life and property (Maddox, 2014).
2. River Flood occurs when the water exceeds capacity. Due to intense rainfall over a long period, floods can affect and damage rivers downstream, which often breaks and swamp nearby areas and affects property (EnvironmentalTechnology, 2014).

3. Flash floods can occur anywhere, including places far from the river. Due to heavy rainfall and the ground cannot absorb and drainage the water as quickly (EnvironmentalTechnology, 2014). This flood type led to danger and damage quickly, such as erosion that can cause the building to collapse.

4. Urban flood can occur from several causes: flash floods, coastal floods, river floods, or heavy rainfall. The cause is a lack of drainage system, and soil cannot store water in an urban area. Causing to drainage cannot well drain and then get deposited somewhere else in the city on the streets and causing economic damages are high (FloodSite, 2008).

2.2 Flood in Thailand

Thailand is located in the Pacific Rim in a tropical belt, which is vulnerable to natural disaster impacts such as flooding, typhoons, etc., but less than many of the Indo-Asia-Pacific region countries. However, it is vulnerable due to seasonal weather and climate change in the region. Flood is the most severe and frequent hazard in Thailand. It is both familiar and destructive because the impact varies regionally, and every part of Thailand suffers from flood-related damages annually (CFE-DM, 2018).

Typically, floods are caused by heavy rainfall over a long time. Continuous heavy rainfalls trigger flash floods or sudden flooding and overbank flow. Floods are one of the most frequent natural disasters in Thailand, impacting households, life, public and private property. The influence of the weather is the leading cause of floods in Thailand. These are the southwest monsoon from May to September, The northeastern monsoon from October to December, the monsoon through northern, northeastern, central regions, and a tropical cyclone such as tropical storm, a tropical depression, and typhoon (DDPM, 2015).

Thailand faced numerous floods, including the 2011 floods caused by torrential rain from monsoons in July 2011. Around 4 million households and 13 million people were impacted; 2,329 houses were destroyed, 96,833 houses were partially damaged, 657 people died, and three people were reported missing. According to the World Bank, the damage was approximately THB 1,440 Billion (ThaiWater, 2012). Floods from July to October 2013 in northern and northeast provinces experienced sporadic floods. Multiple tropical storms added to the heavy rainfall that led to flooding. Forty-five provinces were affected, 61 people were dead, and more than 3.5 million are affected due to the floods (IFRC, 2013). In October 2016, that hit Nakhonsawan Province killed three people and inundated large areas of farmland and almost 30,000 houses. Across the country, 14 provinces were affected with Ayutthaya Province particularly hard hit (Maxwell, 2016). In May 2017, Northern Provinces were affected by floods. Seven provinces and 61 villages were affected by the flash flood. The Kamphaeng Pet being the worst affected province: 800 houses were damaged. Around 2,000 families in Uttaradit Province were evacuated to a safer place. Approximately 853 houses were reported to damage from other provinces like Chiang Mai, Phitsanulok, Loei, Udon-Thani, and Lampang (Reliefweb, 2017).

2.3 Flood events in Sukhothai Province

According to the Hydro and Agro Informatics Institute (HAII), Sukhothai is one of the most affected provinces by floods (HAII, 2012). The Yom River's narrow width at the lower part of Sukhothai than the upper part (**Figure 2**) and heavy rainfall in Payao and Phrae Province located upstream of the basin results in flood Sukhothai Province. Every year, this phenomenon occurs when the amount of water flowing into Sukhothai Province (particularly, Mueang Sukhothai, Si Samrong, Sawankhalok, and Kong Krailat damage) has a large volume. An overflow of the banks and erosion due to ineffective drainage capacity resulted from a shallow riverbed and its small cross-section (Sriariyawat et al., 2013). The high and severe flooding causes damage to both community and agricultural area (ThaiWater, 2019).

In 2006, there are three incidences of floods (May, August-September, and September-October) in five provinces due to heavy rainfall and mudflow, which affected 121,380 people, 39,460 households, and 50.59 km^2 (31,619 Rai) of cultivated areas. Meanwhile, five districts of Sukhothai Province comprising of Ban Dan Lan Hoi, Si Satchanalai, Si Samrong, Sawankhalok, and Thung Saliam were affected. Three people death and two missing.

In 2008, floods occurred from September to November because of heavy rainfall that flooded for more than 15 days affecting 7,057 Rai of agricultural land and an estimated loss of about 36 million baht.

In 2009, heavy rainfall of 199.5 mm. was recorded in Si Satchanalai District, which caused two incidences of a flash flood (June and November - October) in nine villages affecting 2000 households. Further, flooding influenced by Ketsana depressive storm affected 20 Provinces, 87 Districts, 503 Sub-Districts, 3,584 villages, 394,752 people, 105,155 households, and 213.25 km^2 (133,253 Rai) of agricultural areas, including Kong Krailat district in Sukhothai Province.

In 2011, floods occurred from January to October due to rainfall, La Nina phenomenon, and storms; Haitang, NESAT, Nalgae, Haima, which caused flash floods in Phrae, Chiang Rai, Tak, Nan, Phayao, and Sukhothai Province. During the flood, 411,573 people and 82 households were affected along with three dead and estimated the damage of 255.36 km^2 (159,598 Rai) of cultivated land from 46 Districts. At the same time, Sukhothai Province was affected by the NOCK-TEN storm. It experienced flooding over 1593.02 km^2 (995,637 Rai) of areas. More than 120,000 people were affected, including eight deaths, and an estimated 480 km^2 (300,000 Rai) of rice fields were damaged (data as of September 11, 2014).

In June 2012, the Yom River's water flowed from Phrae Province overflow into three districts, 12 sub-districts, and 69 villages. 2,564 households were affected, 6,480 people were affected, and one person died. Rice fields were damaged 17.63 km2 (11,019 Rai).

In 2017, the Talus depression storm caused flooding in 17 Provinces, including Sukhothai, which experienced a flood over an area of 154.38 km^2 or 96,490 Rai (i.e., 19% of the total flooding area). In September 2017, the DOKSURI storm directly affected Thailand, causing heavy rain in 44 provinces. During the storm, 4,720 km^2 (950,000 Rai) of agricultural lands were inundated, affecting 4,833 households, including Sukhothai Province, which experienced a flood in 507.18 km^2 (316,990 Rai).

2.4 Hazard Concept

According to ADPC, a hazard is any situation that leads to loss and damage to people, property, services, environment, or potentially damaging events. The occurrence chances within a specified period in a given area (ADPC, 2001). Moreover, a hazard can occur by a phenomenon or human activity that damages social and economic, including the environment (UN, 2016).

2.4.1 Types of hazards

A commonly used hazard classification includes the following five categories of hazard as follows:

- Atmospheric hazards are mainly processes operating in the atmosphere, such as Tropical Cyclones, Tornadoes, Droughts, and Severe Thunderstorms (Nelson, 2018).
- Hydrologic hazards were characterized by a severe excess or lack of water, including Flood, Drought, Coastal erosion, and Soil erosion (CNCS, 2019).
- Geologic hazards originate from internal earth processes or are associated with rapid gravity-induced downward debris movements such as mass movements, landslides, rockslides, surface collapses, debris, or mudflows (CNCS, 2019; UN, 2016).
- Biologic hazards are hazards related to diseases of plants, animals, and humans (CNCS, 2019).
- Technologic hazards or Man-Made hazards are caused by humans or industrial conditions, dangerous procedures, infrastructure failures such as pollution, toxic waste, dam failures, transport accidents, factory explosions, fires, and chemical spills (UN, 2016).

2.4.2 Flood hazard

Flood hazard assessment has been developed, taking into each area's characteristics. Moreover, Flood hazard assessment is to understand the probability that occurs over an extended period and estimate this probability over the years to decades to support risk management (Nelson, 2018). In addition, it can be further to assess specific risks, which consider the exposed areas' socioeconomic characteristics such as industrial activities, population density, land use (UNEP-DHI, 2017).

Furthermore, flood hazard mapping is an essential tool for planning in flood-prone areas. It creates easy-to-read, rapidly accessible, and facilitates identifying areas at risk of flooding and mitigation, flood risk management, assists local authorities in managing flood, and helps prioritize mitigation and response efforts (Bapalu & Sinha, 2005). Flood hazard maps are frequently created using GIS and an efficient method of combining various maps and digital elevation models (Sanyal & Lu, 2003).

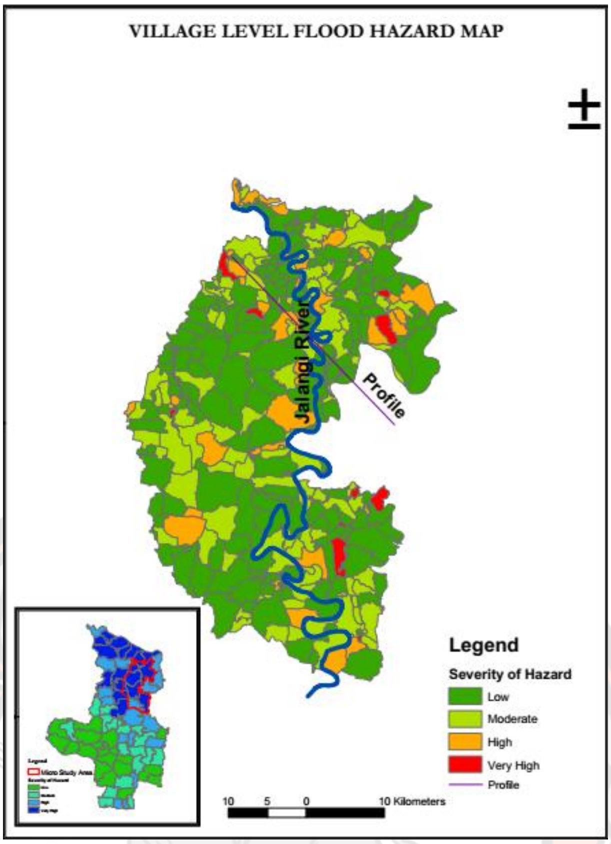


Figure 4 Example of a flood hazard map

Source: Sanyal & Lu (2003)

Therefore, flood hazard assessment and mapping were used to identify areas at risk of flooding and improve flood risk management and other disaster management. Typically look at the expected extent and depth of flooding in a given location, based on various scenarios (UNEP-DHI, 2017).

2.5 Vulnerability Concept

Vulnerability is factors or constraints of an economic, social, physical, environment or geographic nature, which reduce the ability to cope with the impact of hazards (ADPC, 2001). Vulnerability refers to the characteristics and circumstances of a community, system, or asset that make it susceptible to damaging effects (UN, 2016). There are four main types of vulnerability (ODPM, 2013; Westen, 2004) as followed:

1. Physical vulnerability refers to the potential for physical impact on the physical environment, expressed as elements at risk such as population density, a settlement, the site, design, and materials used for critical infrastructure and for housing

2. Economic vulnerability refers to the potential impacts of hazards on economic assets and processes.

3. Social vulnerability is the potential impact of events on groups such as the poor, pregnant or lactating women, children, and elderly; consider public awareness of risk and groups' ability to self-cope with catastrophes.

4. Environmental vulnerability is the potential impacts of events such as flora, fauna, ecosystems, biodiversity.

Vulnerability assessment evaluates the impacts of threats from potential hazards to vulnerabilities that establish realistic risk reduction goals and allocates resources effectively. There are many vulnerability assessment methods, for example, the Vulnerability indicators method, Vulnerability curve method, Disaster loss data method, modeling methods (Nasiri, Yusof, Johari, Ali, & Ahmad, 2016).

Furthermore, the vulnerability mapping could provide information that can be used to reduce the impact of disasters by creating safe and environmentally conscious land use management. The local governments and planners can use the relevant information to supplement and improve their land-use policies and practices and assess the vulnerability of specific areas (Edwards, Gustafsson, & Näslund-Landenmark, 2007).

2.6 Risk Concept

Risk is the probability that adverse consequences may arise when hazards interact with vulnerable areas, people, property, and the environment (ADPC, 2001). According to UN (2016), risk is the combination of the probability of an event and its negative consequences.

Risk assessment is a process to define the nature and extent of such risk by analyzing hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods, and the environment on which they depend (UNDP, 2010).

According to EU Directive, "flood risk" is the likelihood of a flood event together with the actual damage to human health and life, the environment, and economic activity associated with that flood event (EU, 2007). Flood risk is a function of flood hazard and flood vulnerability by the overlapping areas of hazard and vulnerability (Apel, Aronica, Kreibich, & Thieken, 2008). The following equation is used to generate a flood risk map.

$$\text{Flood Risk} = \text{Hazard} \times \text{Vulnerability} \qquad \text{Eq. (2.1)}$$

A hazard is a dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. Within the risk management framework, vulnerability pertains to consequence analysis. It generally defines the potential for loss to the elements at risk caused by the occurrence of a hazard and depends on multiple aspects arising from physical, social, economic, and environmental factors, which are interacting in space and time (UN, 2016).

2.7 Flood Damage Assessment

Flood damage is evaluated from the existing database, collected from an interview survey or secondary sources such as local authorities and the internet (Romali, Yusop, Sulaiman, & Ismail, 2018). Flood damages can be divided into two types are direct damage and indirect damage. Direct damages occur due to the physical contact of floodwater with humans, property. Indirect damages are induced by the direct impacts and occur outside the flood event (Merz, Kreibich, Schwarze, & Thieken, 2010). Furthermore, both types of damage can be classified into tangible and intangible. Tangible damages can be specified in monetary values such as damage to buildings, residential, and agriculture. Intangible damages cannot be specified in monetary values such as casualties, health impact, and ecological (Youssef et al., 2015). See **Table 1**.

Table 1 Types of flood damages

	Tangible	**Intangible**
Direct	Building and contents damage, Infrastructure damage, Agricultural soil erosion, Harvest destruction, Evacuation and rescue measures, Business interruption, Clean-up costs.	Loss of life, Injuries, Psychological distress, Cultural heritage damage, Negative effects on ecosystems.
Indirect	Public services interruption, Induced production losses to companies outside the flooded area, tax revenue loss due to migration of companies in the aftermath of flood, business interruption.	Trauma, loss of trust in authorities and health and psychological damage.

Source: Youssef et al. (2015)

For flood, the damage is related to flood parameter in damage assessment, which the flood stage-damage function curve can present. The damage level depends on parameters, such as flood depth, flood duration, velocity, and frequency of flooding. Flood depth is the most parameter used in the damage function curve and can be represented by depth-damage or depth percent damage curve (Romali et al., 2018).

Flood stage-damage function curve is one of the approaches to assess flood damage. It can be divided into two methods; based on existing databases and following from the questionnaire survey, land use and land cover known as a synthetic stage-damage function. The synthetic stage-damage function can divided into two types, depending on exiting database and valuation surveys (Rahmati, Pourghasemi, & Zeinivand, 2015).

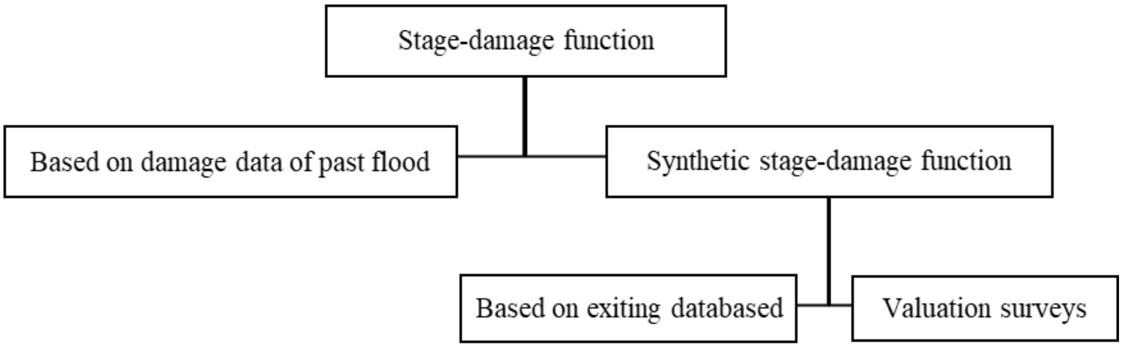


Figure 5 Types of stage-damage function approaches

Source: Romali et al. (2018)

2.8 The Frequency Ratio (FR)

The bivariate statistics analysis method, based on spatial distribution/probability of factors, considered conditioning factors (Slope, elevation, Rainfall, Etc.). Probability analysis considers the statistical relationships between historical target location and conditioning factor (AlThuwaynee, 2019). The frequency ratio is calculated using the following equation 2.2

$$FR = \frac{PH}{PS} \qquad \text{Eq. (2.2)}$$

Where PH is the number percentage of flood hazards in each class, and PS is the percentage of each class's study area. In this analysis, if the FR value lower than 1 indicates a weak correlation, on the other hand, the value of FR more than 1 indicates a strong correlation. The frequency ratio index is calculated using the following equation 2.3

$$FSI = \sum_{i=1}^{n} FR_i \qquad \text{Eq. (2.3)}$$

Where FR_i is the value of FR in each factor and n is the number of factors.

2.9 The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a multi-objective, multi-criteria decision-making approach that enables the user to arrive at a scale of preference drawn from a set of alternatives (Saaty, 1997). AHP process was developed by Prof. Thomas L. Saaty. The procedure for using the AHP is summarized as follows: First, the problem/factors and determines the kind of knowledge sought that is defined. The second step is to establish priorities among the hierarchy elements by making a series of judgments based on pairwise comparisons of the elements. Each factor is rated against every other factor by assigning a relative dominant value between 1 and 9 to the intersecting cell (R.Ramanathan, 2001; Saaty, 1997), as shown in **Table 2**. The third step is to synthesize the judgments to determine the priorities to be assigned to these factors. The fourth step is to check the consistency of the judgments.

Table 2 Relative weight of the factors

Weight	Definition	Description
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one parameter over another
5	Strong importance	Experience and judgment strongly favor one parameter over another
7	Very strong importance	One parameter is favored very strongly s and is considered superior to another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one parameter as superior to another is of the highest possible order of affirmation
2,4,6,8	Intermediate	When compromise is needed, values between two adjacent judgments are used

Sources: Ramanathan (2001) and Saaty (1997)

In the AHP, the consistency ratio is defined as a consistency ratio of 0.10 or less is acceptable to continue the AHP analysis. The Consistency Ratio (CR) is calculated using the formula, CR = CI/RI, in which the Consistency Index (CI) is measured through the following equations 2.4 as follows.

$$CI = \frac{\lambda_{max}-n}{n-1} \qquad \text{Eq. (2.4)}$$

Where λ_{max} is the maximum eigenvalue of the judgment matrix. n is the number of factors. The value of RI is related to the dimension of the matrix (**Table 3**). It shows Random Consistency Index for various n (Saaty, 1980).

Table 3 Random Consistency Index

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty (1980)

2.10 Geographic Information System (GIS)

A geographic information system or GIS is defined as a system that analyzes, manages, storage data, and presents information as a map (Campbell & Shin, 2012). Moreover, GIS is an essential tool for planning and management, modeling and mapping large areas, for example, an application such as land use planning, impact analysis, and other applications (Escobar, Hunter, Bishop, & Zerger, 2019). GIS is handy and effective in disaster management such as flood, drought, landslide, and earthquake that impact the loss of life, property, and environment every year. GIS can present a disaster event by combining layers of data and presenting it to the map to identify the event's situation and level through many dimensions and help and mitigate disaster (Herath, 2020). Spatial analysis in geographical information systems (GIS) is a process to derive the result from computer processing, explore, and examine it. This analysis has the suitability of specific locations for estimating and predicting, interpreting, and understanding change outcome, and much more for spatial problem-solving (ESRI, 2018). Example of Spatial analysis in geographical information systems as follows.

1) The Density toolset is used to calculate the density of input features data within a neighborhood around each output raster cell.

2) The Hydrology toolset is used to model the flow of water across a surface, create a stream network, or delineate watersheds.

3) The Interpolation toolset is used to create a continuous (or prediction) surface from sampled point values such as IDW and Kriging.

4) The Overlay tools are used for superimposed multiple data sets together to identify their relationships (Clarke, 1997).

2.11 Spatial Modeling

According to Haggett and Chorley (1967), spatial modeling is one component of the modeling process about the spatial relationship of features in the real world, and studying and simulating spatial objects or phenomena occurs. Spatial modeling is a process for analyzing spatial data combine with a GIS to analyze and easy understanding. Furthermore, it can help to understand and address a particular problem solving and planning in both complex and straightforward (Techopedia, 2014). Spatial data models have two primary data to represent the real world. It contains a vector and a raster as follows (Buckley, 1997).

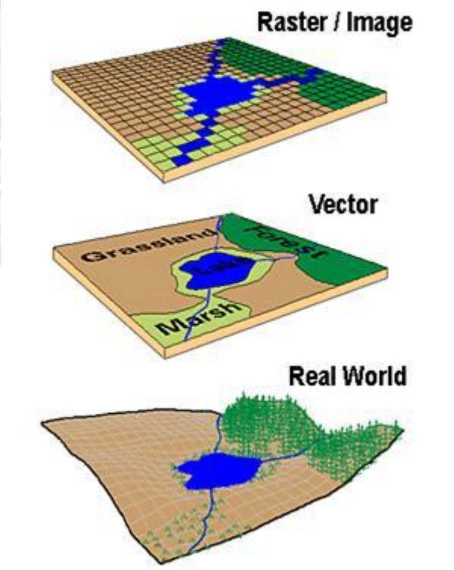


Figure 6 Vector and Raster layer represent this real world

Source: Buckley (1997)

1. Vectors are composed of three main elements: Points are spatial objects with no area but can be specified by coordinates (X and Y) in coordinate space. Lines are spatial objects that connected points (nodes) with no actual width, such as a road. Furthermore, Polygons are closed areas that can be made up of a circuit of line segments and represent 2D space.

2. Raster is represented by grid-cell divided into cells identified by row and column, and a coordinate (X, Y) is assigned to each cell.

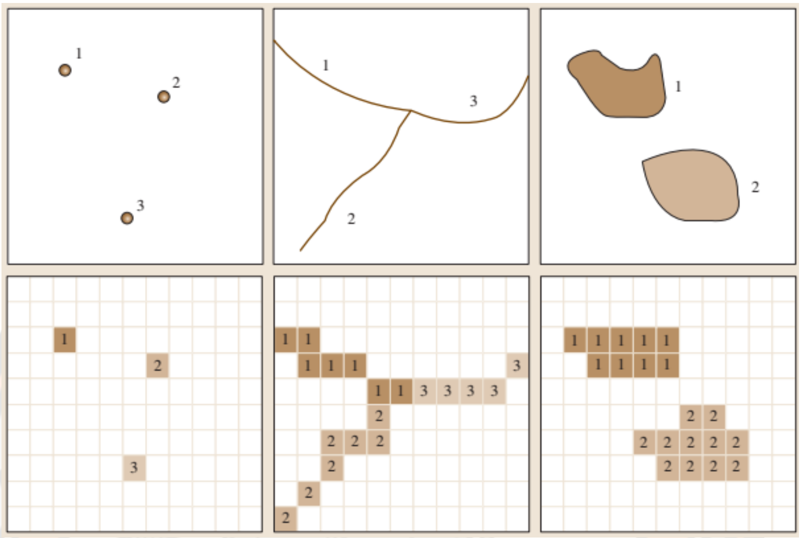


Figure 7 Vector and Raster data

Source: Wolfgang (2012)

The modeling process can divide into four types as follows (Fresnostate, 2019):

1) Binary Model uses logical expressions to select spatial features from a composite feature layer or multiple raster. A binary model's output is in binary format: 1 (true) and 0 (false).

2) Index Model calculates each unit area's index value and produces a map based on the index values, and depends on overlay operations for data processing.

3) Regression Model relates between a dependent variable and independent variables in making an equation and can use overlay operations in a GIS to combine variables needed for the analysis.

4) Process Model integrates existing knowledge in the real world and equations for quantifying the processes.

2.12 Related research

Table 4 Summaries of the literature review

Title	Objective	Study area	Method	Result
Sriariyawat, A. et al. (2013). Approach to estimate the flood damage in Sukhothai Province using flood simulation.	To proposes an approach for estimating flood damage cost in Sukhothai province in Yom river basin (2011)	Sukhothai Province in Yom river basin.	Simulation by using Rainfall-Runoff-Inundation (RRI) model. Estimate flood damage in 2011 based on the simulated flood area.	27% error in damage cost value is believed to be in a range acceptable for a rough estimation, which shows RRI simulation could be useful in assessing flood damage.
Samanta, S. et al. (2018). Flood susceptibility analysis through remote sensing, GIS and frequency ratio model.	To identify and map out flood risk zones in the Markham river basin. To create wall-To-wall data sets that are considered as input into the FR model. To categorize potential flood prone area, create a flood hazard map and also to carry out impact analysis which can be useful to local government administrators, researchers and planners for devising flood mitigation plans.	The Markham river basin, Papua New Guinea (PNG).	Frequency ratio model and validation using area under curve (AUC) and compare the method with Multi-criteria decision support approach (MCDA)	Flood susceptibility map and FR model produced better results compared to MCDA.

Table 4 (Cont.)

Title	Objective	Study area	Method	Result
Duangpiboon, S. et al. (2018). Flood susceptibility mapping using geographic information system and frequency ratio analysis in The Lang Suan Watershed, southern Thailand.	To produce a flood susceptibility map by using GIS and FR analysis.	The Lang Suan Watershed, southern Thailand.	Frequency ratio model and validation using area under curve (AUC)	Flood susceptibility map
Anucharn, T. et al. (2017). Flood Susceptibility Map Based on Frequency Ratio Method at Songkhla Lake Basin in the Southern of Thailand.	Geographic Information System (GIS) and factors that contribute to the flooding (altitude, slope, surface drainage, stream network density, and land use and land cover) were applied in order to create the flood susceptibility map	Songkhla Lake Basin in the Southern of Thailand	Frequency ratio model and validation using area under curve (AUC)	1. Flood susceptibility map. 2.The result of flood susceptibility with Land Use area and district area.

Table 4 (cont.)

Title	Objective	Study area	Method	Result
Lee, S. et al. (2018). Spatial assessment of urban flood susceptibility using data mining and geographic information system (GIS) tools.	To map the regional flood susceptibility of study area by using the data mining and GIS techniques.	Seoul metropolitan area in South Korea	Frequency ratio model and Logistic regression model. The validation using area under curve (AUC)	Flood susceptibility map from FR model and LR model
Cao, C. et al. (2016). Flash flood hazard susceptibility mapping using frequency ratio and statistical index methods in Coalmine Subsidence areas.	Producing flash flood hazard susceptibility maps (FFHSM) using frequency ratio (FR) and statistical index (SI) models.	The Xiqu Gully (XQG) of Beijing, China	Frequency ratio (FR) and statistical index (SI) models. This study also tested different classification schemes for the values for each conditional parameter.	Flash flood hazard susceptibility map using natural breaks method, Statistical Index-natural breaks (SI) and Frequency Ratio-manual classification. FR modeling using natural breaks was more appropriate for generating FFHSM.

Table 4 (Cont.)

Title	Objective	Study area	Method	Result
Hadi L. A. et al. (2017). GIS Based Multi-Criteria Decision Making for Flood Vulnerability Index Assessment.	To explore the potential integration between GIS and MCDM to undertake flood vulnerability index based on previous studies and expert opinions, the flood vulnerability components were defined.	Kedah, Malaysia.	Rank sum and AHP methods.	Flood Vulnerability Index maps using Rank Sum and AHP.
Behanzin I.D. et al. (2015). GIS-Based Mapping of Flood Vulnerability and Risk in the Bénin Niger River Valley.	To contribute to the existing body of knowledge by applying GIS-based method to assess the flood vulnerability and risk profile.	Benin Niger River Valley.	1. Modify flood hazard map already existing. 2. The overall vulnerability index for flood vulnerability assessment. 3. Risk map assessed through the formula.	1. Flood hazard map. 2. Flood Vulnerability map. 3. Flood risk map.

Table 4 (Cont.)

Title	Objective	Study area	Method	Result
Rimba, B, A. et al 2017). Physical Flood Vulnerability Mapping Applying Geospatial Techniques in Okazaki City, Aichi prefecture, Japan.	Integrated RS,GIS and AHP to determine the physical flood vulnerable area	The middle part of Aichi prefecture japan	AHP Field Survey Flood inundation Validation: POD, POFD, CSI, Bias, AUC and ROC	1.Flood vulnerable area 2.Bulding in area vulnerable to flooding
Dandapat, K. and Panda, G. K. (2017). Flood Vulnerability analysis and risk assessment using analytical hierarchy process.	To develop an approach for identifying, categorizing and quantifying elements at risk and their vulnerabilities to flood. Analysis the people's vulnerability and risk in the flood plain area due to flood and coping strategies devoted by them	Paschim Medinipur, in the south part of West Bengal.	AHP method for vulnerability assessment (physical parameters, social parameters, and capacity) and using composite vulnerability index and Risk assessment.	Flood vulnerability map in each parameter and flood risk map.

Table 4 (Cont.)

Title	Objective	Study area	Method	Result
Vishwanath, V. H. et al. (2018). Flood Hazard, Vulnerability and Risk Assessments for Uttarakhand State in India.	To investigation of a variety of topographical and hydrological factors responsible for flash flood events and applied to a geoprocessing framework using MCA.	Uttarakhand is a state in the Northern part of India	AHP method and Multi-criteria analysis for flood risk analysis.	Flood hazard, vulnerability, and risk map.
Muhadi A. N., (2015). Flood Damage Assessment In Agricultural Area In Selangor River Basin	Creating a flood damage map, Geographical Information System (GIS) was combined with the flood model to provide an ideal tool for the analysis of the flood damage and the effect of mitigation to flood damage.	SELANGOR RIVER BASIN	Simulations using various return periods were carried out to determine the flood extents and flood depths, and overlay with land use.	Flood Damage Map in each period, Estimation of Direct Flood Losses in Oil Palm Plantation, Estimation of Direct Flood Losses in Fruits and Vegetable Area both before and after mitigation.

CHAPTER III
RESEARCH METHODOLOGY

This chapter presents a description of the research processes. It consists of the study area, data collection, and the relevant factor in this research, sampling, and sample size for the questionnaire survey. In addition, the process of conducting flood hazard maps, flood vulnerability maps, and flood risk maps using the FR and AHP method and flood damage assessment were also described in details.

3.1 Study Area

The study area is Sukhothai Province is located in the Yom River basin and one of Thailand's upper central or lower Northern Provinces. It consists of nine districts (or Amphoe), namely Mueang Sukhothai, Ban Dan Lan Hoi, Khiri Mat, Kong Krailat, Si Satchanalai, Si Samrong, Sawankhalok, Si Nakhon, and Thung Saliam Districts as shown in **Figure 8**. Neighboring Provinces are Phrae, Uttaradit, Phitsanulok, Kamphaeng Phet, Tak, and Lampang. The total area is 6,596.1 km^2 (Wikipedia, 2019). In 2018, the population was 597,257 people (DepartmentofProvincialAdministration, 2019). According to SRTM DEM, the lowest elevation is 20 meters above mean sea level (MSL). The highest location is 1,233 meters above MSL.

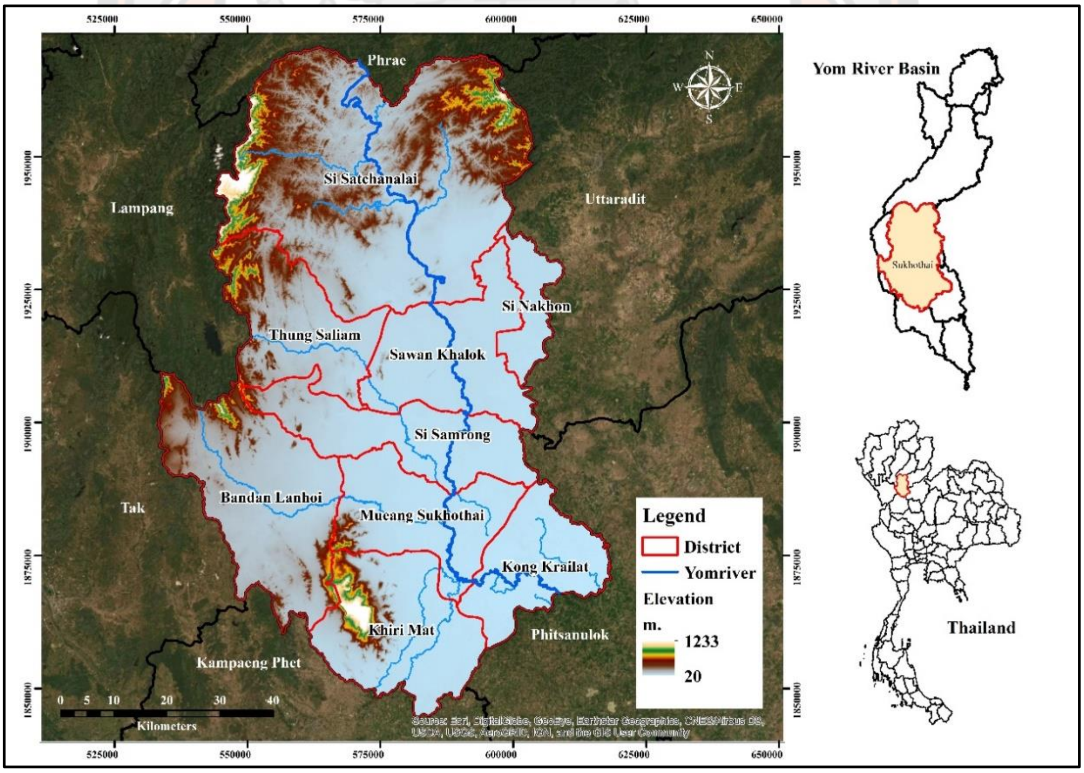


Figure 8 Map of Sukhothai Province

The topography of Sukhothai Province has mostly featured the basin plains in the north, with highlands and mountains continuing to the west, central plains, and southern high lands. Rivers flow from the north to the south through Sri Satchanalai, Sawankhalok, Sri Samrong, Mueang Sukhothai, and Kong Krailat. The highest Luang hill is located about 1,185 meters above MSL. The Yom River is an essential river for agricultural subsistence. The feature of the Yom River has a high slope especially in the river upstream. Therefore, it has problems in the rainy season, has more water than needed, and flows to the south rapidly, causing flooding in the basin plain. On the other hand, there is less water during the summer season, causing a lack of water for agricultural subsistence (SukhothaiProvincialOffice, 2018).

The general climate of Sukhothai Province is influenced by the southwest monsoons in the rainy season, the northeast monsoons in the winter season, and the summer season is the period of the change in monsoons from northeast to southwest. It has three seasons; the summer season (February-May), the rainy season (May-October), and the cold season (October-February). The average temperature of the Sukhothai province is 27.6 degrees Celsius. The average highest and the lowest temperature are 37.7 and 18.5 degrees Celsius, respectively. April is the hottest month, whereas January is known to be the coldest as shown in **Figure 10**. The annual average rainfall is 1,144.95 milliliters. The highest rainfall occurs during September at around 267.9 milliliters, and the least rainfall is in November at around 5.4 milliliters in **Figure 9** (LDD, 2015).

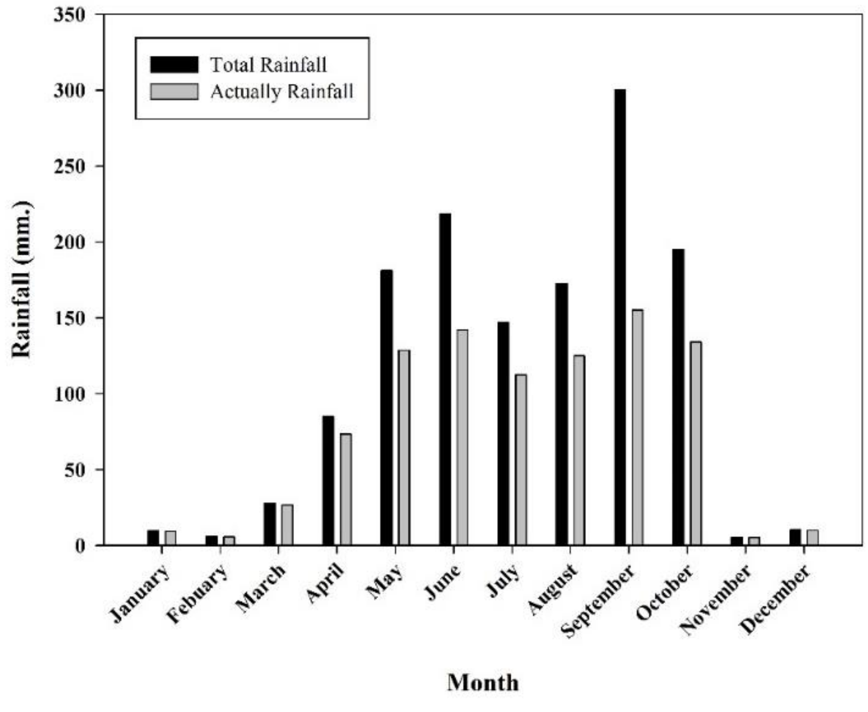


Figure 9 Monthly Rainfall of Sukhothai Province (1983-2013)

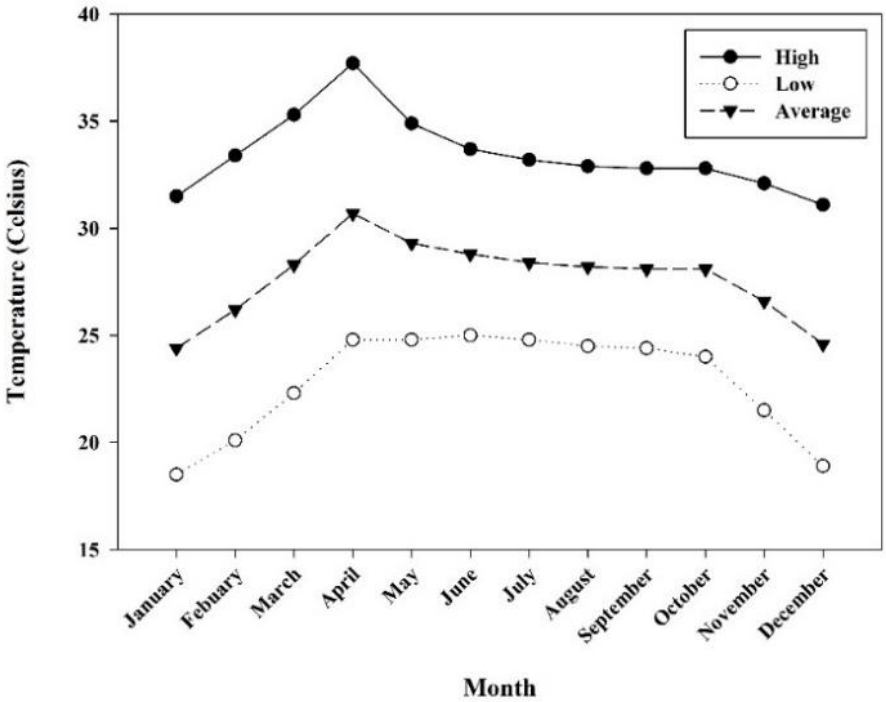


Figure 10 Monthly Temperature of Sukhothai Province (1983-2013)

3.2 Data Collection

This research collected both primary and secondary data as followed:

3.2.1 Primary data

The primary data was collected by questionnaire survey in the highest-risk flood area at Sukhothai Province. The questionnaire was used to collect general information, flood experienced, residential and agricultural damage, and the suggestion and comment of the respondent.

3.2.2 Secondary data

The secondary data acquired from different sources and generated from the GIS technique, as presented in **Table 5**. To generate flood hazard map, flood vulnerability map, and flood risk map in Sukhothai Province.

Table 5 A list of data requirement

No.	Data	Year	Data Sources	Descriptions
Flood hazard factors				
1	Rainfall	1988-2017	TMD	Average annual rainfall 30 years.
2	Elevation	2000	USGS website	Resolution 30 x 30 meters
3	Slope	2000	USGS website	Generated from SRTM DEM.

Table 5 (Cont.)

No.	Data	Year	Data Sources	Descriptions
4	Land Use/Land Cover	2016	LDD	Shape file
5	Soil Drainage	2016	LDD	Shape file
6	Road Density	2020	https://download.geofabrik.de/asia/thailand.html	Shape file
7	Drainage Density	2000	USGS website	Generated from SRTM DEM.
8	Flood area		GISTDA	Raster
Flood Vulnerability Analysis.				
9	Population density	2010	NSO Thailand	Table
10	Age	2010	NSO Thailand	Table
11	Gender	2010	NSO Thailand	Table
12	Poverty data	2010	NSO Thailand	Table
13	Income data	2010	NSO Thailand	Table
Questionnaire and field survey.				

3.3 Methodology

This study used the FR, AHP, and Flood Vulnerability Index (FVI) for generated a flood hazard map, flood vulnerability map, flood risk map, and collected questionnaires for a flood damage assessment at Sukhothai Province. **Figure 11** shows the research methodology of this study.

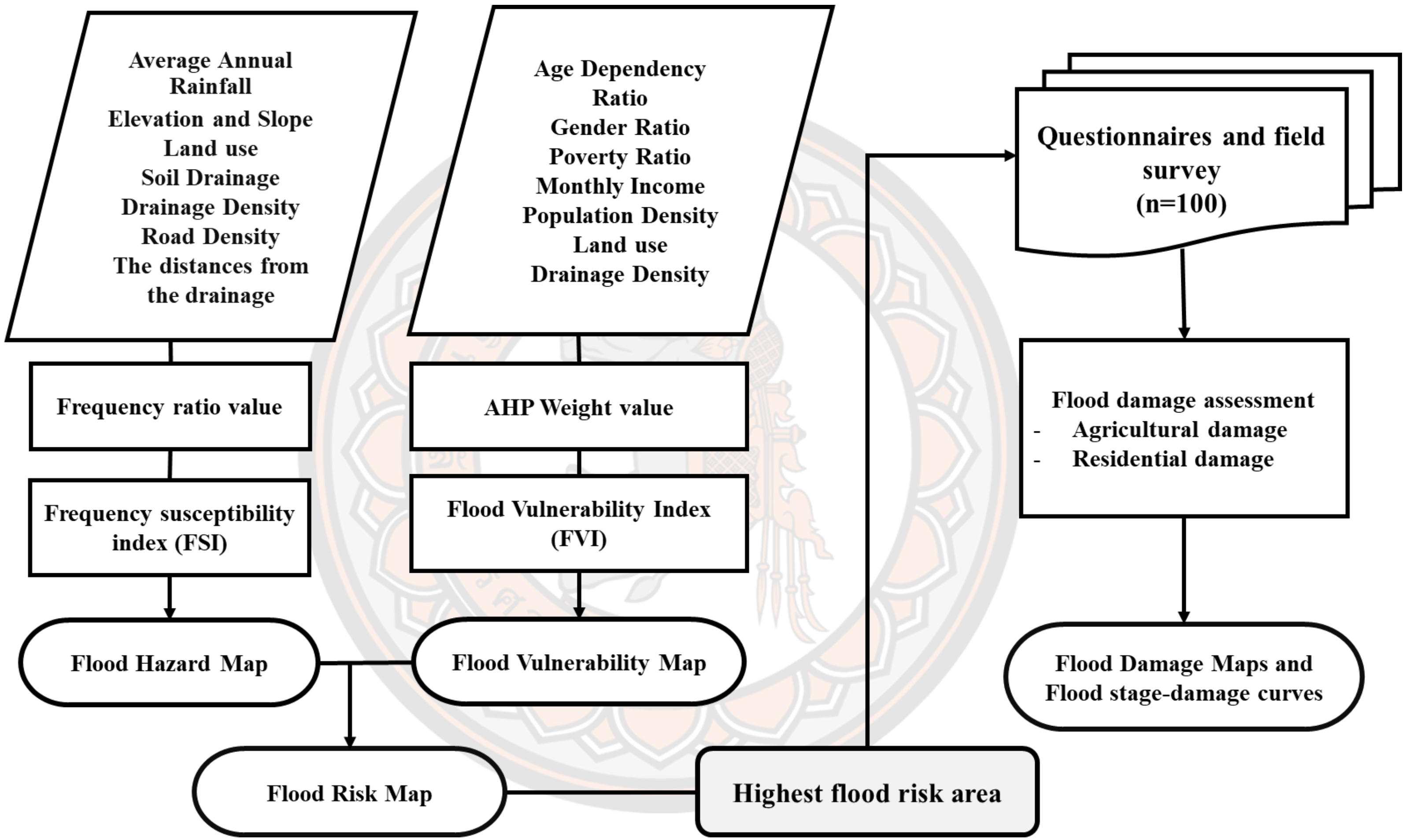


Figure 11 The Research Methodology Framework

3.3.1 Flood hazard analysis

The GIS technique was used for flood hazard analysis. It consists of eight factors as follows; flood area in 2004-2018 from Geo-Informatics and Space Technology Development Agency (GISTDA), average annual rainfall data (1988-2017) obtained from Thai Meteorological Department (TMD), elevation and slope derived from SRTM DEM, land use and soil drainage obtained from Land Development Department (LDD), drainage density, road density, and the distance from the drainage. Each conditioning factor was transformed into a grid in GIS.

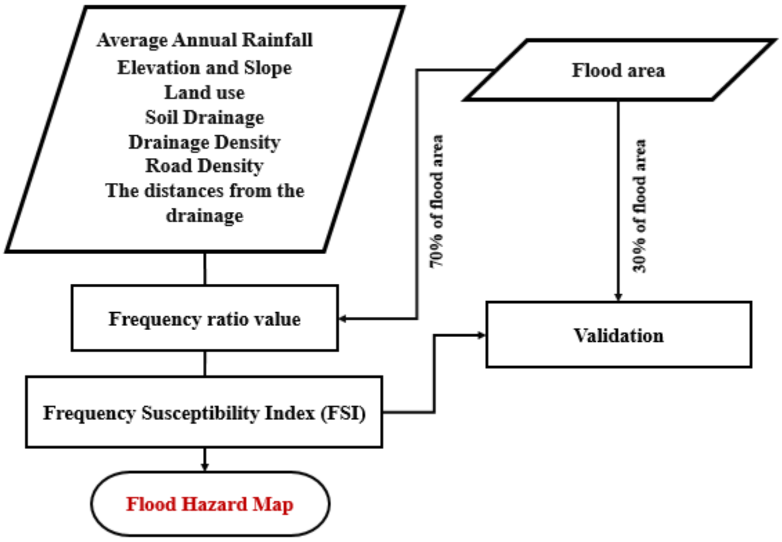


Figure 12 Methodology of flood hazard analysis

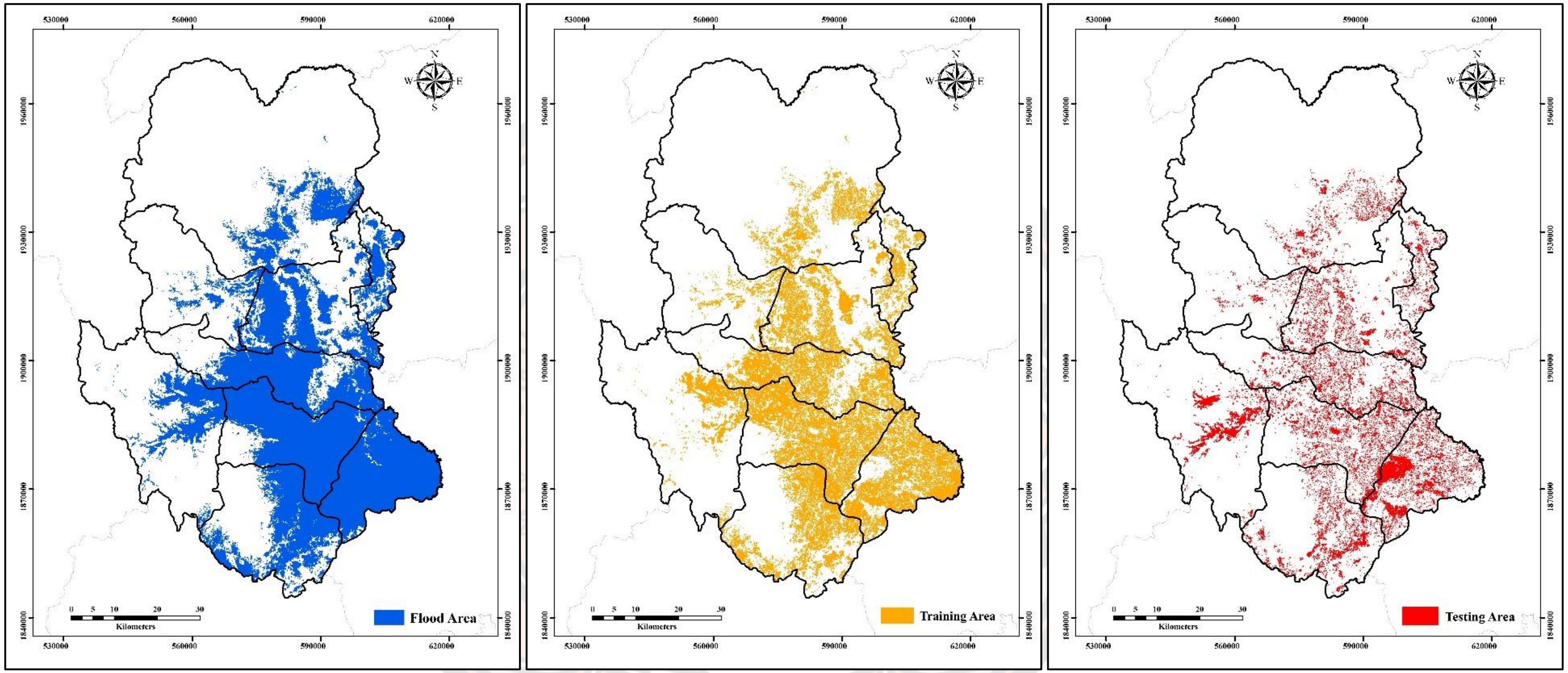
Flood hazard conditioning factors:

1. Flood inventory area

A flood inventory area shows the spatial distribution of flood hazards in the study area and used as a based map for producing flood hazard maps (Cao et al., 2016). Flood inventory area derived from GISTDA in 2004-2018. It has divided into two parts; 70 percent of all flood areas were used as training parts to generate flood hazard maps, and the remaining 30 percent as testing part to validate by the Area Under Curve (AUC). Subset feature in the Geo-statistical analyst tool was used to random the area. See **Figure 13** shows the flood area, training area, and testing area, respectively.

2. Average annual rainfall (mm)

Average annual rainfall data for 30 years obtained from the TMD. This study contains 19 meteorological stations (12 stations in Sukhothai Province and 7 stations in the nearby Province). The Inverse Distance Weighted (IDW) interpolation method was calculated. The rainfall range was divided into five classes by Natural Breaks (Jenks) classification method.



(a) (b) (c)

Figure 13 a) Flood area in 2004-2018 from the GISTDA, (b) Training area, and (c) Testing area.

3. Elevation (m)

The elevation is the essential factor in controlling floods in a given area. Floodwaters flow from higher elevations to lower elevations, and flat lowland areas may flood faster than the higher elevation (Botzen, Aerts, & van den Bergh, 2012; Das, 2019; Mojaddadi, Pradhan, Nampak, Ahmad, & Ghazali, 2017; Youssef, Pradhan, & Hassan, 2010). The elevation was prepared from SRTM DEM with 30x30 meters resolution. It was classified into five classes by Natural Breaks (Jenks) classification method.

4. Slope (degree)

The slope influences the amount of surface runoff and infiltration. Flat areas more easily accumulate water, and by the increase in slope degree, the risk of flooding would be less (Cao et al., 2016; Khosravi, Nohani, Maroufinia, & Pourghasemi, 2016). The slope generated from SRTM DEM by Slope tool in GIS software. It was classified into five classes by Natural Breaks (Jenks) classification method.

5. Land use

Land use changes; causeing a risk of flooding, for instance good forested area is less likely to experience a flood due to water infiltration (Cao et al., 2016; Duangpiboon et al., 2018). Land use was derived from LDD. It was classified into five classes following department namely Agriculture land (A), Forestland (F), Urban land (U), Water land (W), Miscellaneous land (M).

6. Soil drainage

Soil drainage is very important factors as they control the quantity of water infiltrate into the ground. The decrease of soil drainage capacity will give the chance of increasing flood hazards in the areas (Ouma & Tateishi, 2014). Soil with well drainage will help reduce flooding. The soil drainage derived from LDD. It was classified into four classes as adopted department namely No data, poorly to somewhat poorly drained, well to moderately well drained, and very well drained.

7. Drainage density

The area has more drainage density helps to drain the water effectively (Anucharn & Iamchuen, 2017; Duangpiboon et al., 2018). The drainage was extracted from SRTM DEM. It is used hydrology tools in ArcGIS software. Drainage density was calculated by equation 3.1. It was classified into five classes by Natural Breaks (Jenks) classification method.

$$\text{Drainage density} = \frac{\text{Length (km)}}{\text{Area (km}^2\text{)}} \qquad \text{Eq. (3.1)}$$

8. Road density

The area has more road density will hinder the drainage and lead to flooding. Road density was calculated by equation 3.1 as well. It was classified into five classes by Natural Breaks (Jenks) classification method.

9. The distance from the drainage

The area is located near the drainage network, generally suffer flooding higher than areas far away as the nearby locations are within the flow path (Das, 2019; Mahmoud & Gan, 2018). Therefore, five concentric buffers were compiled using the buffer tool in ArcGIS, each of 1,000-meter width demarcated around each drainage to generate the map.

3.3.2 The FR method

The FR method is based on the relationship between flooding occurrence and each conditioning factor to exhibit the relationship between flood locations and the conditioning factors in the study area (Lee & Talib, 2005).

The FR, a ratio between the occurrence and absence of floods in each cell, was calculated for each factor's type that had been identified as significant concerning causing floods. An area ratio for each factor's type to the total area was calculated. Further, frequency ratios for each factor's type were calculated by dividing the flood occurrence ratio by the area ratio as equation 2.2

The frequency ratio is typically used as a guide to where further floods are probable to occur. If the ratio is greater than 1, the relationship between floods and the factor's type indicates a strong correlation. If the ratio is less than 1, the relationship between flood and each factor's type indicates a weak correlation.

Finally, the ratios calculated the flood susceptibility index as equation 2.3 to create flood hazard mapping.

3.3.3 The validation by the AUC

This research was validated the results in regard of success rate and prediction accuracy of the model. The success rate was calculated using training flood area and the prediction accuracy was calculated using testing flood area. The area under curve (AUC) was used to evaluate.

Finally, the flood hazard map produced from the FR model was validated using flood inventory area where the area under the curve method was used. Therefore, the success rate result was obtained using the training dataset, which used 70% of the flood inventory areas. The prediction accuracy was calculated using the testing dataset for the 30% that were not used in the training process. Therefore, AUC values close to 1 (or 100%) indicated that a model is accurate and reliable (Samanta et al., 2018; Youssef et al., 2015).

3.3.4 Flood vulnerability analysis

The AHP and FVI method were used for flood vulnerability analysis in the GIS technique. It contains seven factors: Population density, Age dependency ratio, Gender ratio, Poverty ratio, Monthly income. These factors were derived from National Statistical Office. Land use and Drainage density.

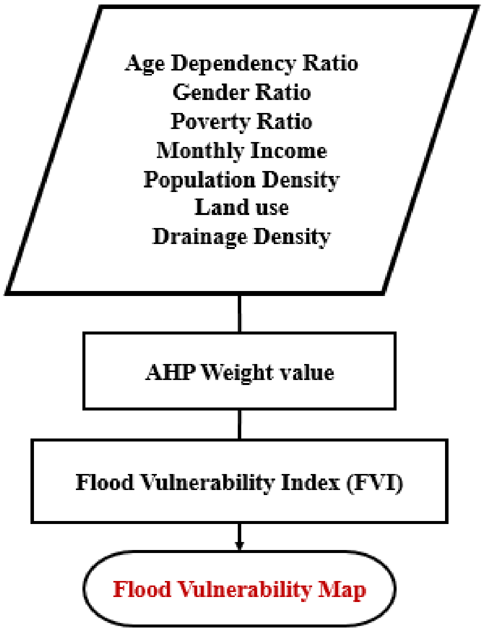


Figure 14 Methodology of flood vulnerability analysis

Factors influencing flood vulnerability:

1. Drainage density

The high density of drainage network will increase the risk to be flooded. Wetland areas are more prone to flooding (Peck, Karmakar, & Simonovic, 2007).

2. Land use

The areas with special natural features can be considered vulnerable because they are unique and possibly home to rare species of flora or fauna and decrease the magnitude and the impact of the flood hazard. Especially, cultivated area in the rural area (Dandapat & Panda, 2017; Kumpulainen, 2006).

3. Population density

The higher vulnerability was higher density, while lower vulnerability was lower density (Balica, Douben, & Wright, 2009; Kumpulainen, 2006). The population density was calculated as in equation 3.2

$$\text{Population density} = \frac{\text{The number of people}}{\text{Area (km}^2\text{)}} \qquad \text{Eq. (3.2)}$$

4. Age dependency ratio

The young and the elderly are more vulnerable to natural hazards both because of their restricted mobility and difficulty with evacuation during emergencies and their financial dependence (Cutter, Emrich, Webb, & Morath, 2009; Fekete, 2010; Müller, Reiter, & Weiland, 2011). The age dependency ratio was calculated as in the following equation 3.3

$$\text{Age dependency ratio} = \frac{\text{Population age (0-14 years)+(65+years)}}{\text{Population age (15-64 years)}} \times 100 \quad \text{Eq. (3.3)}$$

5. Gender ratio

Women are generally described as more vulnerable to natural hazards than men because of their stronger, sector-specific jobs and lower wages (Fekete, 2010; Müller et al., 2011; UNDP, 2006). The gender ratio was calculated as in the following equation 3.4

$$\text{Gender ratio} = \frac{\text{Male Population}}{\text{Female Population}} \times 100 \quad \text{Eq. (3.4)}$$

Where; the ratio = 100, there is a perfect balance between the sexes, the ratio is < 100, there are more females than males, and the ratio is > 100, there are more males than females.

6. Poverty ratio

Affects people's ability to protect themselves and their assets, as well as their ability to live in areas having less exposure to risk. Poor people are the most severely affected by all natural disasters (UNDP, 2006).

7. Monthly income

Low income people lack financial resources to recover resource (Hebb & Mortsch, 2007).

3.3.5 The AHP method

This research determined that the values of the parameters relative to each other depended on the literature review. The weighting factor in AHP has to build a pair-wise comparison matrix with scores in **Table 6** shows 7 x 7 matrix of factor. Each factor was rated against every other factor by assigning a relative dominant value between 1 and 9 (as **Table 2**) to the intersecting cell. The diagonal elements of the matrix are always the number 1 and only need to fill up the upper triangular matrix.

Table 6 The pair-wise comparison matrix for each factor

Factors	1	2	3	4	5	6	7
1.Age dependency ratio	1	2	1/3	3	2	3	3
2.Gender ratio	1/2	1	1/3	2	2	3	3
3.Population density	3	3	1	5	3	5	3
4.Poverty ratio	1/3	1/2	1/5	1	2	2	2
5.Monthly Income	1/2	1/2	1/3	1/2	1	3	2
6.Dranaige density	1/3	1/3	1/5	1/2	1/3	1	1/3
7.Land use	1/3	1/3	1/3	1/2	1/2	3	1
Total	6.00	7.67	2.73	12.50	10.83	20.00	14.33

Table 7 Computation of the weights for each factor

Factors	1	2	3	4	5	6	7	Total	W
1.Age dependency ratio	0.17	0.26	0.12	0.24	0.18	0.15	0.21	1.33	0.190
2.Gender ratio	0.08	0.13	0.12	0.16	0.18	0.15	0.21	1.04	0.149
3.Population density	0.50	0.39	0.37	0.40	0.28	0.25	0.21	2.39	0.342
4.Poverty	0.06	0.07	0.07	0.08	0.18	0.10	0.14	0.70	0.100
5.Monthly Income	0.08	0.07	0.12	0.04	0.09	0.15	0.14	0.69	0.099
6.Dranaige density	0.06	0.04	0.07	0.04	0.03	0.05	0.02	0.32	0.045
7.Land use	0.06	0.04	0.12	0.04	0.05	0.15	0.07	0.53	0.075
Total	1	1	1	1	1	1	1		1

Table 8 Estimation of the consistency ratio for each factor

Factors	1	2	3	4	5	6	7	WSV	CV
1.Age dependency ratio	0.19	0.30	0.11	0.30	0.20	0.14	0.23	1.46	7.66
2.Gender ratio	0.10	0.15	0.11	0.20	0.20	0.14	0.23	1.12	7.52
3.Population density	0.57	0.45	0.34	0.50	0.30	0.23	0.23	2.61	7.62
4.Poverty ratio	0.06	0.07	0.07	0.10	0.20	0.09	0.15	0.74	7.47
5.Monthly Income	0.10	0.07	0.11	0.05	0.10	0.14	0.15	0.72	7.26
6.Dranaige density	0.06	0.05	0.07	0.05	0.03	0.05	0.03	0.33	7.40
7.Land use	0.06	0.05	0.11	0.05	0.05	0.14	0.08	0.54	7.14
Total	1.14	1.14	0.93	1.25	1.07	0.90	1.08		52.07

To check the consistency of the judgments in AHP, the consistency ratio is defined as CR. A Consistency Ratio (CR) of 0.10 or less is acceptable to continue the AHP analysis (Saaty, 2012). The consistency ratio (CR) is calculated using the equation, CR = CI/RI in which the Consistency Index (CI) was calculated using the following equations 3.5

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad \text{Eq. (3.5)}$$

Where λ_{max} is the maximum eigenvalue of the judgement matrix. n is number of factor. Therefore, the calculated value of CI was 0.073.

The value of RI was related to the dimension of the matrix and will be extracted from **Table 3**. Therefore, the value of RI was 1.32

Thus, the Consistency Index (CI) was 0.073, RI was 1.32 and calculated consistency ratio is 0.055, which is less than 0.10 and is acceptable.

3.3.6 Flood vulnerability index

A flood vulnerability index was calculated using equation as follow (L. A. Hadi et al., 2017).

$$FVI = \sum_{i=1}^{n} (R_i \times W_i) \qquad \text{Eq. (3.6)}$$

Where, R_i is the rating of the factor in each point, W_i is the weight of each factor and n is the number of the criteria. Finally, the FVI value that was applied for flood vulnerability mapping and classified by Natural Breaks (Jenks) into five classes are Very high vulnerability, High vulnerability, Moderate vulnerability, Low vulnerability, and Very low vulnerability.

3.3.7 Flood risk mapping

Flood risk is defined in this study area as a function of flood hazard and flood vulnerability by the overlapping areas of hazard and vulnerability (Apel et al., 2008). The following equation is used to generate a flood risk map.

$$\text{Flood risk} = \text{Hazard } x \text{ Vulnerability} \qquad \text{Eq. (3.7)}$$

Finally, the flood risk that was applied for flood risk mapping and classified by Natural Breaks (Jenks) into five classes are Very high, High, Moderate, Low, and Very low.

3.3.8 Flood damage assessment from the questionnaires survey

This research will focus on the damage of the agricultural (Paddy field) area that is the receptors of flooding other than the urban area, and the residential (House) area. The estimated flood damage to agricultural land and their product, and damage to the residential area will be calculated to generated map and damage curve.

Questionnaire Survey: The objective of the questionnaire is to study and to understand flood event and flood damage in the study area in both urban and rural area. The questionnaire divides into five sections as follows:

Section A is general information,
Section B is flood experienced/information,
Section C is residential property damage,
Section D is agricultural damage, and
Section E is the suggestions and comments.

Population: Population of the present research is the number of population in the high and very high-level in flood-risk area in Sukhothai province, Thailand.

Sampling group: According to Yamane (1967) provides a simplified formula to calculate sample sizes as equation as follow.

$$n = \frac{N}{1+N(e)^2} = \frac{127040}{1+127040(0.1)^2} \quad \text{Eq. (3.8)}$$

Where n is the sample size, N is the household number, and e is the level of precision. In this study, using Yamane (1967) formula of simple size with error 10% and with confidence coefficient of 90%.

CHAPTER IV
RESULTS AND DISCUSSION

This chapter presents data analysis results and discussion. It consists of flood hazard assessment, flood vulnerability assessment, and flood risk assessment and maps. It also presents the results of the flood damage assessment from the questionnaire in Sukhothai Province.

4.1 Spatial assessment of flood hazard based on the FR method

A flood hazard map was generated by the FR method in the GIS technique. It consists of relevant factors, namely historical flood area, average annual rainfall, elevation, slope degree, land use, soil drainage, drainage density, road density, and the distance from drainage. However, the high value of FR indicated an influence on a flood. On the other hand, the low value of FR indicated less influence (**Table 9**).

The average annual rainfall range was around 518.83 to 1,197.40 mm. The maximum rainfall amount was 14.76% of the study area, whereas the moderate rainfall amount was 39.98% of the area. It was almost covered the whole province—especially Si Satchanalai, Sawankhalok, Si Samrong, Mueang Sukhothai, and Ban Dan Lan Hoi Districts. By applying the FR method, it was found that the rainfall has the highest FR value of 0.31 in class of 518.83 – 776.95 mm. as shown in **Figure 15(a)**.

According to DEM, the elevation of Sukhothai Province was between less than 105.62 to 1,233 m. above MSL. The highest elevation was found in the north and west of the study area. Most floods occurred at the east, central, and south, covering 60.53% of the area, where the elevation was less than 105.62 m., where the FR has the highest values (0.42). However, the FR is equal to 0 at higher elevations, as shown in **Figure 15(b)**.

The slope degree ranges between less than 4.419 degrees and 66.295 degrees over the study area. The result showed that the FR value. The slope of fewer than 4.419 degrees was the highest value (0.366). About 68.93% of the study area was found flood occurrence due to the study area is almost flat in the central to south, as shown in **Figure 15(c)**.

In the study area as shown in **Figure 15(d)**, agriculture, forest, urban, water, and miscellaneous area are accounted for 59.90%, 31.38%, 5.23%, 2.63%, and 0.69% respectively. The agricultural area had the highest FR value (0.37), followed by water, urban, miscellaneous, and forest areas, with FR is equal to 0.39, 0.32, 0.27, and 0.01, respectively. Therefore, forest areas in the north of area are shown in the least likely floods.

The soil drainage factor consists of seven classes, namely no data, very well drained, well to moderately well drained, poorly to somewhat poorly drained, miscellaneous, water body, and urban area are accounted for 30.80%, 0.48%, 31.35%, 36.97%, 0.06%, 0.08%, and 0.28% of the study area, respectively. The poorly to somewhat poorly drained class has the highest FR value of 0.57, indicating probably flood occurrence at the central and south of the area as shown in **Figure 15(e)**.

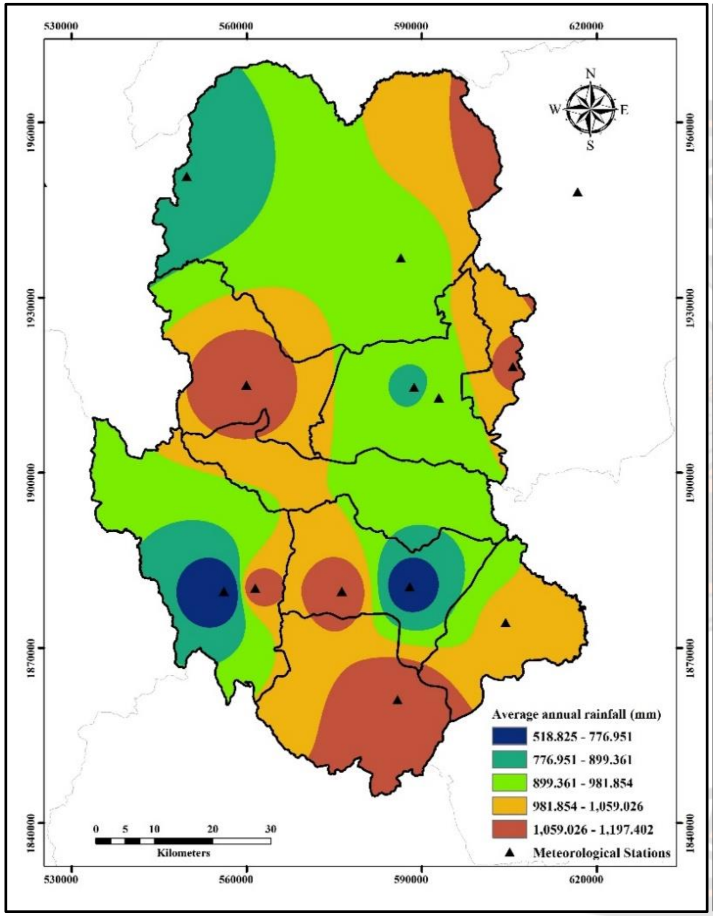
The drainage density factor, a class of 110.77-183.55 km/km^2 has the highest FR value (0.39), whereas the class of less than 36.35 km/km^2 has a lower FR value. The very low drainage density was covered the whole Province, about 84.72%, while moderate to very high drainage density was found along the river as shown in **Figure 15(f)**.

For the road density, a class of 2,108.85-3,754.78 km/km^2 had the highest FR value (0.43), whereas the class of less than 822.96 km/km^2 had the lower FR value (0.12). Nevertheless, moderate to very high density classes were the most affected by the flood. It was found in the eastern and southern parts of the area as shown in **Figure 15(g)**.

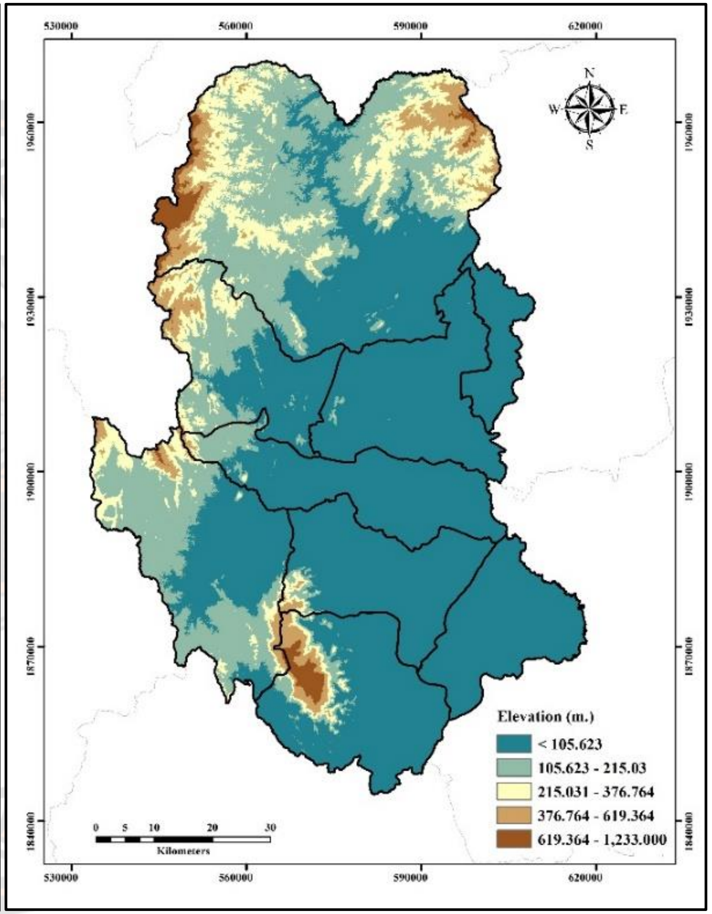
In terms of the distances from the drainages of less than 1,000 m. have the highest FR values of 0.35. It was found along with the river network over Sukhothai Province. In contrast, distances more than 5,000 m. have a lower FR value (0.2). Therefore, it will be the least affected by floods as shown in **Figure 15(h)**.

Based on the equation 2.3, the FSI value range from 65.97 to 2,405.83. The lower FSI values are associated with the lower flood susceptibility in the area. On the other hand, the higher values are associated with susceptibility to flooding occurrence. Thus, the FSI values were categorized into five classes: very low (65.97-488.06), low (488.06-1,194.60), moderate (1,194.60-1,524.94), high (1,524.94-2,259.01), and very high (2,259.01-2,405.83).

In **Figure 16** and **Table 10**, the areas of high and very high hazard classes were covered about 23.12% and 35.64% of the whole Province, respectively. These areas were identified at Si Samrong, Mueang Sukhothai, Kong Krailat, and Khiri Mat, in particular, where located in the central and south of the study area. Additionally, the areas with the lower elevations and flat slopes are more vulnerable to flooding, including agricultural land in a vulnerable area. People living in flood-prone areas should be aware of the dangers of flooding. Moderate hazard class was accounted for 2% of the total area. The area of very low and low hazard classes were about 29.30% and 9.94% where are located in high elevation and high slope degree area of Si Satchanalai, Thung Saliam, Ban Dan Lan Hoi, and Khiri Mat, in particular. Most of the very low and low hazard areas are forest and partially agricultural areas.

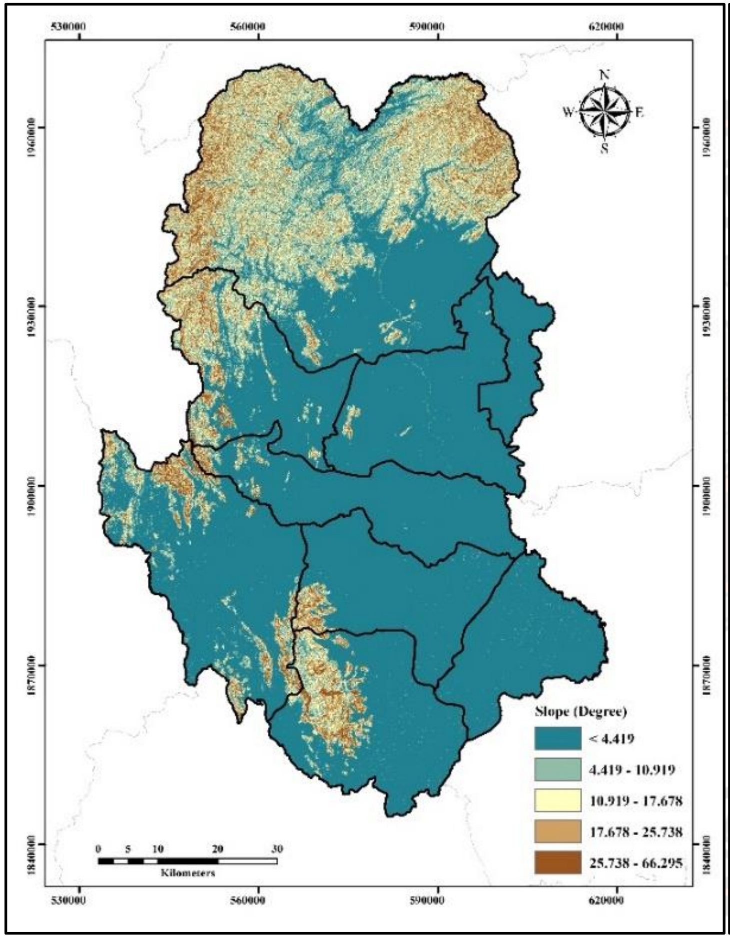


(a)



(b)

Figure 15 Factor influencing flood hazard (a) Average annual rainfall, (b) Elevation, (c) Slope degree, (d) Land use, (e) Soil drainage, (f) Drainage density, (g) Road density, (h) The distances from the drainages



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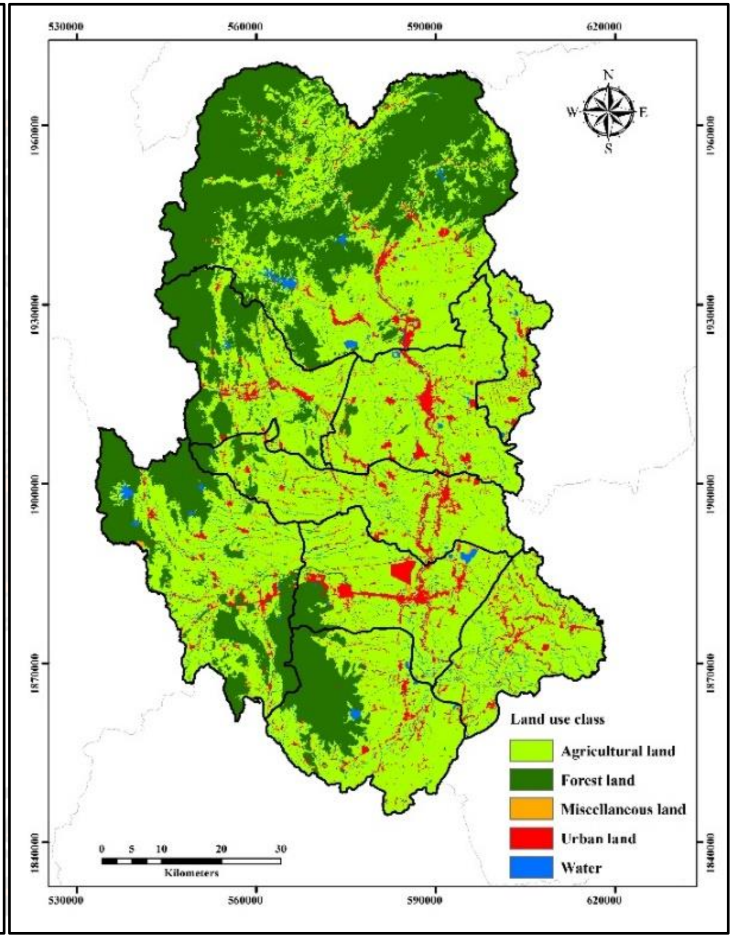
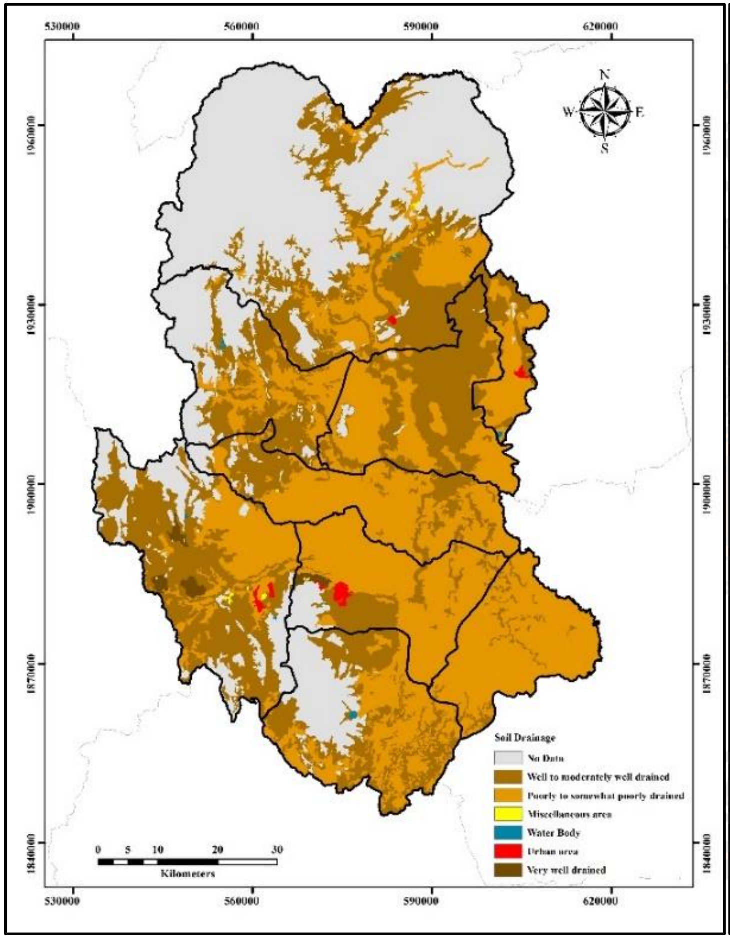
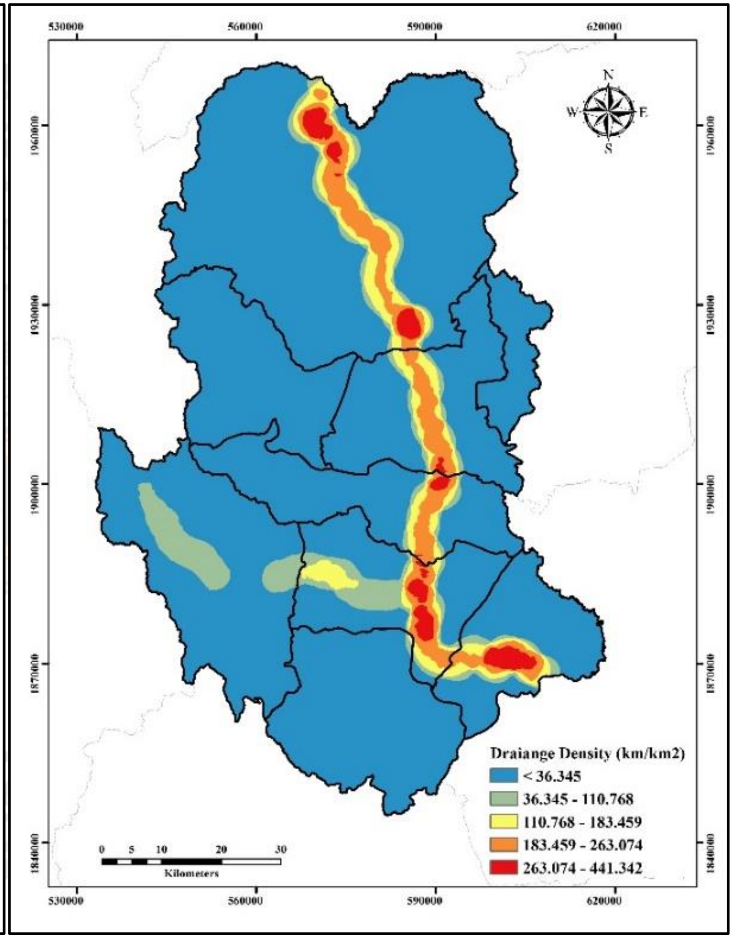


(d)

Figure 15 (Cont.)

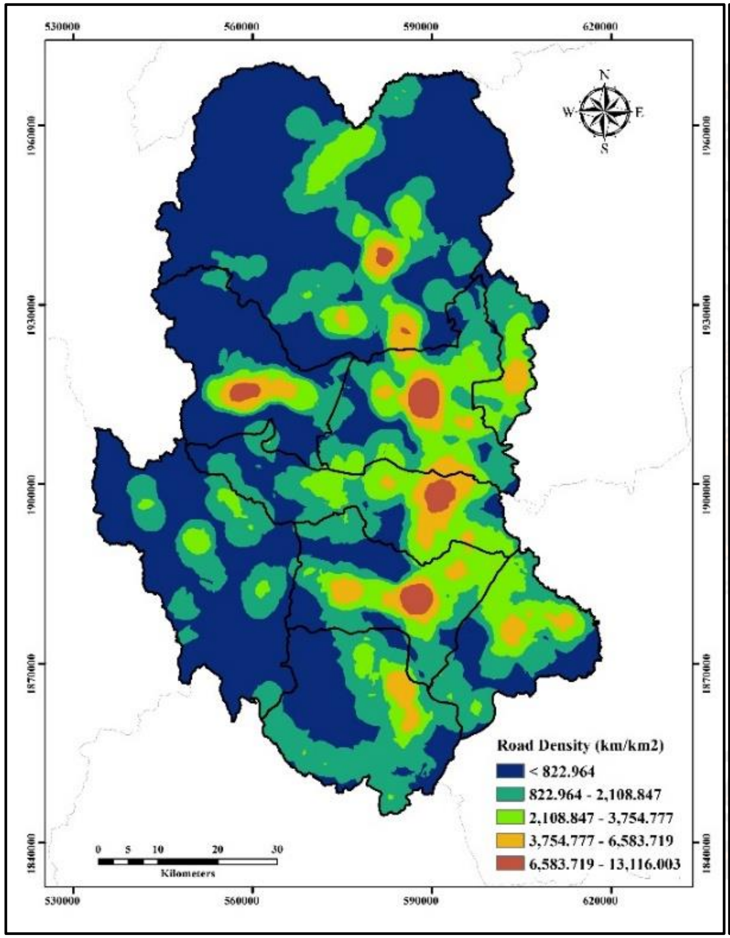


(e)

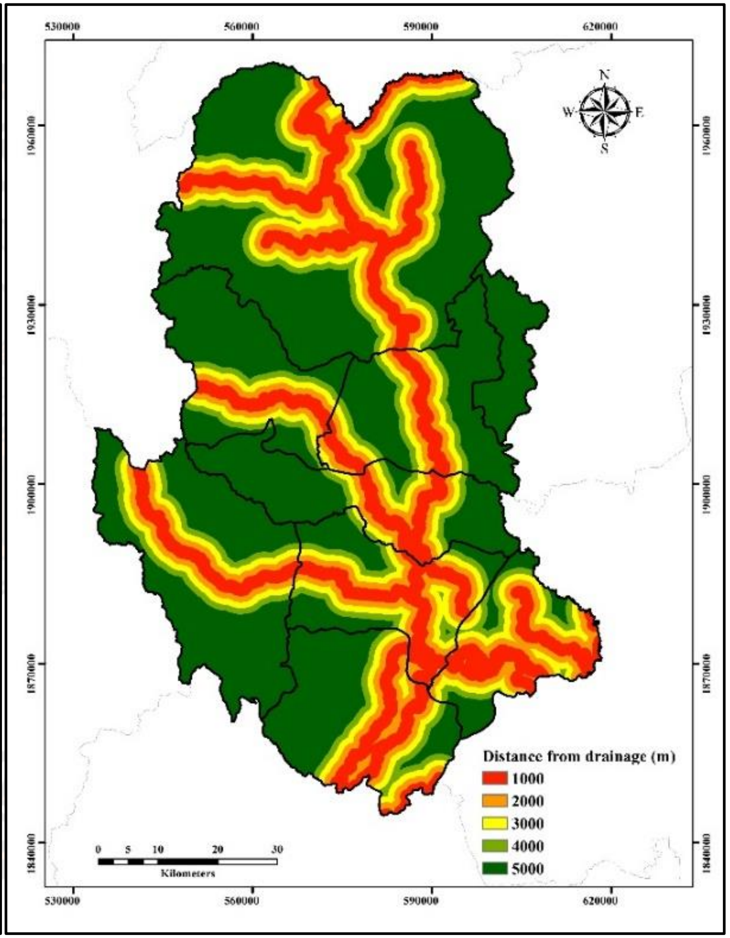


(f)

Figure 15 (Cont.)



(g)



(h)

Figure 15 (Cont.)

Table 9 Frequency ratio analysis of flood conditioning factors

Factors	Classes	Number of total pixels in this study		Number of flood occurrence pixels		FR value
		Pixels number	Percentage (%)	Pixels number	Percentage (%)	
Average annual rainfall (mm.)	518.83 - 776.95	182530	2.47	56736	3.00	0.31
	776.95 - 899.36	951679	12.85	139798	7.41	0.15
	899.36 - 981.85	2960604	39.98	759600	40.24	0.26
	981.85 - 1,059.03	2217474	29.95	650184	34.44	0.29
	1,059.03- 1,197.40	1092704	14.76	281484	14.91	0.26
Elevation (m.)	< 105.62	4481626	60.53	1874650	99.31	0.42
	105.62 - 215.03	1703525	23.01	12110	0.64	0.01
	215.03 - 376.76	754720	10.19	840	0.05	0.00
	376.76 - 619.36	344184	4.65	16	0.00	0.00
	619.36 - 1,233	119616	1.62	0	0.00	0.00
Slope (degree)	< 4.42	5103197	68.93	1868325	98.99	0.37
	4.42 - 10.92	819476	11.07	12589	0.67	0.02
	10.92 - 17.68	721237	9.74	3032	0.16	0.00
	17.68 - 25.78	542874	7.33	2635	0.140	0.01
	25.78 - 66.3	216887	2.93	1035	0.06	0.01
Land Use	Agricultural land	4435486	59.90	1654650	87.65	0.37
	Forest land	2323648	31.38	14222	0.75	0.01
	Miscellaneous land	64214	0.87	17266	0.92	0.27
	Urban land	387105	5.23	125279	6.64	0.32
	Water land	194538	2.63	76385	4.05	0.39
Soil Drainage	No data	2280462	30.80	14804	0.78	0.01
	Very well drained	35464	0.48	607	0.03	0.02
	Well to moderately well drained	2320392	31.34	323310	17.13	0.14
	Poorly to somewhat poorly drained	2737477	36.97	1545475	81.87	0.57
	Miscellaneous area	4202	0.06	636	0.03	0.15
	Water Body	6092	0.08	1242	0.07	0.20
	Urban area	20902	0.28	1728	0.09	0.08
Drainage Density (km/km^2)	< 36.35	6273127	84.72	1503529	79.64	0.24
	36.35 - 110.77	405410	5.48	127502	6.75	0.31
	110.77 - 183.46	280753	3.79	110105	5.83	0.39
	183.46 - 263.07	329759	4.45	101791	5.39	0.31
	263.07 - 441.34	115942	1.57	44875	2.38	0.39
Road Density (km/km^2)	< 822.96	3538697	47.79	410804	21.76	0.12
	822.96 - 2,108.85	2237577	30.22	783315	41.49	0.35
	2,108.85 - 3,754.78	1129826	15.26	485048	25.69	0.42
	3,754.78 - 6,583.72	392447	5.30	165533	8.77	0.42
	6,583.72 - 13,116.00	106444	1.44	43102	2.28	0.41

Table 9 (Cont.)

Factors	Classes	Number of total pixels in this study		Number of flood occurrence pixels		FR value
		Pixels number	Percentage (%)	Pixels number	Percentag e (%)	
The distance s from the drainag e (m.)	1000	1162542	15.70	408438	21.64	0.35
	2000	923228	12.47	307575	16.29	0.33
	3000	807338	10.90	236361	12.52	0.29
	4000	703222	9.50	184287	9.76	0.26
	>5000	3808661	51.43	751141	39.79	0.20

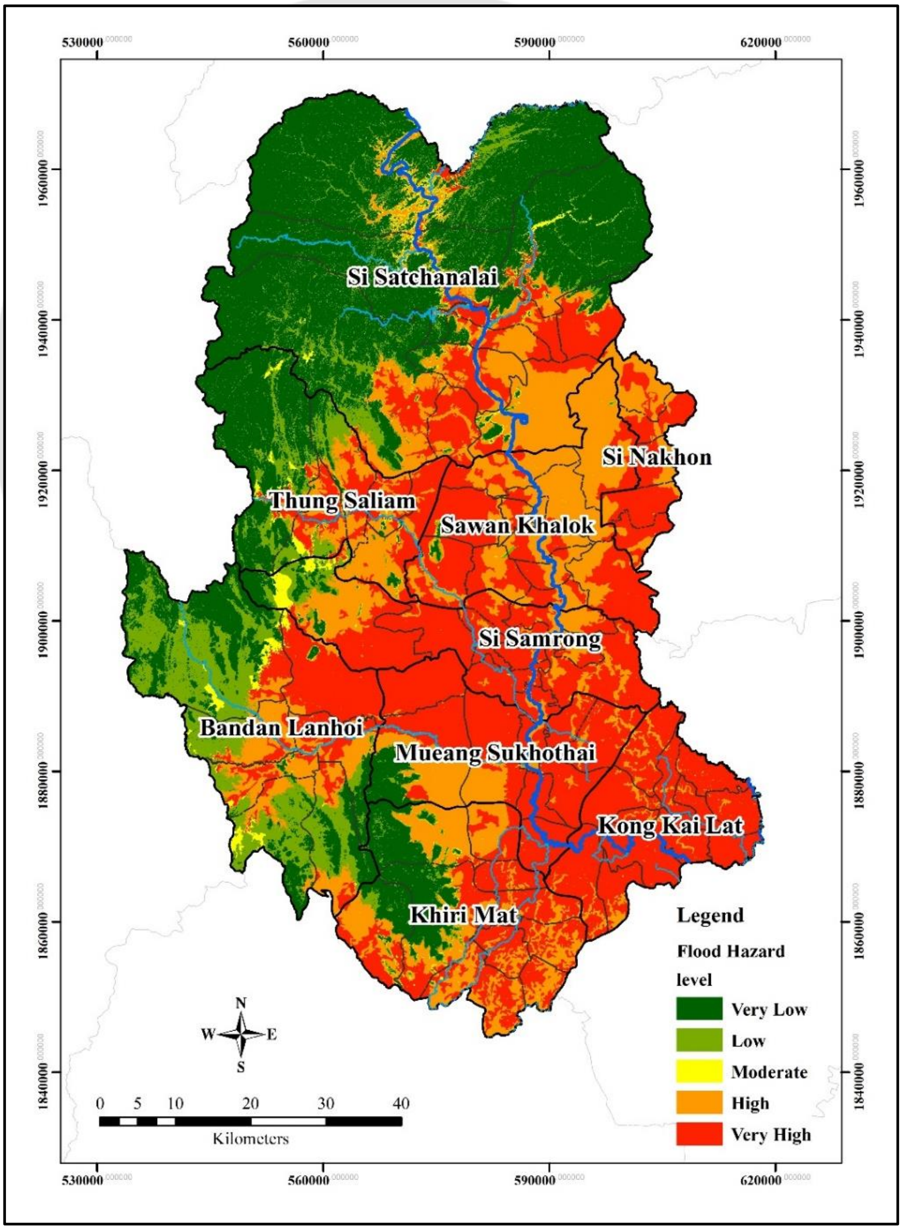


Figure 16 Flood hazard map in Sukhothai Province

Table 10 Flood hazard classification in Sukhothai Province

Flood hazard classes	FSI values	Area	
		km^2	%
Very low hazard	65.97 - 488.06	1952.48	29.30
Low hazard	488.06 - 1,194.60	662.36	9.94
Moderate hazard	1,194.60 - 1,524.94	132.94	2.00
High hazard	1,524.94 - 2,259.01	1540.69	23.12
Very high hazard	2,259.01 - 2,405.83	2374.83	35.64

4.2 Flood hazard validation

The AUC was used to validate the flood hazard map generated by the FR method to assess the reliability and efficiency of the flood hazard map. The success rate result was obtained by using the training dataset, which used 70% of the flood areas. The prediction accuracy was calculated using the testing dataset for the 30% that were not used in the training process. Therefore, AUC values close to 1 (or 100%) indicated that a model is accurate and reliable (Samanta et al., 2018; Youssef et al., 2015). In this study, the results of the success rate and the prediction rate curves have an AUC equal to 95.05% and 94.77%, respectively (**Figure 17**). Moreover, this result is in agreement with Anucharn's (2017) finding which showed the flood susceptibility map in the Songkhla lake basin at the southern of Thailand validation effort under the curve. It shows that the success rate was 88.12%, and the prediction rate was 86.27%, as well as Samanta's (2018) finding, which showed the success rate and prediction rate were calculated as 94% and 97%, which validates the FR model used in this flood susceptibility analysis in Papua New Guinea. Therefore, both the success and prediction rate curves, in this case, revealed the ability to predict flood hazards.

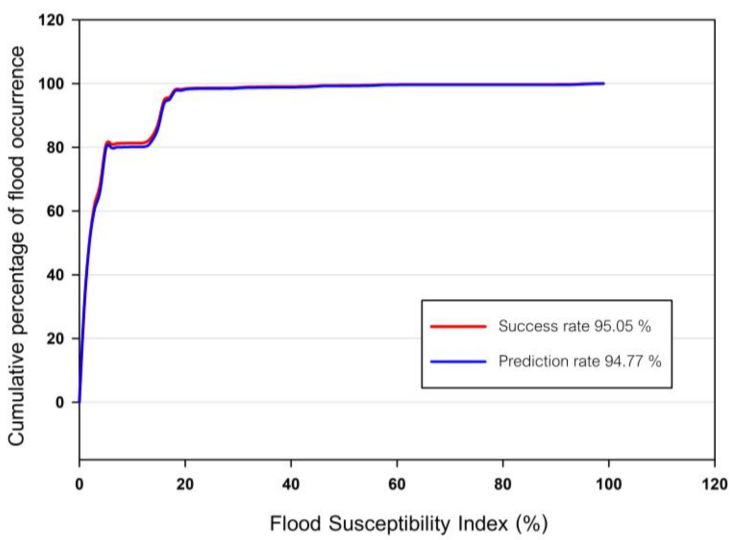


Figure 17 The AUC related to the validation of the flood hazard map

4.3 Spatial assessment of flood vulnerability based on AHP method

A flood vulnerability map was generated by the AHP method in the GIS technique. It consists of relevant factors, namely age, gender, population density, poverty ratio, monthly income, drainage density, and land use. However, the score of each factor was determined by previous research studies or literature. Therefore, the high weight value of each factor indicated a vulnerability to a flood. On the other hand, the low-weight value indicates less vulnerability as **Table 11**.

The age groups of 0–14 years old and above 60 years old are generally dependent populations highly vulnerable to floods due to lack of mobility and difficulty evacuating during emergencies (Dandapat & Panda, 2017). The Sub-District areas of Hat Siao (Si Satchanalai District), Mueang Sawan Khalok (Sawankhalok District), Ban Rai (Si Samrong District), Thani (Mueang Sukhothai District), Wang Takhro (Ban Dan Lan Hoi District), Ban Krang (Kong Krailat District), Si Khiri Mat, Sam Phuang, and Nong Krading (Khiri Mat District) were most vulnerable to age ratio as shown in **Figure 18(a)**.

The female population is highly vulnerable to flood hazards due to their less strong involvement than men, lower wages, and specific jobs (Behanzin, Thiel, Joerg, & Boko, 2015; Dandapat & Panda, 2017; Müller et al., 2011). There are four districts with a female population than males, namely, Si Nakhon, Sawankhalok, Si Samrong, and Thung Saliam (except Thai Chana Suek and Ban Mai Chai Mongkhon Sub-Districts) as shown in **Figure 18(b)**.

Population density is regarded as one of the most critical indicators in determining flood vulnerability. The higher density indicated the higher vulnerability (Dandapat & Panda, 2017; Müller et al., 2011). The population density results revealed that the highest population density range is 1,134.44-3,714.01 people/km^2. Thani Sub-District (Mueang Sukhothai District) has the most population density as shown in **Figure 18(c)**.

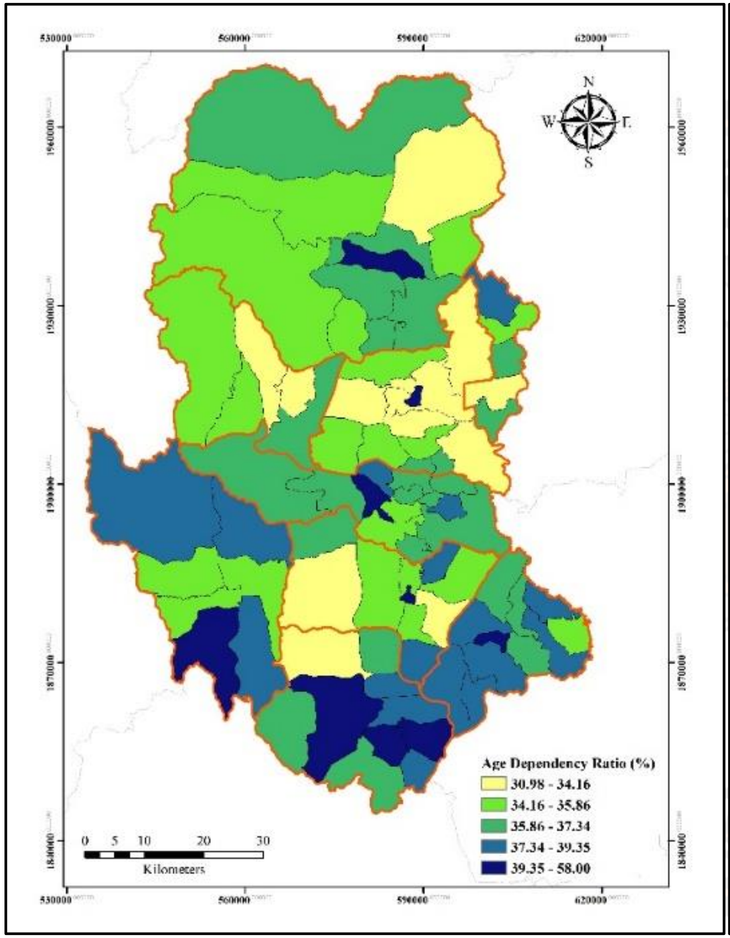
The poverty ratio and income level, Poverty affects the population's ability to protect themselves and assets and live in risk areas. The poor people are the most severely affected by floods. In addition, Low-income people lack financial resources to recover resources (Hebb & Mortsch, 2007; UNDP, 2006). The most poverty ratio was Ban Namphu Sub-District, and the lowest monthly income was Si Khiri Mat (Khiri Mat District) with 2,615 Baht per month as shown in **Figure 18(d and e)**.

Drainage is essential in controlling flood hazards as its densities denote the nature of the soil properties. The higher the density, the higher the catchment area is susceptible to erosion, resulting in sedimentation at the lower grounds. The drainage density of 263.07-441.34 km/km^2 was the most vulnerable to floods. Furthermore, agricultural, miscellaneous, and urban areas were highly vulnerable due to continuous land-use change and increased water runoff—these areas related to soil stability and infiltration (Ouma & Tateishi, 2014; Rimba et al., 2017) as shown in **Figure 18(f and g)**.

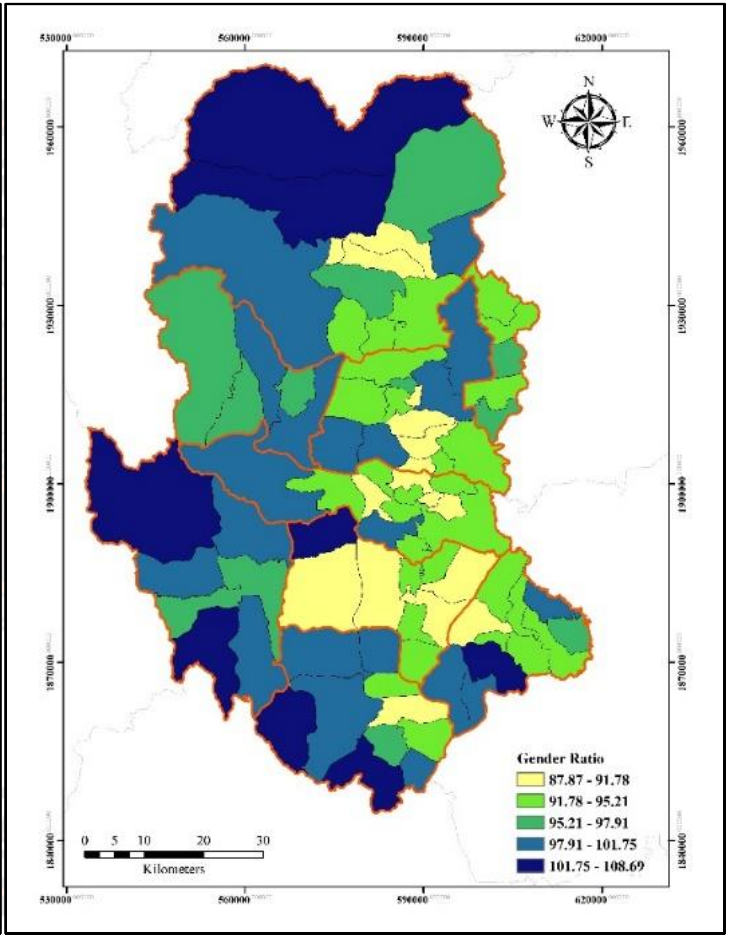
The results showed that population density is the most important factor influencing flood vulnerability as the weight of 0.34 followed by the age group (0.19), the gender ratio (0.15), the poverty ratio (0.10), the monthly income (0.01), land use (0.08), and drainage density (0.05).

Based on the equation 3.6, the FVI value range from 1.49 to 3.43. The lower FVI values are associated with lower flood vulnerability in the area. In contrast, higher values are associated with vulnerability to flooding occurrence. Thus, the FVI values were categorized into five classes: very low (1.49-2.20), low (2.20-2.49), moderate (2.49-2.75), high (2.75-3.02), and very high (3.02-3.43).

The results of the flood vulnerability are presented in **Figure 19** and **Table 12**. The very high and high vulnerability classes were covered 25.98% and 16.40% respectively, of the study area—these areas distributed over Sukhothai Province such as Tha Chanuan, Dong Duai Sub-Districts, and Kong Krailat District. The moderate class was covered 22.20% of the total area. The low and very low classes were covered 2.01% and 33.41% of the area. It was mostly found in the northern part of the Province such as Si Satchanalai District.

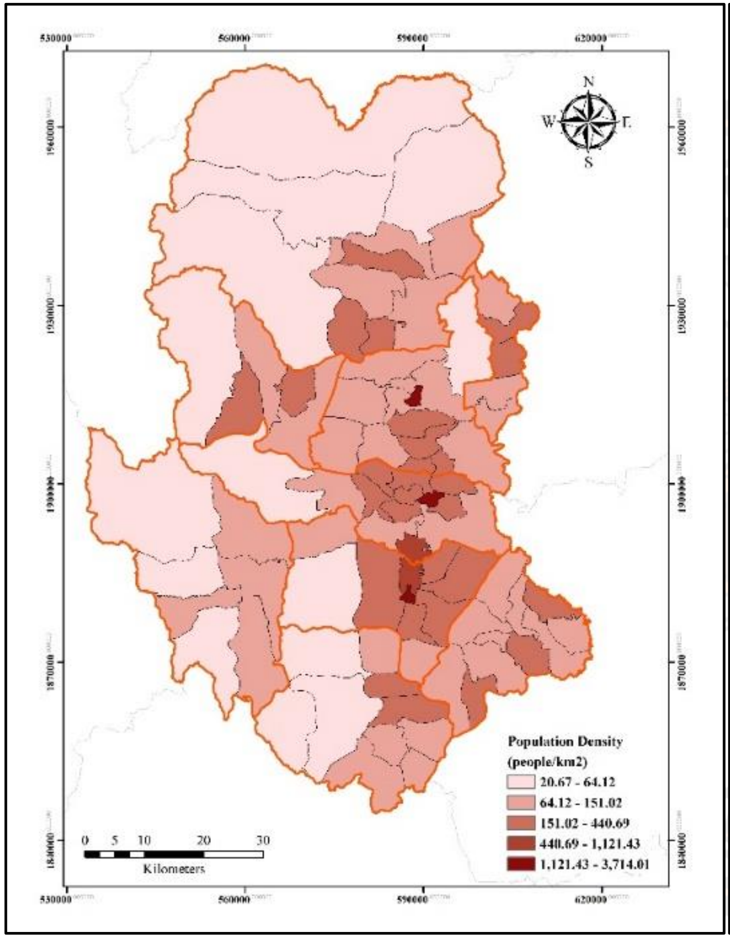


(a)



(b)

Figure 18 Factor influencing flood vulnerability (a) Age ratio, (b) Gender ratio, (c) Population density, (d) Poverty ratio, (e) Monthly income, (f) Drainage density, and (g) Land use



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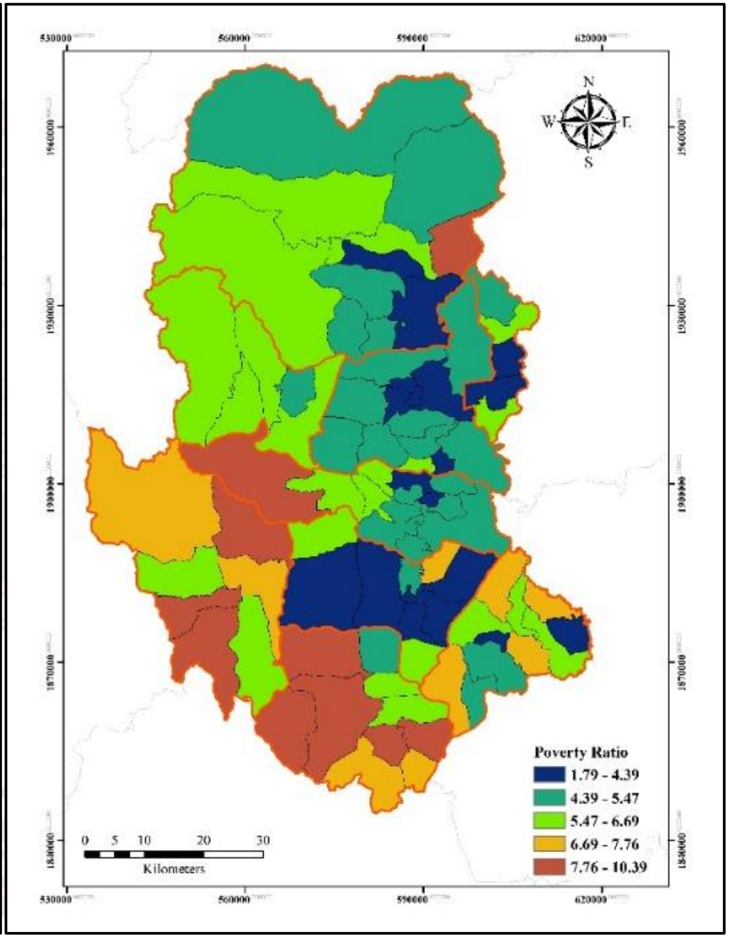
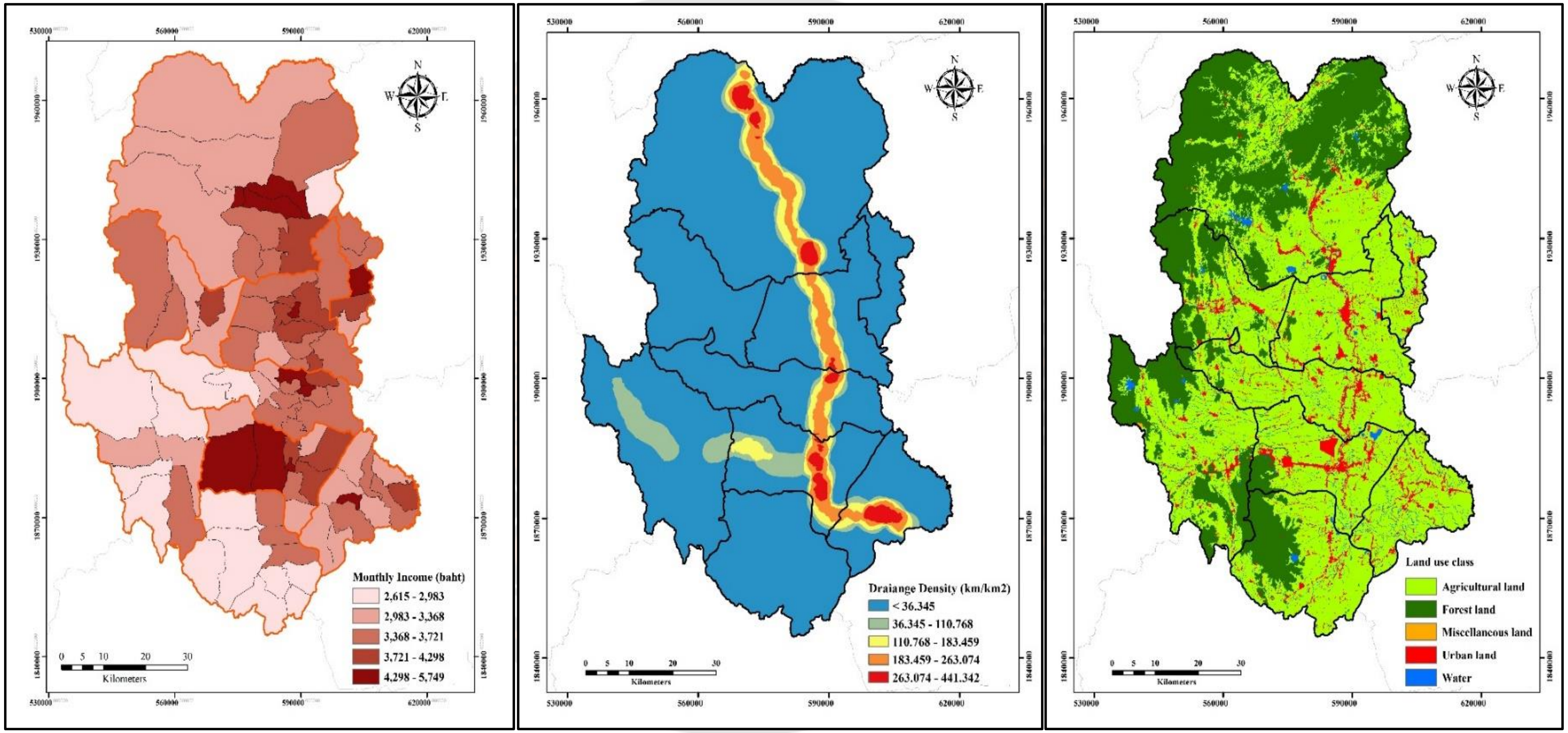


(d)

Figure 18 (Cont.)



(e) (f) (g)

Figure 18 (Cont.)

Table 11 Weighting and rating value of each factor

No.	Factor	Class	Weighting	Rating
1	Age dependency ratio	43.80 - 58.00	0.19	Very High (5)
		37.03 - 39.87		High (4)
		37.03 - 39.87		Moderate (3)
		34.30 - 37.03		Low (2)
		30.99 - 34.30		Very Low (1)
2	Gender ratio	87.87 - 91.83	0.15	Very High (5)
		91.83- 94.62		High (4)
		91.83- 94.62		Moderate (3)
		97.41 - 101.79		Low (2)
		101.79 - 108.69		Very Low (1)
3	Population density	1134.44 - 3714.01	0.34	Very High (5)
		443.23 - 1134.43		High (4)
		229.13 - 443.23		Moderate (3)
		117.74 - 229.13		Low (2)
		20.67 - 117.74		Very Low (1)
4	Poverty ratio	7.80 - 10.40	0.10	Very High (5)
		6.50 - 7.80		High (4)
		3.70 - 5.20		Moderate (3)
		3.70 - 5.20		Low (2)
		1.80 - 3.70		Very Low (1)
5	Monthly Income	2615 - 3153	0.01	Very High (5)
		3153 - 3543		High (4)
		3543 - 3979		Moderate (3)
		3979 - 4704		Low (2)
		4704 - 5749		Very Low (1)
6	Drainage density	263.07 - 441.34	0.045	Very High (5)
		183.46 - 263.07		High (4)
		110.77 - 183.46		Moderate (3)
		36.36 - 110.77		Low (2)
		< 36.35		Very Low (1)
7	Land use	Agriculture land	0.08	Very High (5)
		Miscellaneous land		High (4)
		Urban land		Moderate (3)
		Water land		Low (2)
		Forest land		Very Low (1)

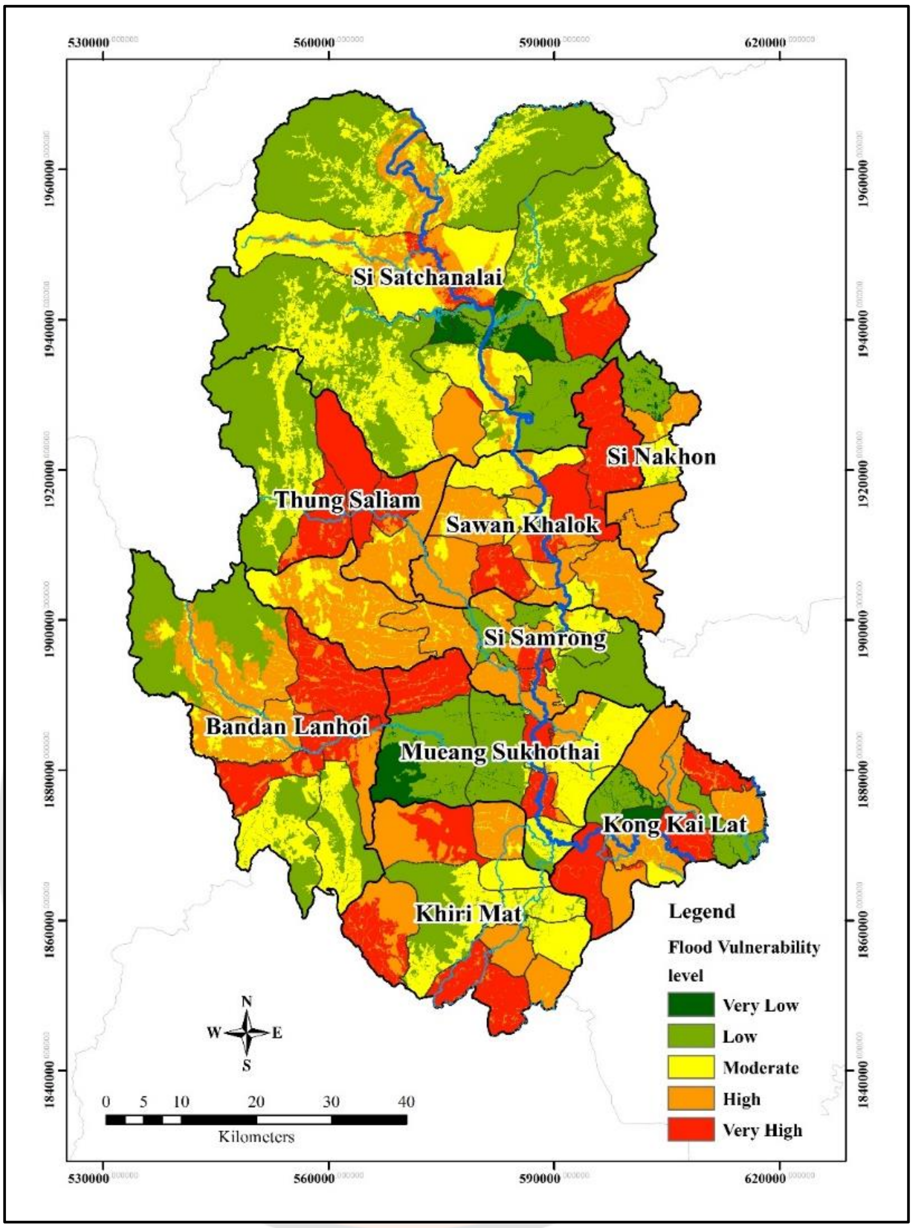


Figure 19 Flood vulnerability map in Sukhothai Province

Table 12 Flood vulnerability classification in Sukhothai Province

Flood vulnerability classes	FVI values	Area	
		km^2	%
Very low vulnerability	1.49 - 2.20	134.10	2.01
Low vulnerability	2.20 - 2.49	2226.30	33.41
Moderate vulnerability	2.49 - 2.75	1479.64	22.20
High vulnerability	2.75 - 3.02	1731.71	25.98
Very high vulnerability	3.02 - 3.43	1092.75	16.40

4.4 Spatial assessment of flood risk

The flood risk map essentially was integrated from the hazard map and vulnerability map prepared according to the FR and AHP methods. The risk of flooding resulting map was divided into five classes of risk, ranging from very low to very high. **Figure 20** and **Table 13** show that the very low, low, and moderate classes cover 26.15%, 11.07%, and 21% of the total area, respectively. The high and very high categories were estimated at 13.56% and 28.22% of the total area.

Accordingly, the high and very high-risk classes were observed at areas along the main river and tributaries, including flat and less slope. Furthermore, these areas were agricultural and urban areas with high population density. The map was identified at Thung Saliam District (i.e., Khao Kaeo Si Sombun Sub-District), Sawan Khalok District (i.e., Khlong Yang, Nai Mueang Sub-Districts), Mueang Sukhothai District (i.e., Pak Khwae, Yang Sai Sub-Districts), Kong Krilat District (i.e., Tha Chanuan, Dong Duai, Kok Raet Sub-Districts). The low and very low risks were covered in the north and west parts of the province. These areas were at a high slope and elevation with a smaller population and characterized by forest and somewhat agricultural areas. The map was noticed in Sri Satchanalai District (i.e., Mae Sin, Ban Kaeng, and Ban Tuek Sub-Districts).

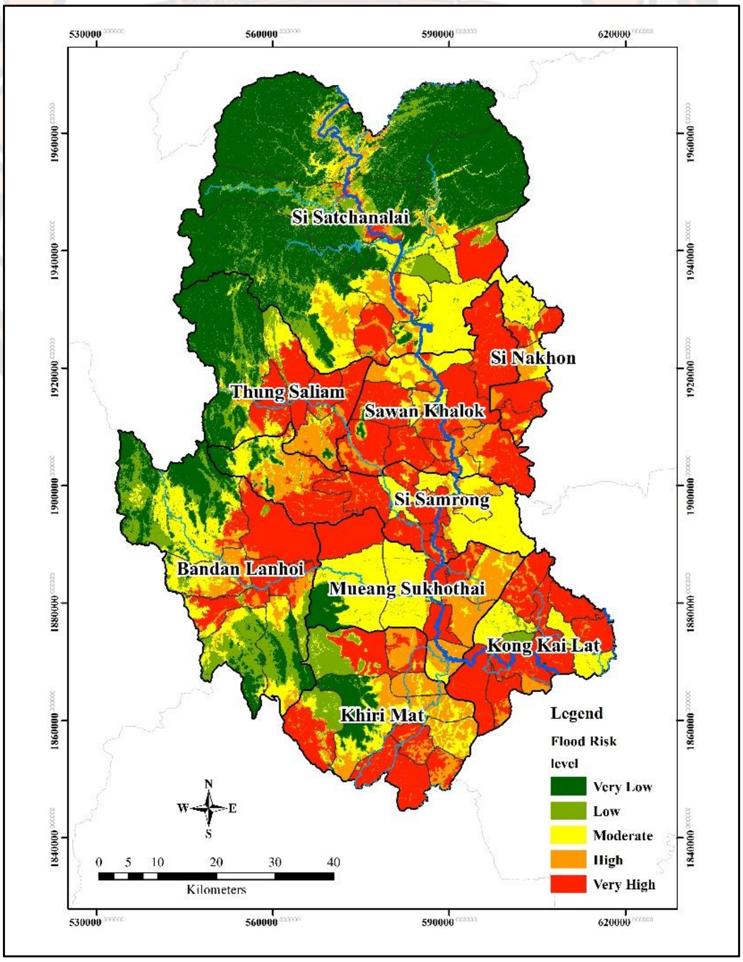


Figure 20 Flood risk map in Sukhothai Province

Table 13 Flood risk classification in Sukhothai Province

Flood risk classes	Area	
	km^2	%
Very low risk	1742.47	26.15
Low risk	737.88	11.07
Moderate risk	1399.03	21.00
High risk	903.34	13.56
Very high risk	1880.58	28.22

4.5 Analysis and assessment of flood damage based on the questionnaires

The questionnaires were collected according to analytical results the highest flood risk area. It consists of five districts, namely Sawankhalok District (Nong Klap Sub-District), Si Samrong District (Thap Phueng Sub-District), Mueang Sukhothai District (Thani, Tan Tia, Pak Khwae, Yang Sai Sub-Districts), Kong Krailat District (Krai Nok, Dong Duai, Nong Tum, and Tha Chanuan Sub-Districts), and Khiri Mat District (Ban Pom Sub-District) as shown in **Figure 21** and **Table 14**.

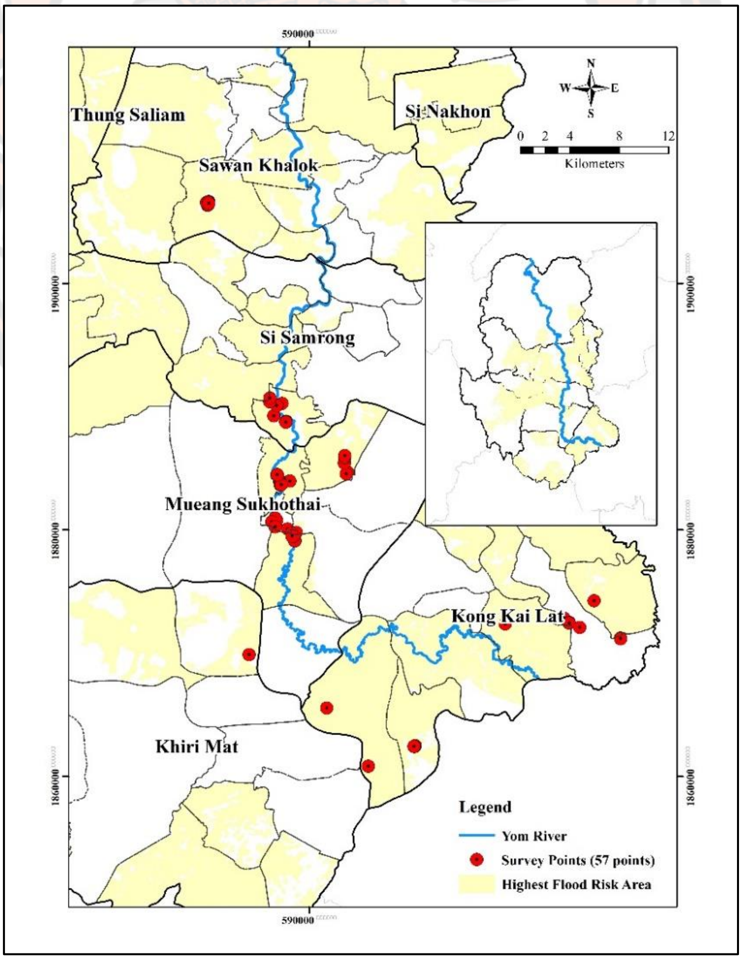


Figure 21 Field survey points in Sukhothai Province

Table 14 The number of questionnaire survey in each district

District	The number of household	Percentage	The number of questionnaire
Mueang Sukhothai	37006	29.13	29
Kong Krailat	22193	17.47	18
Khiri Mat	15682	12.34	12
Si Samrong	25657	20.20	20
Sawankhalok	26502	20.86	21
Total		100	100

The total number of respondents for flood damage was 100 people, with 62% being female and 38% being male. The most of respondent's ages range between 51-60 years. In addition, 62% of respondents are farmers, and agriculture is the primary source of income for the household, with an average income of 5,000 – 10,000 baht per household. Respondents in the five districts in Sukhothai Province were found that 98% of the total had experienced flooding every year, which is caused by seasonal storms and monsoons. Causing heavy rainfall in the area, and the water overflowed the riverbanks. Additionally, the relatively flat terrain was also one of the key factors contributing to the flood. Therefore, it is an area that causing damage to residential and agricultural areas (Appendix A).

4.5.1 Houses damage assessment

1. Flood depth maps from questionnaire

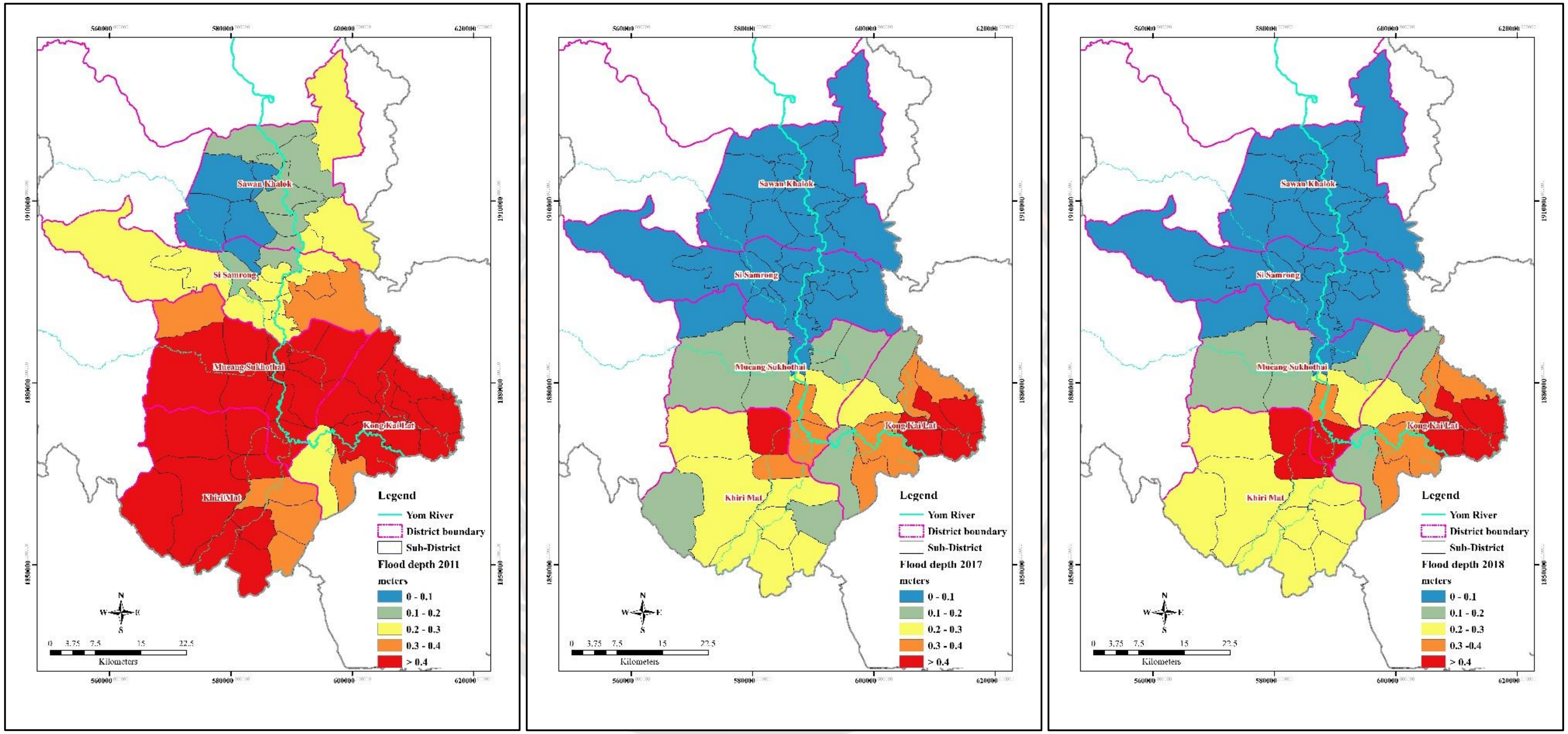
Flood areas faced an increase in water depth as the intensity of the flood damage increased. Flood depth maps were created according to field survey data in 2011, 2017, and 2018 using the Inverse Distance Weighted (IDW) interpolation in GIS. These maps were classified into five classes, namely 0 - 0.1, 0.1 - 0.2, 0.2 - 0.3, 0.3 - 0.4, and more than 0.4 m., respectively.

In 2011, the highest flood depth class was found in Mueang Sukhothai, Khiri Mat, and Kong Krailat Districts and 25 Sub-Districts such as Ban Pom, Pak Khwae, and Krai Nok, with the highest flood depth of 0.65 m. as shown in **Figure 22(a)**.

In 2017, the highest flood depth class was found in Krai Nok, Dong Duai, and Ban Mai Suk Kasem Sub-District (Kong Krailat District) as well as Ban Pom Sub-District (Khiri Mat District), with the highest flood depth of 0.55 m. as shown in **Figure 22(b)**.

In 2018, the class of high flood depth was found in Pak Phra Sub-District (Mueang Sukhothai District), Ban Pom and Thung Luang Sub-Districts (Khiri Mat District), and Krai Nok, Dong Duai, and Ban Mai Suk Kasem Sub-District (Kong Krailat District), with the highest flood depth of 0.56 m. as shown in **Figure 22(c)**.

Therefore, these maps showed that the lower flood depth level was primarily found in the north of the province with the high elevation and slope. However, the highest flood depth areas were found in the central and south areas with a flat area.



(a) (b) (c)

Figure 22 Flood depth maps in (a) 2011, (b) 2017, and (c) 2018

2. Flood duration maps from questionnaire

The duration of the flood is in contact with the house is an essential factor in determining the extent of the damage. Generally, the longer the flood lasts, the more damage it causes to the houses property (Soetanto & Proverbs, 2004). Flood duration maps were created based on field survey data in 2011, 2017, and 2018 using the IDW interpolation in GIS. These maps were classified into five classes, namely 0 - 3, 3 - 5, 5 - 7, 7 - 9, and more than 9 days, respectively.

In 2011, the maximum flood duration was found at Ban Mai Suk Kasem, Krai Nok, Dong Duai, and Kok Raet (Kong Krailat District), Ban Pom, Thung Luang (Khiri Mat District), and Pak Phra Sub-Districts (Mueang Sukhothai District) with duration of 9-13 days as shown in **Figure 23(a).**

In 2017, the maximum flood duration was found at Ban Mai Suk Kasem, Krai Nok Sub-Districts (Kong Krailat District) with duration of 9-10 days as shown in **Figure 23(b)**.

In 2018, the maximum flood duration was found at Ban Mai Suk Kasem, Krai Nok Sub-Districts (Kong Krailat District) with duration of 7 days as shown in **Figure 23(c).**

Consequently, figure 24 depicts the flood duration maps for the study area in 2011, 2017, and 2018. The maps showed areas with long-duration in the central and southern parts and downstream of the Yom River in Sukhothai Province.

3. The percentage of houses damage value maps from questionnaire

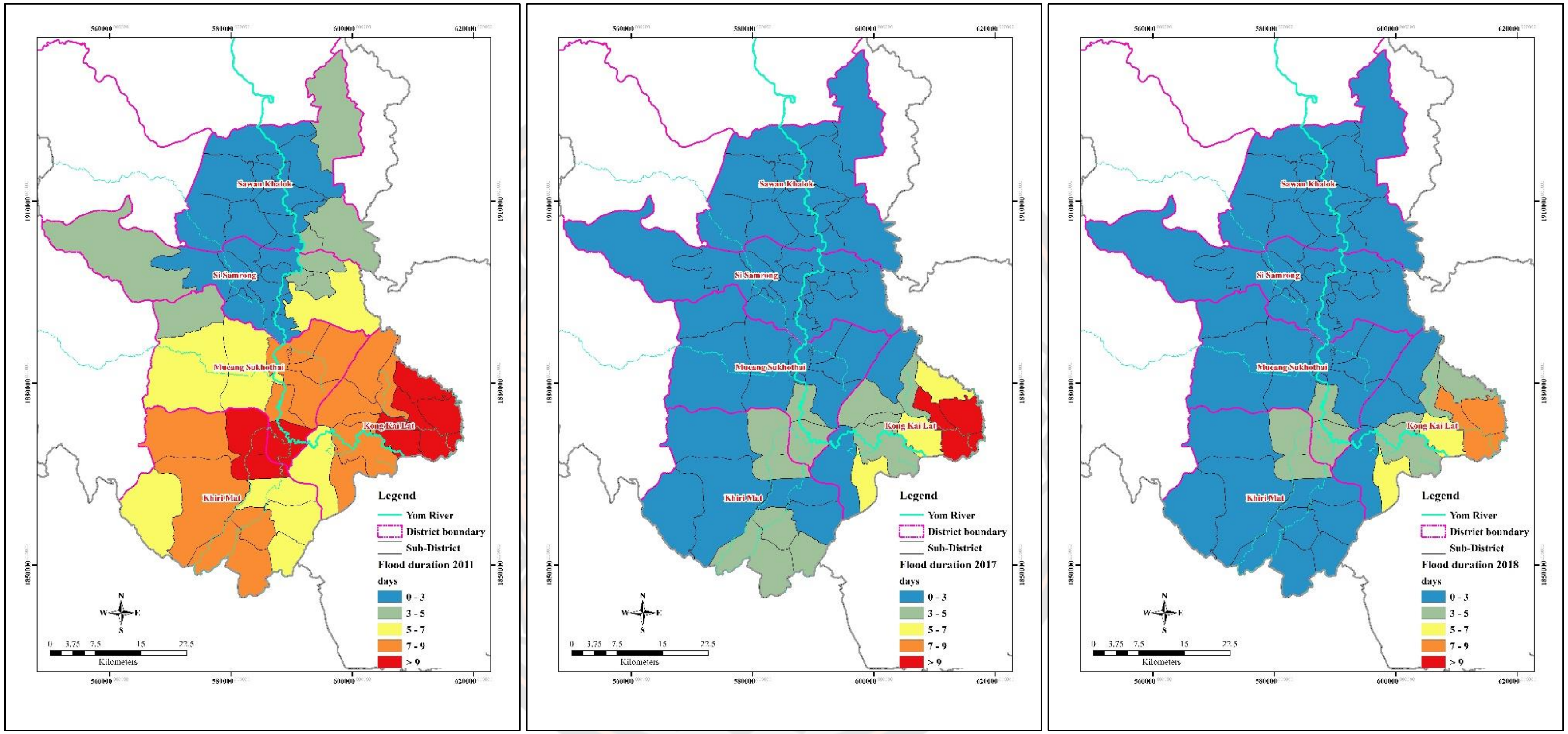
The percent of houses damage value maps were created based on field survey data in year of 2011, 2017, and 2018 using the IDW interpolation in GIS. These maps were classified into five classes, namely 0-5, 5-10, 10-15, 15-20 and more than 20 percentage, respectively.

In 2011, the most severe houses damage was observed at Pak Khwae and Tan Tia Sub-Districts (Mueang Sukhothai District). It also was found at Kok Raet, Ban Mai Suk Kasem, Krai Nok, Dong Duai Sub-District (Kong Krailat District), as well as Ban Pom Sub-District (Khiri Mat District), ranging from more than 20% to 52.66% as shown in **Figure 24(a)**. These areas were mostly at along with the river and lower elevation.

In 2017, the most severe houses damage was identified at Ban Mai Suk Kasem and Krai Nok Sub-Districts (Kong Krailat District), ranging from more than 20% to 22.07% as shown in **Figure 24(b**). In addition, the map showed that the lower damage was covered in the north part of the province.

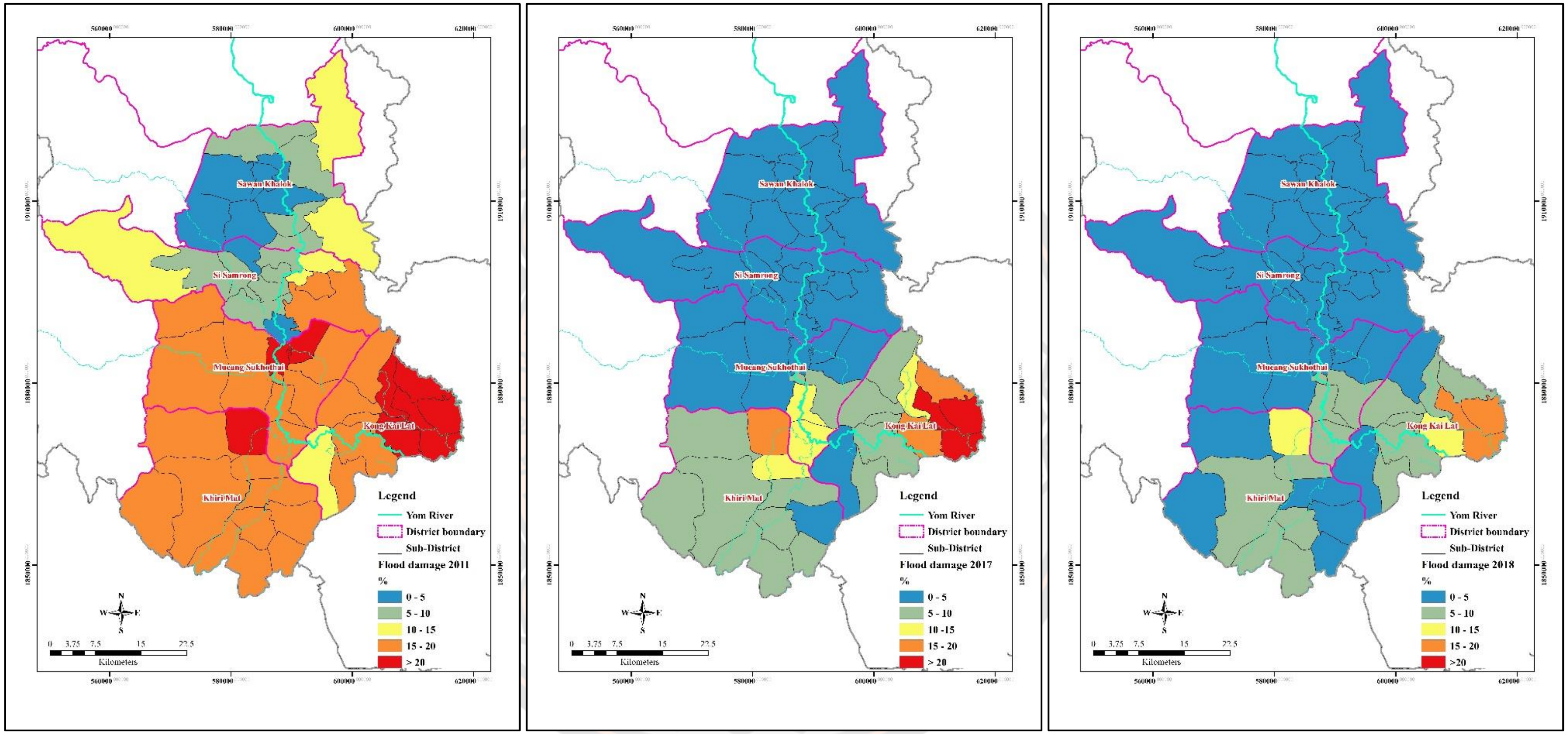
In 2018, the most severe houses damage was identified at Ban Mai Suk Kasem and Krai Nok Sub-Districts (Kong Krailat District), ranging from 15% to 20%, as shown in **Figure 24(c)**. However, fewer damage areas were covered in the north to the central part of the province.

Therefore, these maps showed that the high percentage of houses damage was primarily found central and south of the province with the lower elevation and flat areas. However, the lower house damage areas were covered in the north and some parts of central areas.



(a) (b) (c)

Figure 23 Flood duration maps (a) 2011, (b) 2017, and (c) 2018



(a) (b) (c)

Figure 24 The percentage of houses damage value maps in (a) 2011, (b) 2017, and (c) 2018

4. Flood depth-duration damage curve for houses damage

Figure 25 and **Table 15** show houses damage from the questionnaire survey conducted within the study area based on the 2011 floods. The result showed that the percentage of damage was more severe with an increasing floodwater level at more than 2 m, more than nine days, and the damage was 100%.

Table 15 Damage percentage for houses 2011

Damage Percentage for Houses 2011				
Flood depth (m)	**Flood duration (days)**			
	1-3	**4-6**	**7-9**	**>9**
0-1	0%	0%	16.07%	33.64%
1-1.5	0%	0%	16.25%	52.50%
1.5-2	0%	0%	16.25%	100.00%
>2	0%	0%	16.25%	100.00%

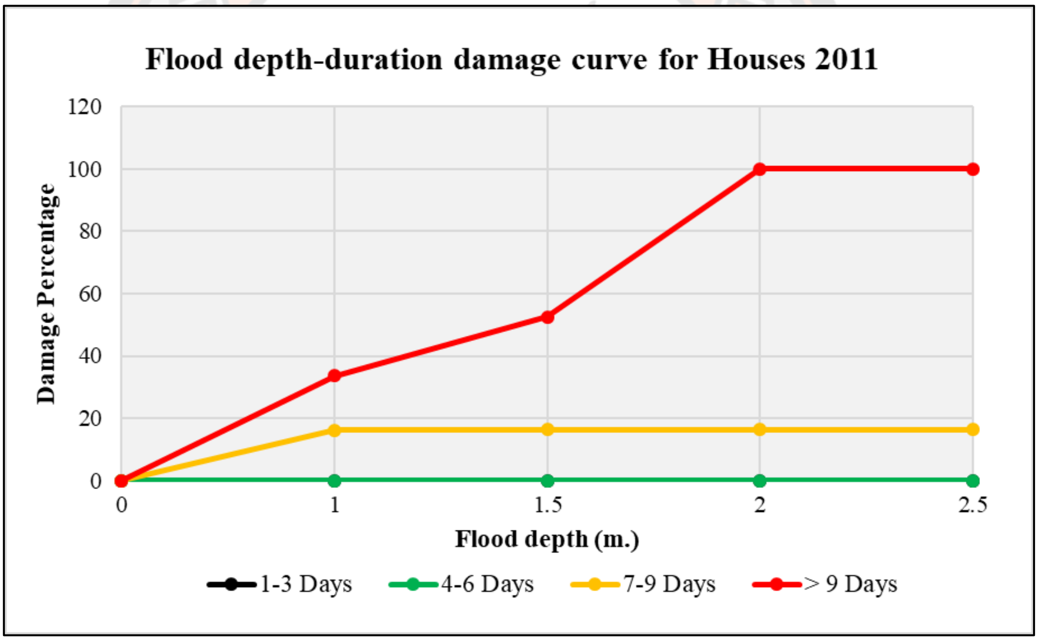


Figure 25 Flood depth-duration damage curve for houses damage 2011

Figure 26 and **Table 16** show houses damage from the questionnaire survey conducted within the study area based on the 2017 floods. The result showed that the percentage of damage was more severe with an increasing floodwater level at more than 1.5 m, more than nine days, and the damage was approximately 42.5%.

Table 16 Damage percentage for houses 2017

Damage Percentage for Houses 2017				
Flood depth (m)	**Flood duration (days)**			
	1-3	**4-6**	**7-9**	**>9**
0-1	0%	10%	13.13%	25.50%
1-1.5	0%	10%	25.00%	42.50%
1.5-2	0%	10%	25.00%	42.50%
>2	0%	10%	25.00%	42.50%

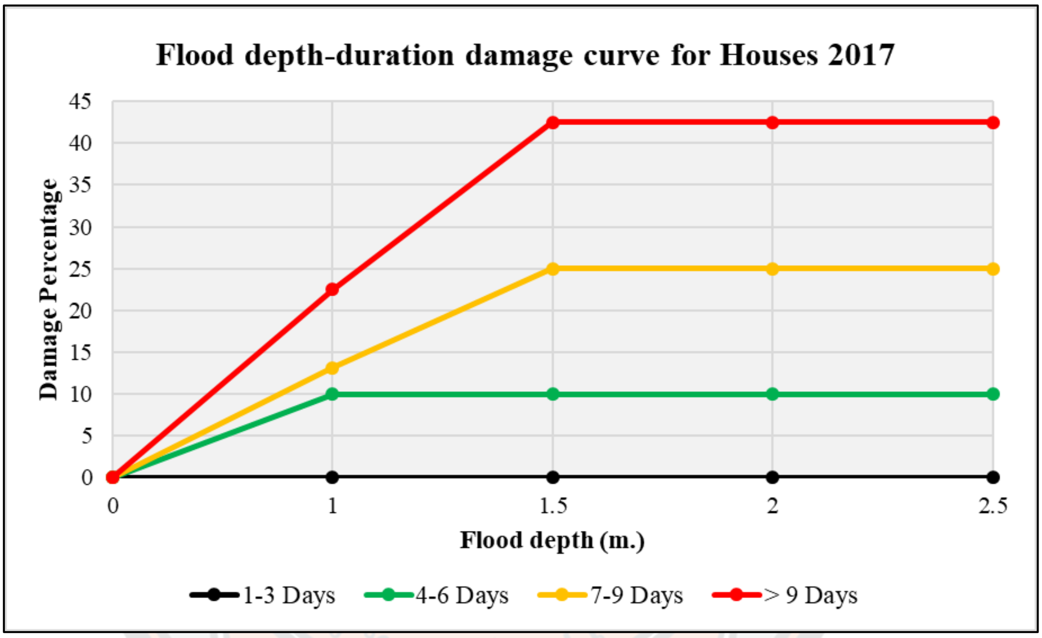


Figure 26 Flood depth-duration damage curve for houses damage 2017

Figure 27 and **Table 17** show houses damage from the questionnaire survey conducted within the study area based on the 2018 floods. The result showed that the percentage of damage was more severe with an increasing floodwater level at more than 1.5 m, more than nine days, and the damage was approximately 30%.

Table 17 Damage percentage for houses 2018

Damage Percentage for Houses 2018				
Flood depth (m)	**Flood duration (days)**			
	1-3	**4-6**	**7-9**	**>9**
0-1	0%	10%	14.17%	17.50%
1-1.5	0%	10%	25.00%	30.00%
1.5-2	0%	10%	25.00%	30.00%
>2	0%	10%	25.00%	30.00%

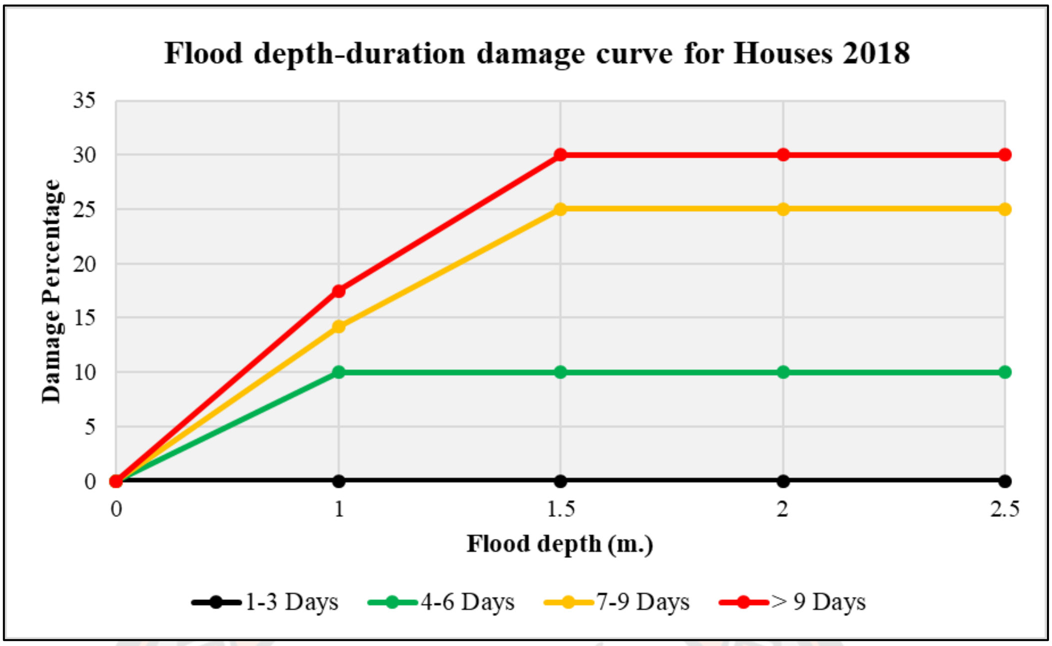


Figure 27 Flood depth-duration damage curve for houses damage 2018

Figure 28 and **Table 18** show average houses damage from the questionnaire survey conducted within 3 study years. The result showed that the percentage of damage was more severe with an increasing floodwater level at more than 2 m, more than nine days, and the damage was approximately 65%.

Table 18 Damage percentage for houses from 3 study years

Damage Percentage for Houses from 3 study years				
Flood depth (m)	**Flood duration (days)**			
	1-3	**4-6**	**7-9**	**>9**
0-1	6%	13%	18%	27%
1-1.5	6%	13%	18%	37%
1.5-2	6%	13%	18%	65%
>2	6%	13%	18%	65%

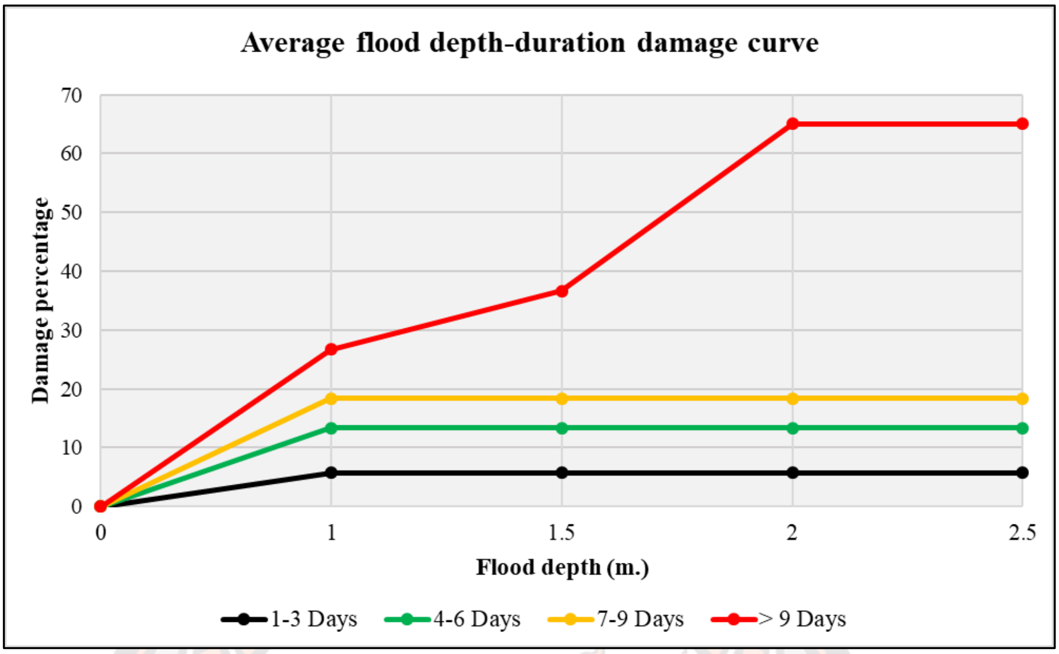


Figure 28 Average flood depth-duration damage curve for houses damage from 3 study years

4.5.2 Paddy field damage assessment

1. Flood depth maps from questionnaire

Flood depth maps were created based on field survey data in 2011, 2017, and 2018 using the IDW interpolation in GIS. These maps were classified into five classes, namely 0 - 0.5, 0.5 - 0.7, 0.7 - 0.9, 0.9 - 1.1, and more than 1.1 m. respectively.

In 2011, the highest flood depth class was covered whole province such as Nong Klap Sub-District, Sawankhalok District, with a floodwater level of 2.031 m. as shown in **Figure 29(a)**.

In 2017,Sawankhalok (i.e. Nong Klap, Mueang Bang Khlang, Na Thung, and Wang Mai Khon Sub-Districts) and Kong Krailat Districts (Dong Dueai and Krai Nok Sub-Districts) were found the highest flood depth level (more than 1.1 m.) as shown in **Figure 29(b)**.

In 2018, Nong Klap Sub-District, Sawankhalok District was found the highest flood depth level (1.27 m.) followed by Dong Dueai Sub-District, Kong Krailat District (1.24 m.) as shown in **Figure 29(c)**.

Therefore, these maps showed that the highest flood depth level was covered the whole province in 2011, while in years of 2017 and 2018 were found the highest flood depth level in the north and south parts of the province.

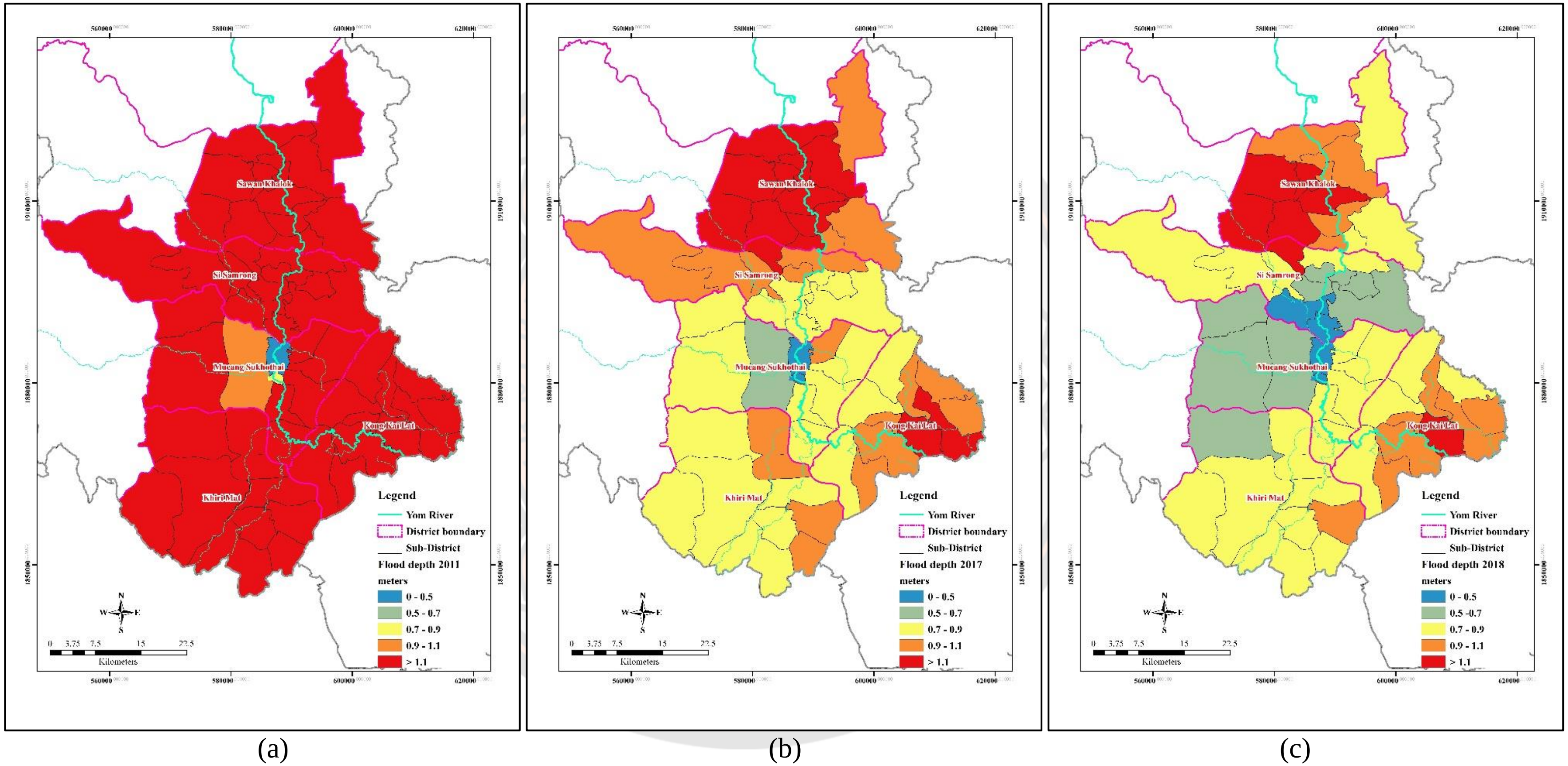


Figure 29 Flood depth maps in (a) 2011, (b) 2017, and (c) 2018

2. Flood duration maps from questionnaire

Flood duration maps were created based on field survey data in 2011, 2017, and 2018 using the IDW interpolation in GIS. These maps were classified into five classes, namely 0 - 5, 5 - 7, 7 - 9, 9 - 11, and more than 11 days respectively.

In 2011, the average duration of flooding for paddy field was 0-34 days, as shown in **Figure 30(a)**. The maximum flood duration class was identified that in eight Sub-Districts. For instance, Thung Luang (Khiri Mat District), Dong Duai (Kong Krailat District) with duration of 34 days.

In 2017, the average duration of flooding for paddy field was 0-17 days as shown in **Figure 30(b)**. The maximum flood duration class was found in eight Sub-Districts such as Thung luang, Ban Pom Sub-Districts (Khiri Mat District) with duration class of 15-17 days.

In 2018, the average duration of flooding for paddy field was 0-13 days as shown in **Figure 30(c)**. The maximum flood duration class was found at Thung luang, Ban Pom (Khiri Mat District), Yang Sai, Pak Phra (Mueang Sukhothai District) Sub-Districts, and a duration class of 10-13 days.

Consequently, these maps depict the flood duration maps for the study area. The maps showed areas with long-duration in the whole province in 2011 and 2017. However, in 2018 long-duration was found in the central parts of the province.

3. The percentage of paddy field areas damage maps from questionnaire

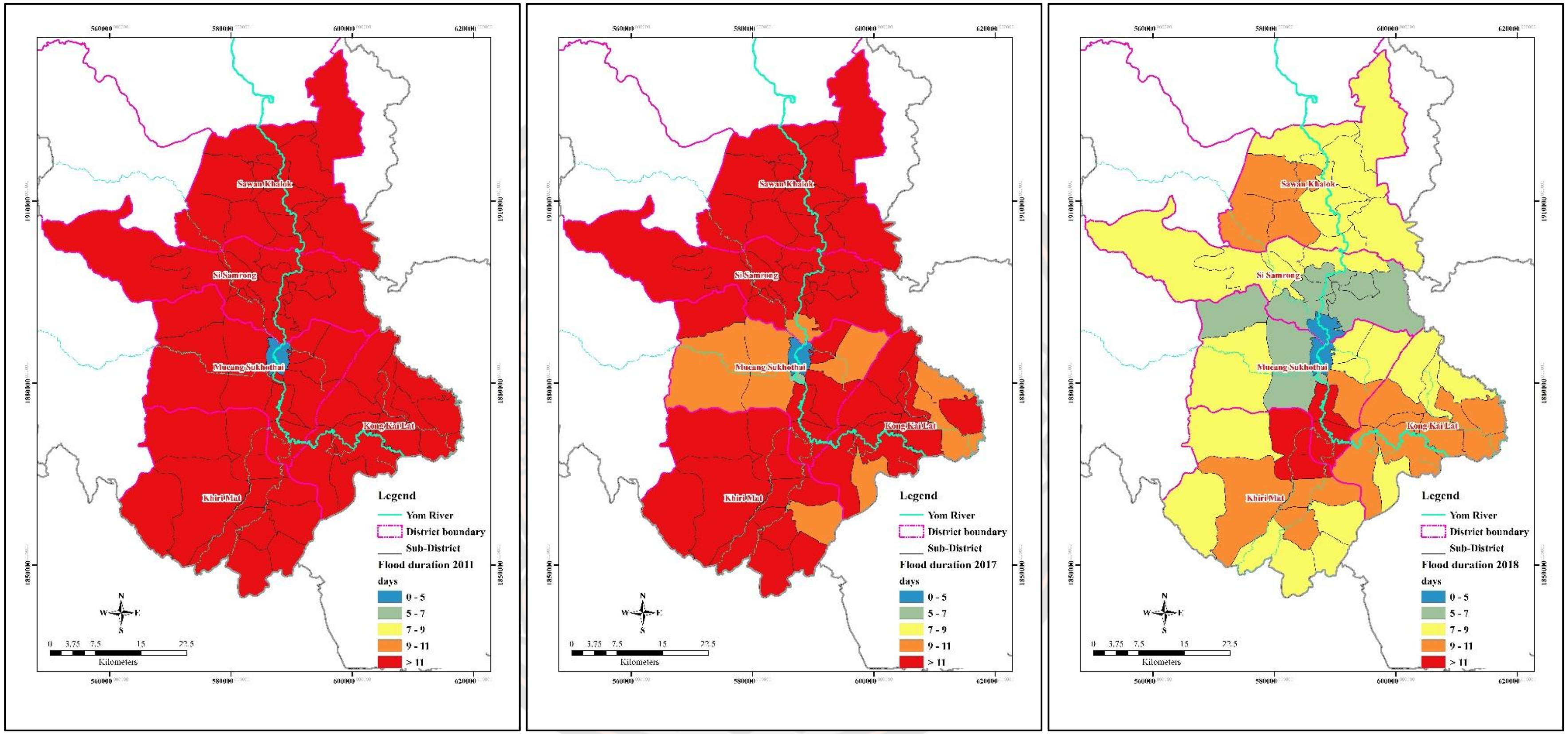
The percentage of paddy field damage maps were created based on field survey data in 2011, 2017, and 2018 using the IDW interpolation in GIS. These maps were classified into five classes, namely 0-20, 20-30, 30-40, 40-50 and more than 50 percent respectively.

In 2011, the average flooding damage for the paddy field range was 33.60% to 77.10%. The most severe damage was observed at Tha Chanuan Sub-District, Kong Krailat District, with 77.10% of damage, as shown in **Figure 31(a)**.

In 2017, the average flooding damage for the paddy field range was 22.20% to 59.34%. The most severe damage was identified at Nong Klap Sub-District, Sawankhalok District, with 60.43% of damage as shown in **Figure 31(b)**.

In 2018, the average flooding damage for the paddy field range was 21.06% to 59.34%. The most severe damage was identified at Nong Klap Sub-District, Sawankhalok District, with 59.34% flood damage (**Figure 31(c)**).

Therefore, these maps showed that a high percentage of paddy field damage was covered in the whole Province in 2011. On the other hand, in 2017 and 2018 were found in the north and some parts of central the Province. However, the low damage areas were covered in the central and south parts of the areas.



(a) (b) (c)

Figure 30 Flood duration maps in (a) 2011, (b) 2017, and (c) 2018

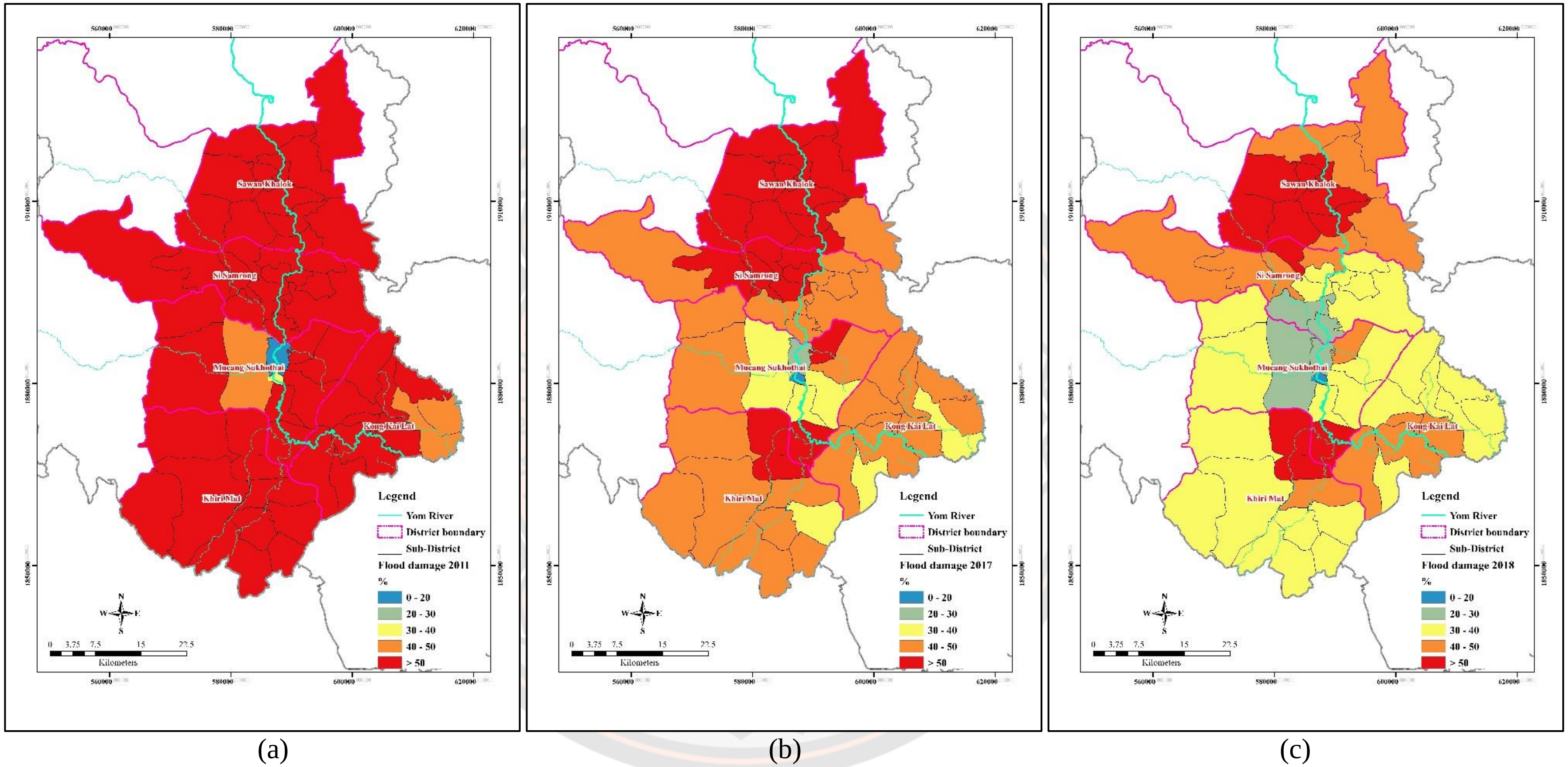


Figure 31 The percentage of paddy field damage maps in (a) 2011, (b) 2017, and (c) 2018

4. Flood depth-duration damage curve for paddy field damage

Paddy grows in the monsoon season from May to October, and flooding occurs in the study area in the monsoon season. According to the growth phase of the rice plant in the reproductive stage, The yield of paddy is about 73-74 baskets (or 1.1 Tons) per Rai in monsoon rice crop, and the prices of paddy are 9,662 in 2011, 7,905 in 2017, and 7,892 Baht in 2018 per Tons (Department of agriculture extension, 2561).

Figure 32 and **Table 19** show paddy field damage estimates from the questionnaire survey conducted within the study area based on the 2011 floods. The result showed that the percentage of damage for paddy field area was more severe with an increasing floodwater level at more than 2 m, more than 21 days, and the damage was approximately 93.33%. According to **Table 20**, the highest damage value for the paddy field in flood depth 0 to more than 2.5 m. in 2011 is 9,941.12 Baht per Rai.

Table 19 Damage percentage for paddy field 2011

Damage percentage for paddy field 2011				
Flood depth (m)	**Flood duration (days)**			
	1-7	**8-14**	**15-21**	**>21**
0-1.5	0%	0%	40%	67.5%
1.5-2	0%	81.25%	88%	93.04%
2-2.5	0%	81.25%	88%	93.33%
>2.5	0%	81.25%	88%	93.33%

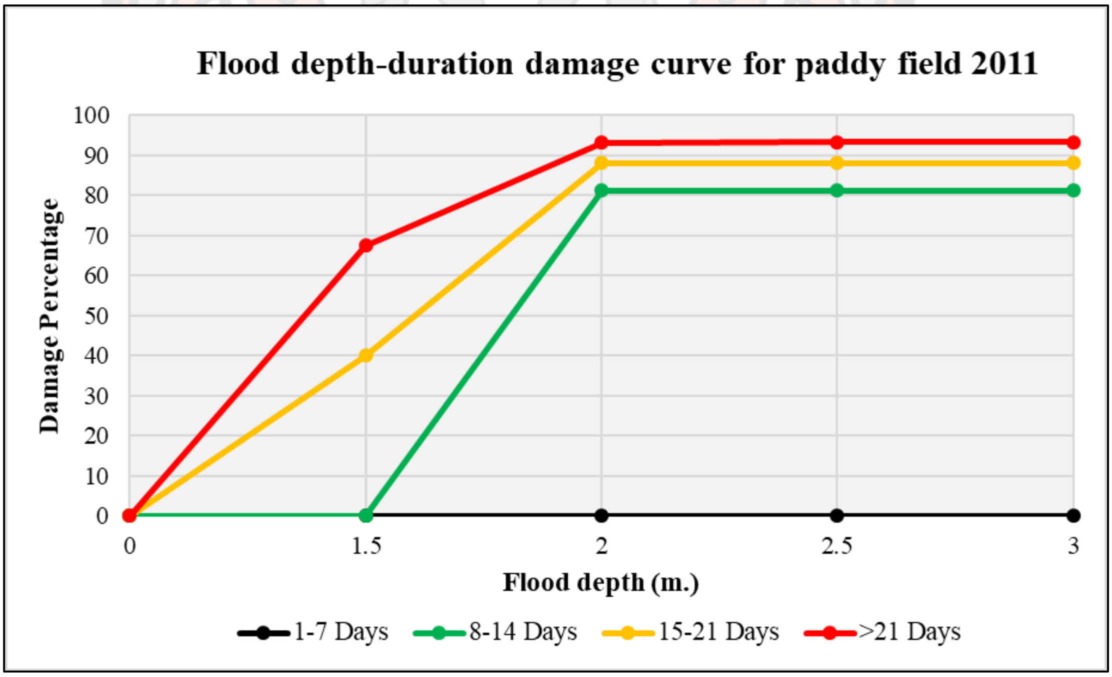


Figure 32 Flood depth-duration damage curve for paddy field 2011

Table 20 Damage value for paddy field in 2011

Damage value for paddy field in 2011				
Flood duration (days)	**Flood depth (m)**			
	0-1.5	**1.5-2**	**2-2.5**	**>2.5**
1-7	0	0	0	0
8-14	0	8654.10	8654.10	8654.10
15-21	4260.48	9373.06	9373.06	9373.06
>21	7189.56	9910.25	9941.12	9941.12

Note: Baht/Rai

Figure 33 and **Table 21** show paddy field damage estimates from the questionnaire survey conducted within the study area based on the 2017 floods. The result showed that the percentage of damage for paddy field area was more severe with an increasing floodwater level at more than 2.5 m, more than 21 days, and the damage was 100%. According to **Table 22**, the highest damage value for the paddy field in flood depth 0 to more than 2.5 m. in 2017 is 8,712.77 Baht per Rai.

Table 21 Damage percentage for paddy field 2017

Damage percentage for paddy field 2017				
Flood depth (m)	**Flood duration (days)**			
	1-7	**8-14**	**15-21**	**>21**
0-1.5	0%	56.79%	83.24%	93.42%
1.5-2	0%	65%	85.94%	97.22%
2-2.5	0%	65%	85.94%	100%
>2.5	0%	65%	85.94%	100%

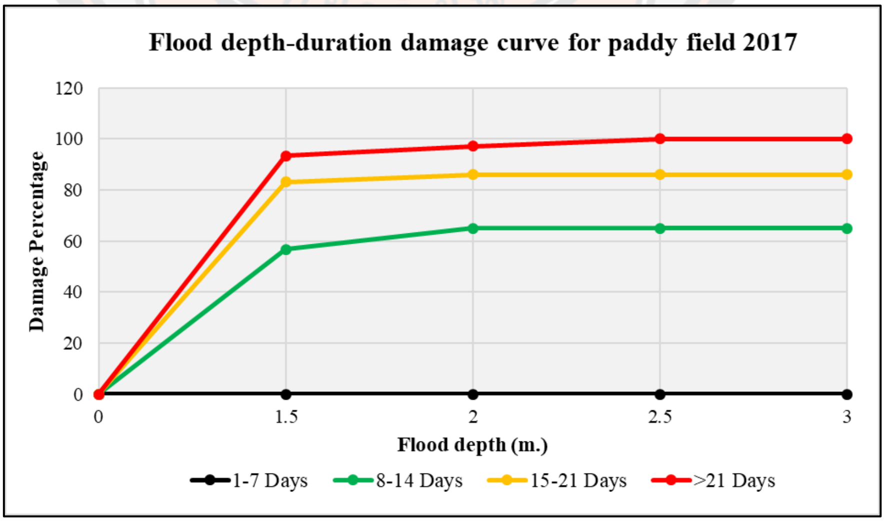


Figure 33 Flood depth-duration damage curve for paddy field 2017

Table 22 Damage value for paddy field in 2017

Damage value for paddy field in 2017				
Flood duration (days)	**Flood depth (m)**			
	0-1.5	**1.5-2**	**2-2.5**	**>2.5**
1-7	0	0	0	0
8-14	4962.74	5680.62	5680.62	5680.62
15-21	7274.28	7510.44	7510.44	7510.65
>21	8139.56	8470.75	8712.77	8712.77

Note: Baht/Rai

Figure 34 and **Table 23** show paddy field damage estimates from the questionnaire survey conducted within the study area based on the 2018 floods. The result showed that the percentage of damage for paddy field area was more severe with an increasing floodwater level at more than 2.5 m, more than 8 days, and the damage was 100%. According to **Table 24**, the highest damage value for the paddy field in flood depth 0 to more than 2.5 m. in 2018 is 8,712.77 Baht per Rai.

Table 23 Damage percentage for paddy field 2018

Damage percentage for paddy field 2018				
Flood depth (m)	**Flood duration (days)**			
	1-7	**8-14**	**15-21**	**>21**
0-1.5	0%	60.48%	82.73%	92%
1.5-2	0%	72.22%	86.92%	100%
2-2.5	0%	100%	100%	100%
>2.5	0%	100%	100%	100%

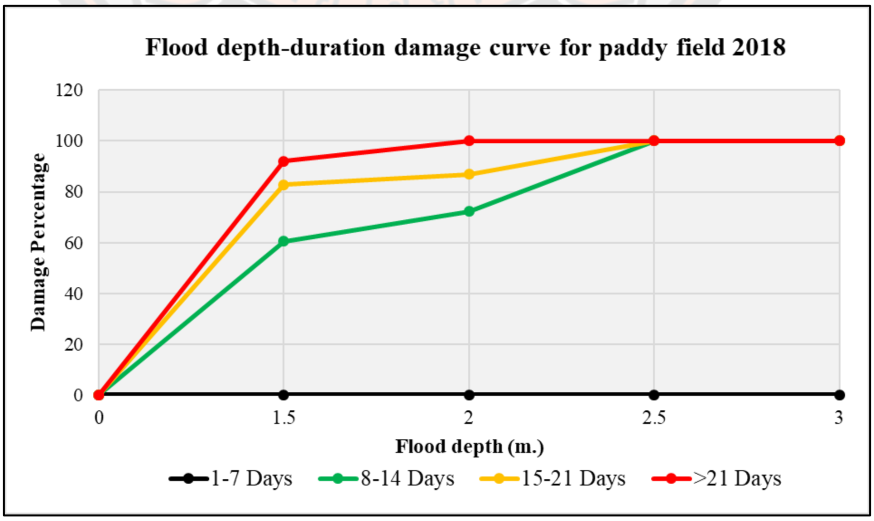


Figure 34 Flood depth-duration damage curve for paddy field 2018

Table 24 Damage value for paddy field in 2018

Damage value for paddy field in 2018				
Flood duration (days)	**Flood depth (m)**			
	0-1.5	**1.5-2**	**2-2.5**	**>2.5**
1-7	0	0	0	0
8-14	5269.15	6292.55	8712.77	8712.77
15-21	7207.84	7573.41	8712.77	8712.77
>21	8015.75	8712.77	8712.77	8712.77

Note: Baht/Rai

Figure 35 and **Table 25** show paddy field damage estimates from the questionnaire survey conducted within 3 study years. The result showed that the percentage of damage for paddy field area was more severe with an increasing floodwater level at more than 2.5 m, more than 21 days, and the damage was 97%. According to **Table 26**, the highest damage value for the paddy field in flood depth 0 to more than 2.5 m. is 9,056.44 Baht per Rai.

Table 25 Damage percentage for paddy field from 3 study years

Damage Percentage for paddy field from 3 study years				
Flood depth (m)	**Flood duration (days)**			
	1-7	**8-14**	**15-21**	**>21**
0-1.5	0%	38%	62%	74%
1.5-2	0%	55%	85%	92%
2-2.5	0%	55%	85%	94%
>2.5	0%	55%	85%	97%

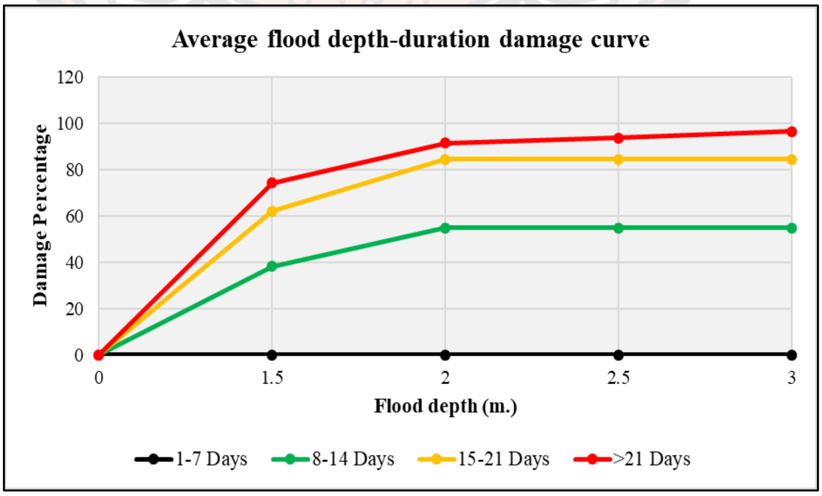


Figure 35 Average flood depth-duration damage curve for paddy field from 3 study years

Table 26 Damage value for paddy field in 3 study years

Damage value for paddy field in 3 study years				
Flood duration (days)	**Flood depth (m)**			
	0-1.5	**1.5-2**	**2-2.5**	**>2.5**
1-7	0	0	0	0
8-14	3577.15	5152.80	5152.80	5152.80
15-21	5825.43	7924.39	7924.39	7924.39
>21	6957.15	8588.00	8783.19	9056.44

Note: Baht/Rai

4.6 Discussion

This research has combined flood hazard and flood vulnerability to assess flood risk and collected data from questionnaires to flood damage assessment in Sukhothai Province. Nine influence factors were considered for the flood hazard maps using the FR method. On behalf of the AHP method was applied with seven factors' weight to identify flood vulnerability areas. The outcomes are the potential flood hazard map, flood vulnerability map, flood risk map, flood damage maps, and damage curves.

A flood hazard map is one of the most critical components of any flood mitigation strategy to prevent and mitigate future flood situations, which helps to reduce the negative results and reduce flood-related fatalities and economic losses of flood hazards (Das, 2019; Wubalem & Meten, 2020). Flood hazard mapping has implementing using various methods by different and numerous studies such as hydrological based, quantitative (FR), qualitative (AHP), and machine learning techniques. (Jayakrishnan, Srinivasan, Santhi, & Arnold, 2005; Rahmati et al., 2015; Tehrany, Pradhan, & Jebur, 2015; Youssef et al., 2010). Each method has different capabilities and can be affected by a variety of uncertainty. For example, machine-learning technique are widely used. Nevertheless, long processing times, the need for high-performance computing systems as well as specific software, and strict selection criteria for input parameters (Tehrany, Pradhan, & Jebur, 2013; Wubalem & Meten, 2020). Therefore, the FR method is easily understandable and can produce flood hazard analysis and mapping as well as based on the relationship between spreading of flooding and each conditioning factor, to exhibit the relationship between flood locations and the conditioning factors in the study area (Lee & Talib, 2005). It is essential to analyze past food records to estimate future food events in any area (Samanta et al., 2018). In the study, the nine factors selected for the flood hazard consisted of flood inventory area, average annual rainfall, elevation and slope, land use, soil drainage, drainage density, road density, and the distance from the drainage were considered (Anucharn & Iamchuen, 2017; Duangpiboon et al., 2018; Samanta et al., 2018). The study reveals that Those high to very high flood hazard areas are characterized by heavy rainfall upstream, poorly to somewhat poorly drained soil, lower elevation and slope degree, and closer to the main river as seen in the study of Duangpiboon et al. (2018) and Samata et al. (2018). The high and very high levels of flood hazard were located in the central and south of the study area such as Si Samrong, Mueang Sukhothai, Kong Krailat, and Khiri Mat Districts as shown in **Figures 16**.

In general, vulnerability refers to the physical, social, economic, and environmental conditions, which increase the susceptibility of the exposed elements to the impact of hazards (UN, 2016). The AHP method is an effective method in evaluating problems involving multiple and diverse criteria as well as the measurement a decision-making method for solving complex problems that involve multiple variables, a high degree of uncertainty, many alternatives vulnerability assessments (Ouma & Tateishi, 2014; Vishwanath & Tomaszewski, 2018). Therefore, flood vulnerability assessment based on the AHP approach is well suited to effectively differentiate vulnerability to disasters spatially (Hoque, Ahmed, Pradhan, & Roy, 2019; Roy & Blaschke, 2011). Based on earlier studies, seven flood vulnerability factors, namely population density, age dependency ratio, gender ratio, poverty ratio, monthly income, land use, and drainage density were considered. However, the weight value of each factor was determined by previous research studies or literature (Dandapat & Panda, 2017; Niyongabire & Rhinane, 2019; Rimba et al., 2017). From the results, it is shown that the population density was the most factor influencing flood vulnerability as seen in the study of Aphittha (2021). It illustrates that the location with the higher population density is the most vulnerable to flood hazards. The very high and high vulnerability were covered 25.98% and 16.40% of the study area—these areas distributed over Sukhothai Province such as Tha Chanuan, Dong Duai Sub-Districts, and Kong Krailat District.

Flood risk is the probability that floods of a given intensity and a given loss will occur in a certain area within a specified time period and results from the interaction of hazard and vulnerability (Merz, Kreibich, Thieken, & Schmidtke, 2009). The flood risk assessment is an amalgamation of both hazard and multiple vulnerability dimensions and each is assessed differently with respect to the level of impact it has on the society or environment (S. Sharma, Roy, Chakravarthi, & Rao, 2017). Many researchers have been successful in there to assess flood risk (Hailin et al., 2009; Scheuer, Haase, & Meyer, 2010; S. V. S. P. Sharma, Rao, & Bhanumurthy, 2012). Therefore, the flood risk map was created from the flood hazard map and flood vulnerability map in GIS software. The high and very high-risk areas were found along with the main river and tributaries, including flat areas. These areas were found in the central and south of the province. The map was identified at Mueang Sukhothai District (i.e., Pak Khwae, Yang Sai Sub-Districts), Kong Krailat District (i.e., Tha Chanuan, Dong Duai, Kok Raet Sub-Districts). However, the low and very low risks were covered in the north and west parts of the province with a high slope and elevation and a smaller population. The high-risk area should be of utmost step for developing flood management strategies, allowing disaster managers to prepare for emergencies. Notably, it supports spatial decision-making, the development of disaster impact reduction strategies, and the overall effectiveness of disaster management in the study area (Armenakis, Du, Natesan, Persad, & Zhang, 2017; Merz et al., 2009).

Flood damage assessment is essential for providing information to support decision-making and policy development in flood risk management (Chung, Takeuchi, Fujihara, & Oeurng, 2019). This study created flood depth-duration damage curves by a questionnaire investigation approach in 2011, 2017, and 2018. The highest flood damage level was found in high flood depths and over high risk flood area long flood duration area. This finding is consistent with that of Khaing, T. W. (2019) who assessed of flood damage in Myanmar. The result showed that the highest flood depth level of house damage was found in the central and south of the study area where are the flat area with long-duration flood along the Yom River. The most severe house damage was observed at Ban Mai Suk Kasem and Krai Nok Sub-Districts (Kong Krailat District). In addition, the flood depth-duration damage curve showed that the damage was more severe, at the floodwater level more than 2 meters in 2011 and more than 1.5 meters in 2017 and 2018, with flood duration longer than nine day. In the paddy field, the highest flood depth level was found the north and south of the area, except in 2011, covered the whole study area with long flood duration. The most severe paddy field damage was observed at Tha Chanuan Sub-District (Kong Krailat District) and Nong Klap Sub-District (Sawankhalok District). In addition, the flood depth-duration damage curve showed that the damage was more severe at the floodwater level more than 2 meters in 2011 and more than 1.5 meters in 2017 and 2018, with longer than 9-21 days. The highest damage cost for the paddy field in flood depth more than 2.5 m. is around 8,712.77, 8,712.77, and 9,941.12 Baht per Rai of year 2011, 2017, and 2018, respectively.

This study could be beneficial for mitigation of floods hazards, since it also considered historical data and influencing factors as well as can support the future analysis. It is seen that flood hazard, flood vulnerability, and flood risk maps are essential in disaster management planning, since the maps are easy to define risk zones and prioritize prevention or response. In addition, flood damage assessment will help authorities for planning and deciding to allocate their budget to those agricultural disaster victims over Sukhothai Province in the future.

CHAPTER V

CONCLUSION AND RECOMENTATION

This chapter presents the conclusion was based on the purpose, research questions and results of the study, and recommendations.

5.1 Conclusion

The purpose of this study is to conduct a flood risk assessment using the FR, AHP, and GIS techniques to identifying flood risk areas and assessing flood damage based on a questionnaire survey in Sukhothai Province, Thailand. The FR method was applied to create a flood hazard map with nine influence factors were considered. In addition, there are seven factors inducing flood vulnerability maps using the AHP method. Then they were categorized into five classes: very low, low, moderate, high, and very high. As a result, flood hazard, vulnerability, risk, and flood damage maps and curves are the outcomes.

The high and very high flood hazard levels were primarily found at the central and south of the study area, such as Si Samrong, Mueang Sukhothai, Kong Krailat, and Khiri Mat Districts. The areas prone to high and very high floods are 1,540.69 km^2 (23.12% of the total areas) and 2,374.83 km^2 (35.64% of the total areas). Likewise, it found that the hazard map was highly accurate and efficient. It produced a high accuracy value of AUC, which had a success rate of 95.05% and the prediction rate of 94.77%. Consequently, it confirmed that the map could be used for flood management planning in Sukhothai Province.

There are seven factors inducing a flood vulnerability map. The result showed that the population density is the most critical factor influencing flood vulnerability as the weight of 0.34 followed by the age group (0.19), the gender ratio (0.15), the poverty ratio (0.10), the monthly income (0.01), land use (0.08), and drainage density (0.05). Additionally, the results revealed high and very high vulnerability areas distributed over Sukhothai Province, such as Tha Chanuan and Dong Duai Sub-Districts (Kong Krailat District). An area of flood vulnerability mainly found a high level of 1,731.71 km^2, or 25.98% of the total area, and a very high level of 1,092.75 km^2 (16.40%).

The flood risk map was integrated from the hazard map and vulnerability map. The result showed that the high and very high-risk areas were found along with the main river and tributaries with 13.86% and 28.22% of the study area, respectively. The map was identified at Thung Saliam District (i.e., Khao Kaeo Si Sombun Sub-District), Sawan Khalok District (i.e., Khlong Yang, Nai Mueang Sub-Districts), Mueang Sukhothai District (i.e., Pak Khwae, Yang Sai Sub-Districts), Kong Krilat District (i.e., Tha Chanuan, Dong Duai, Kok Raet Sub-Districts). Hence, the high and very high-risk classes were observed along the main river and tributaries, including flat and lower slopes. These areas were agricultural and urban areas with high population density.

Flood depth, flood duration, and damage maps for the houses and paddy fields damage were developed based on questionnaire data in 2011, 2017, and 2018. The highest flood depth level that caused house damage was found in the central and southern area along the Yom River of the study area with the flat area and long duration flood. The highest percent of houses damage was found at 52.66% in 2011, 22.07% in

2017, and 17.02% in 2018, respectively. The most severe house damage was observed at Ban Mai Suk Kasem and Krai Nok Sub-Districts (Kong Krailat District).

The highest flood depth level that caused paddy field damage covered the whole province in 2011, while in 2017 and 2018 were found in the north and south parts of the province with long-duration floods. The highest percent of paddy field damage was found at 77.10%, 60.43%, and 59.34% in 2011, 2017, and 2018, respectively. The most severe damage was observed at Tha Chanuan Sub-District (Kong Krailat District) and Nong Klap Sub-District (Sawankhalok District). The cost of damage of the paddy fields was calculated using information from the questionnaire in 2011. It was found that the maximum damage value of paddy fields in the study area was 9,941.12 Baht per Rai with floodwater level more than 2 m and flood duration more than 21 days, followed by 8,712.77 Baht per Rai in 2017 and 2018 with floodwater level more than 2.5 m. and flood duration more than 21 days.

The flood map could be a tool for defensive measures and disaster risk management. This map will support decision-making on strategy and operation investments for managing risk. In addition, the flood damage assessment can help decision-makers to allocate the budget to support flood victims with appropriate flood mitigation measures.

5.2 Recommendations

This study was carried out with the major constraint of limited data availability. Therefore, the following recommendations are required for future research.

- Flood hazard maps should be applied hydrological model and generated with different return periods to establish flood hazard zone.
- Flood vulnerability weighting should be based on expert opinion rather than a review of the literature.
- The DEM with high resolution should be used to present the physical features of the areas to effective results.
- Damage assessment should be considered not only the directly damage (i.e. building, infrastructure) but also assess for indirectly damage (i.e. public services interruption)
- Flood depth-duration damage curve for house and paddy fields were developed based on questionnaire survey. However, further study is needed to collect more details for generic damage curve development. An appropriate flood damage curve can be applied in the compensation cost system for flood areas.

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APPENDIX

APPENDIX A: Questionnaire for flood damage assessment

Date: …... /…... /…... Questionnaire no. **……**

Questionnaire Survey

"Assessment of flood risk and flood damage using geospatial techniques: a case study of Sukhothai province, Thailand."

Kamonchat Seejata, Master's Disaster management, Naresuan University.

This questionnaire is a part of the thesis, to conduct a questionnaire survey in Sukhothai Province. Sukhothai Province faces a flood problem almost every year. Therefore, the purposes of this questionnaire are to study and to understand better a flood event and its impact in Sukhothai Province in both urban and rural areas. Furthermore, the researcher will use the information to generate maps, which can help the local authority make decisions about managing flood risk and improving the plan to respond to flooding. There are five parts of the questionnaire as follow:

Part 1: General Information.

Part 2: Flooding Experienced/Information.

Part 3: Residential Property Damage.

Part 4: Agricultural Damage.

Part 5: The suggestions and comments.

Interviewer Name: …………………………...

Interview time: ……………………………….

GPS Coordinate: ……………………………..

Section A: General Information

Please answer all questions by marking check (✓) or by adding text to the blank that matches your response the most.

1.1 Address____

1.2 Gender

[ ] 1.Male [ ] 2.Female

1.3 Age ___________________

1.4 Marital Status

[ ] 1.Single [ ] 2.Married [ ] 3.Divorced

[ ] 4.Widowed [ ] 5.Separate [ ] 6.other_______

1.5 Education

[ ] 1.Primary [ ] 2.Secondary [ ] 3.Vocational School

[ ] 4.Becherler degree [ ] 5.Master degree [ ] 6.Other_______

1.6 Occupation

[ ] 1.Farmer [ ] 2.Merchant/Business [ ] 3. Civil Servant

[ ] 4. Worker [ ] 5.Student [ ] 6.Other_______

1.7 Family Status

[ ] 1.Household Head [ ] 2.Husband [ ] 3.Wife

[ ] 3.Son/Daughter [ ] 4.Grandparent [ ] 5.Other_______

1.8 The number of household

Total_____________ Male______________ Female__________

Under 1 year Male______________ Female__________

1 - 14 years Male______________ Female__________

15 - 25 years Male______________ Female__________

26 – 39 years Male______________ Female__________

40 - 60 years Male______________ Female__________

Over 60 years Male______________ Female__________

1.9 What is the range of your monthly income? (Baht)

[ ] 1. Less than 5,000 [ ] 2.5,000-10,000 [ ] 3.10,000-15,000

[ ] 4.15,000-20,000 [ ] 5.20,000-30,000 [ ] 6.more than 30,000

1.10 What are your main sources of income?

[ ] 1.Agriculture [ ] 2.Livestock [ ] 3.Salary

[ ] 4.Business [ ] 5.Government aid [ ] 6.Other

1.11 The number of a household member with income

Total______________ Occupation:__________________________

Part 2: Flooding Experienced/Information

2.1 Have you had experienced flooding?

[ ] 1.Yes [ ] 2. No (Skip to part 5)

2.2 What do you think to be the main source(s) of flooding? (Please check all that apply)

[ ] 1.Overland flow from nearby river.

[ ] 2.Dam Breaking
[ ] 3.Monsoon/Typhoon.
[ ] 4.Lack of drainage facilities to drain water.
[ ] 5.Other obstruction in nearby watercourse/water body.
[ ]6.Other(Please specify),____________________________________

2.3 How severely have you been affected by the flooding?

Affected	**Level**				
	(5)	**(4)**	**(3)**	**(2)**	**(1)**
Damage to housing (House structure)					
Damage to property (Equipment and theft problem)					
The accidents (drowning, electrocution).					
Transportation (food shortages, travelling)					
Environment (Sewage)					
Occupational (lack of income, layoff, or out of business)					
Mental health (stress, anxiety)					
Hygiene (Leptospirosis, Athlete's foot)					
Basic public utility (water, sanitation, electricity)					

Note: 5 is the very high damage, 4 is the high damage, 3 is the moderate damage, 2 is the low damage, and 1 is the very low damage.

2.4 Which year did you experience flood? ________________________________
2.5 How often do you experience flood in your agriculture area and residential?
[ ] 1.Annually [ ] 2.Once in 2 years [ ] 3.Once in 3 years
[ ] 4.Once in 5 years [ ] 5.Once in 5 years [ ] 6.Other
2.6 The cost of the damage you have suffered in the most recent flood event. (Baht)
[ ] 1.Less than 500 [ ] 2.500 – 1,500 [ ] 3.1,500 – 3,000
[ ] 4.3,000 – 5,000 [ ] 5. More than 5,000 [ ] 6.No damage
2.7 What is the most effective way for you to receive flood information/news?
[ ] 1. Television [ ] 2.Radio [ ] 3.Internet
[ ] 5.Head of village [ ] 5.Poster [ ] 6.Other
2.8 Did you receive assistance?
[ ] 1.Yes from__________________________________
[ ] 2.No
2.9 Did you receive a flood warning?
[ ] 1.Yes from__________________________________
[ ] 2.No

Part 3: Residential Property Damage

3.1 Was your property affected by flooding?
[ ] 1.Yes [ ] 2.No (Skip to Part 4)

3.2 What is the type of property ownership?
[ ] 1. Private owner [ ] 2.Co-ownership [ ] 3.Rent_______
[ ] 4.Other

3.3 Type of property:
[ ] 1.Detached house [ ] 2 . Semi-detached house [ ] 3.Townhouse
[ ] 4.Condominium [ ] 5.Apartment [ ] 6.Other

3.4 How long have you owned or occupied this property? ____________years

3.5 Type of roof:
[ ] 1.Cement [ ] 2.Tile/Ceramics [ ] 3.Wood
[ ] 4.Brick, Stone [ ] 5. Metal, Zinc [ ] 6.Other

3.6 Type of floor:
[ ] 1.Plywood [ ] 2.Wood [ ] 3.Tile
[ ] 4.Brick [ ] 5.Mix [ ] 6.Other

3.7 Type of wall:
[ ] 1.Bamboo [ ] 2.Metal, Zinc [ ] 3.Concrete
[ ] 4.Fibro cement [ ] 5.Brick [ ] 6.Other

3.8 How many floor levels in your house?
[ ]1.One [ ] 2.Two [ ] 3.More than 2

3.9 Height of 1st floor __________________meters

3.10 Height from surface __________________meters

3.11 Did the water enter your house?
[ ] 1.Yes [ ] 2.No

3.12 Please indicate where the flooding occurs, damage include flood water depth

Location	Damage (%)			Water depth			Duration		
	2011	2017	2018	2011	2017	2018	2011	2017	2018
Yard									
First floor									
Other									
No damage									

3.13 How much the cost to repair/replacement the damage of structure?

Type	Damage level 2011			Cost to repairing	Cost to replacement	Duration	Water Depth
	0%	50%	100%				
Floor							
Wall							
Door							
Window							
Type	Damage level 2017			Cost to repairing	Cost to replacement	Duration	Water Depth
	0%	50%	100%				
Floor							

Wall							
Door							
Window							
Type	Damage level 2018			Cost to repairing	Cost to replacement	Duration	Water Depth
	0%	50%	100%				
Floor							
Wall							
Door							
Window							

3.14 How much the cost to repair/replacement the damage of contents?

Item	Damage	Cost (Bath)
Appliances	[ ] Clothes become wet and soaked	
	[ ] Electronic devices do not work anymore	
	[ ] Loss of kitchen utensils	
	[ ] No damage	
Furniture	[ ] Dirty and smelly furniture because of mud	
	[ ] Pillows and mattresses get wet and dirty	
	[ ] Loss of some document	
	[ ] No damage	

Part 4: Agricultural Damage

4.1 Do you has any agricultural land?

[ ] 1.Yes [ ] 2.No (Skip to part 5)

4.2 Do you has any agricultural land?

[ ] 1.Owner [ ] 2.Rent [ ] 3.Shareholder

[ ] 4.Other

4.3 Is your agricultural land in/outside irrigated areas?

[ ] 1. In irrigation [ ] 2.Out irrigation

4.4 How many parcels do you own/cultivate?

_______________Parcels _______________Rai

4.5 What do you cultivate on the land?

2011 1.________________ 2.________________ 3.______________

2017 1.________________ 2.________________ 3.______________

2018 1.________________ 2.________________ 3.______________

4.6 Have this land been flooded? If yes, how much did you lost?

2011 [ ] 1.Yes ______________________ Baht

[ ] 2.No

2017 [ ] 1.Yes ______________________ Baht

[ ] 2.No

2018 [ ] 1.Yes ______________________ Baht

[ ] 2.No

4.7 Seasonal Crops (Planting (P) to Harvest (H) Season)

	Crop		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011		**P**												
		H												
2017		**P**												
		H												
2018		**P**												
		H												
	Crop		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011		**P**												
		H												
2017		**P**												
		H												
2018		**P**												
		H												

4.8 How do you use the product?

[ ] 1.For subsistence [ ] 2.Selling at internal [ ] 3.Selling at external

[ ] 4.Next cropping [ ] 5.Other

4.9 What is the approximate value of the product?

2011 ____________________ Baht/Unit

2017 ____________________ Baht/Unit

2018 ____________________ Baht/Unit

4.10 Damage to agriculture with floodwater depth and flood duration.

Crop	Crop Stage	Damage (%)			Water depth			Duration			Damage value*
		2011	2017	2018	2011	2017	2018	2011	2017	2018	

Part 5: The suggestions and comments

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....

....

Thank you very much for answering the questionnaire

(Kamonchat e