Doctoral Dissertation

The study of the built-up area expansion in the small provincial cities on the floodplains for proposing the method to design land-use policy in the spatial data-scarce environment: case study of Nong Khai City along Mekong River in Thailand

(地理データ整備が不十分な環境下における土地利用政策立案を目的とした氾濫原小都市の市街地拡大に関する研究: メコン川沿いのタイ・ノンカーイを対象として)

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With love, to my beloved family

Abstracts

Floodplain is a fundamental topography in which humankind usually settles and develops the urban area. Despite the beneficial functions of floodplains to support economic growth and human daily life, the settlement in the floodplain is likely to be affected by flood which is a natural phenomenon in this area. Over the past years, the urbanisation across the world caused the built-up lands to sprawl into the peri-urban areas and increased the exposure to floods. Although the expansion of the built-up lands is getting attention from worldwide scholars ranging from the macro-scale to micro-scale, there are limited understandings of the built-up land expansion in Thailand which almost all of the urban centres, like the provincial cities, settle on the floodplains, especially in the small provincial cities, because most studies have focused on land-use changes in the Bangkok Metropolitan Region and regional cities without the consideration of flood. To support the city development that tends to increase and bring with it the exposure to flood, the understanding of the built-up land expansion is required to manage the expansion in the problematic areas. Although there are studies of urban management to cope with the urban sprawl in the flood-prone areas, it is still challenging to implement them in a specific case in the developing countries and small cities due to the limitation of data.

To fulfil the understanding of the built-up land expansion in the data-scarce environment, Nong Khai City was selected as a case study. The various methods with the qualitative and quantitative approaches were integrated in this study to respond to two main objectives of this study: (1) to clarify the patterns of the built-up land expansion in Nong Khai City, which is a small provincial city on a floodplain, from past to future and (2) to apply the GIS technique to the study of land-use change and the urban planning to manage the expansion of the built-up lands in the data-scarce environment in two dimensions: the flood-prone area analysis and the analysis of the suitable areas for urban development.

This study reveals that before the numerous expansions of the built-up areas in Nong Khai City from 1997, in the premodern time, most built-up areas were dense on the natural levee, which was higher than unused lands and agricultural lands in the surrounding areas and free from floodings. However, from 1997 to 2007, the study reveals that most built-up lands expanded in the surrounding areas and towards the south along with Highway No. 2 and 233. The distance from the malls was indicated as the main factor. Then, the built-up lands continued to expand on the southern side in the next period from 2007 to 2017. Besides, the expansion of the built-up lands was also dense on the eastern side around the original settlement and along with the transportation. The agricultural lands were indicated as a crucial factor in the transformation into

the built-up lands in this period. The expansion of the built-up lands in the peri-urban area is in accord with the stagnant population change trend in the core area and the increasing population in the peri-urban areas. According to the prediction about the built-up lands, the expansion of the built-up lands on the southern side, which was the main area in the prior time, will slow down. At the same time, the built-up lands will expand more on the eastern side in 2037. However, the findings of the flood-prone areas and suitable areas for urban development based on the integration of GIS with Weight of Evidence (WoE) and Analytical Hierarchy Process (AHP) indicate that most of the areas on the eastern side of Nong Khai City are flood-prone areas and least suitable area for urban development. The expansion of the built-up lands in Nong Khai City in the future thus is on the risk path to the increase in the exposure to floods. All the findings imply that Nong Khai is in the suburbanisation stage and needs the policies to manage the sprawl of the built-up lands in the peri-urban areas and maintain the economic role in the centre area to retain the population. According to the analysis of the built-up land expansion with different scenarios of policy implementation, the integrated policies (the policy to protect the expansion of the built-up lands in the flood-prone areas and the policy to support the settlement in a suitable area which provides a good environment in term of safety, accessibility, and policy to conserve the assets) are the most efficient way to reduce the expansion of the built-up lands in the flood-prone areas and least suitable area for urban development. The performance of the integration shows that the land-use management of a city in the floodplain cannot only concentrate on either the flood-prone area or the economic development, but it needs to consider everything to support the sustainable growth. As a result, Nong Khai City should be divided into three zones: a zone for urban development, a zone for non-urban development, and a restricted zone. About thirty percent of the total areas should be a restricted zone and avoid the transformation due to flood and waterbodies conservation. Almost fifty percent of the total areas were recommended for urban development with different policies.

Based on the findings, this study provides the scientific evidence to support the understanding of the expansion of the built-up lands in the small cities which required more attention. In addition, the application of GIS to support the urban management in the floodplain areas in the data-scarce environment also proved its performance and are presented through two crucial applications: the analysis of the flood-prone areas to create a flood susceptibility map and the analysis of suitable areas for urban development.

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Introduction

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1.1 Background of the study

Floodplain is a type of fundamental topography in which humankind usually settles and develops the communities. It has attracted the settlement and supported the economic growth (Associated Programme on Flood Management, 2016, p. 24; Dryden et al., 2021; Mazzoleni et al., 2021, p. 1; Schober et al., 2020, p. 1), due to the function of the floodplain that provides water supply for daily life, the fertile soil that is suitable for agricultural activities, the location that is near the water leading to the convenient transportation, commercial, hydropower and the beautiful scenario (Task Force on the Natural and Beneficial Function of the Floodplain, 2002, p. 1–1). In 2015, 34.6% of the world population and more than half of the population and the urban area in South Asia and Southeast Asia were distributed in floodplains (Dryden et al., 2021, p. 5). Dryden et al. (2021) indicated that the urban areas in the floodplains in 2015 were three times higher than those outside. Over the past years, the settlement in the floodplain areas increased worldwide. Cao et al.(2022, p. 1) indicated that the urban areas in the floodplains increased more than four times from1985–2018, and 12.6 % of the urban expansion from 1985 to 2018 occurred in the floodplains. Asia is the main location of the urban area expansion: the urban areas increased from 33.8% to 66.9% of the urban extent. In addition, Mazzoleni et al. (2021, p. 8) indicated that the population and the built-up areas increased in the floodplains in 64% and 80% of the analysed countries across the world, respectively. Furthermore, the built-up areas changed at a higher rate than the population in 70% of the countries between 2000-2015. While more than 80% of the floodplains in Europe and North American were also modified (Rajib et al., 2021).

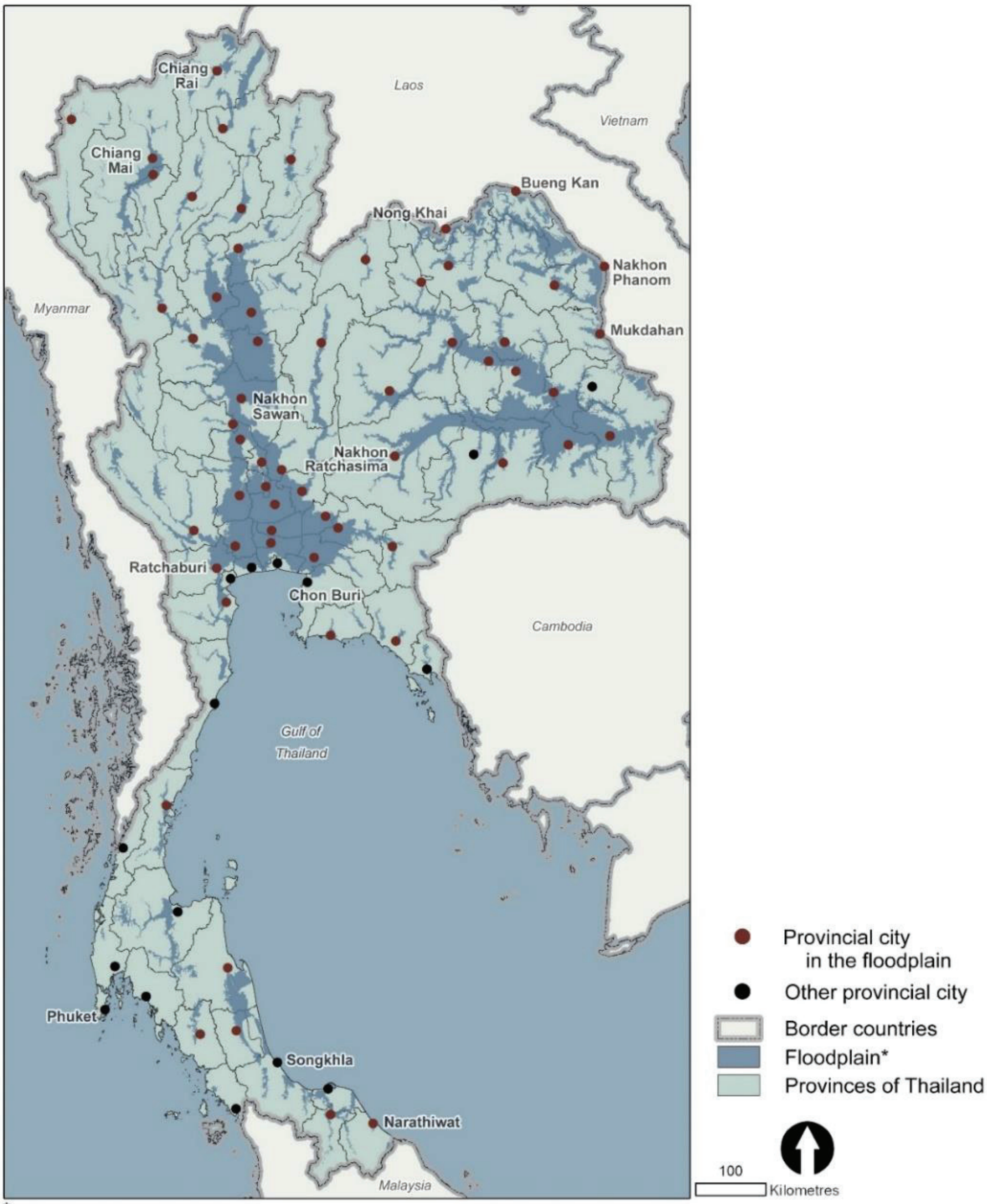
On a micro scale, the expansion of population and built-up areas on the floodplains was also reported worldwide. For example, Schober et al. (2020, p. 7) found that most grassland areas in the river floodplain of Innsbruck, the capital city of Tyrol in Austria, were replaced by highly developed areas. In addition, they also found that the developed areas also increased while the agricultural lands decreased along the floodplains of five Austrian rivers, and the change is still ongoing. The decreasing agricultural lands in the five Austrian river floodplains differ from the River Beas Floodplain of Punjab in India. Brar et al.(2020, p. 55) indicated that while the settlement areas increased, the agricultural lands increased from 1989 to 2015. In addition, Amoateng et al. (2018, p. 85) reported that 88 % of the floodplains and the rivers in Kumasi of Ghana in 1985 were transformed into urban land use in 2013 by encroachment and landfilling to respond to the population growth. Furthermore, Rajib et al. (2021) detected the land-use change in the Floodplain of the Mississippi River Basin between 1941 and 2000 and found that the change in the developed areas is a major land transformation. The trend of other land-use types decreased or fluctuated. The developed areas in the Mississippi River Basin floodplain were steadily increasing. Although many countries reported that the population and the built-up areas decreased in the floodplains between 2000–2015 (Mazzoleni et al., 2021, p. 8). The population and the built-up lands in the Southeast Asia are an ongoing main trend and still increasing, showing no sign of stopping (Cao et al., 2022; Tockner & Stanford, 2002).

The increasing built-up lands and population in the floodplains make the development be on the risk path. Many studies reported that the increase in the population and the built-up areas in the floodplains put pressure on the ecosystem and affect the environmental quality in various dimensions (Brar et al., 2020; Task Force on the Natural and Beneficial Function of the Floodplain, 2002, p. 3–1). Rajib et al. (2021, p. 2) have summarised the effects of land-use transformation in the floodplains as follows: reducing the storage and conveyance of natural flow, amplifying the flood risk due to the climate change, and hindering the ecosystem and human well-being. The replacement of the impervious surface with the natural surface increases the runoff and makes the flood more severe (Task Force on the Natural and Beneficial Function of the Floodplain, 2002, p. 3–3). Shrestha et al. (2021) indicated that a type of land use has a relationship with the surface runoff: the increase of the built-up lands and settlement as well as the decrease of farmlands, forests, and grasslands leads to the higher surface runoff in Xiamen city, China. In addition, Amoateng et al. (2018, p. 90) indicated that the transformation of the river and the floodplain in Kumasi into the urban land use decreased the water available in the river and caused the widespread flooding in the area.

At the same time, the increase of the built-up lands and the population in the floodplains also directly increases the exposure to flood, which is a local hazard in the floodplain areas (Associated Programme on Flood Management, 2016, p. 26). It is a natural phenomenon that helps the floodplain ecosystem and channel stability (Task Force on the Natural and Beneficial Function of the Floodplain, 2002, p. 2–1). Flooding affects the communities and damages life and property (Task Force on the Natural and Beneficial Function of the Floodplain, 2002, p. 1–1). According to the database of EM-DATA (https://public.emdat.be/data), more than 30 million died and 8 billion across the world were affected due to the riverine flood from 1900 to 2021. More than 66% and 85% of death and damages were in Asia, especially Eastern Asia and Southern Asia. The damage and loss due to floods were also reported at the local scale. For example, Ferdous et al. (2019) indicated that people in the Jamuna Floodplain of Bangladesh lost their income and assets during flooding. The expense in the flooding time also increased, making many households indebted. Hence, the growth of the developed area in the floodplain increases the possibility of severe damage and loss of population, assets, and economic activities. Ali (2013, p. 9) indicated that the significant increase in economic development in the floodplain of Indus Basin, Pakistan is the crucial cause of the flood in 2011 which hit the highest loss although the flooded area was smaller than the previous flood. Güneralp et al. (2015) indicated that the exposure to floods in the river floodplains will continue to increase due to the socio-economic forces, and the floodplains will be at high risk in the future. It is similar to the study of Du et al. (2018) which indicated that the built-up areas in the floodplains of China have still increased with a growth rate of 53.38 from 2015 to 2050, implying that the flood exposure continues to increase. Hence, although the settlement in the floodplains provides the beneficial functions of the floodplains, the development of the floodplains should be considered together with the damages from flood, a natural phenomenon in the floodplains which can lead to the loss and damage of the settlement. Mitigating the increasing urban exposure to flooding is a challenge for every country (Cao et al., 2022, p. 8). The restriction or avoidance of the socio-economic development in the floodplains was adopted and recommended to reduce flood exposure, losses, and damages (Associated Programme on Flood Management, 2016, p. 25). Itoshiro et al. (2021, p. 273) indicated that the restriction policy is the most efficient policy; it can reduce the highest expected financial damage in a standard case in Toyama, Japan. In addition, this method is at the lowest cost of risk in the planned duration compared to other measures.

As mentioned above, the urban extent of the built-up area boundary in the floodplain areas is a crucial indicator to estimate flood exposure (Cao et al., 2022, p. 2; Win et al., 2020), and the understanding of the urban extent will help the city planning in the floodplains to gain the benefits from the floodplains in terms of the urban development together with the decrease in the flood risk, the planning should track and balance the conservation, the social and economic development, and the susceptibility to flood damage (Task Force on the Natural and Beneficial Function of the Floodplain, 2002, p. 3–3). Here, the study of land-use change in the flood-prone areas gets more attention (Schober et al., 2020), and is applied to the land-use policy. For example, Junger et al. (2022) studied the land-use change in the Austrian Alpine region from 1826 to 2016 and found that the settlement areas increased, and the relative growth of the settlement development in the flood-prone areas was higher than those in the outside areas. This indicates the increase of flood-damage potential. At the same time, the areas of river channels and wetlands decreased. To manage the flood risk, it is essential to widen the rivers to reduce the damage in the future. Chen et al. (2019) also analysed the change of the built-up land and the cropland in China between 1995 to 2015 to identify the new built-up areas and croplands in the flood zone and determine the exposure of the built-up areas to flood hazards. It is similar to the study of Du et al. (2018), which studied the change of the urban land in the floodplain of China from 1992 to 2015 and found that the urban land increased rapidly by 542.21% and required an effective urban-control policy and flood risk management, especially in the basin which was not equipped with the flood protection. In other geographic contexts such as Lagos of Nigeria (Faisal Koko et al., 2021), Bhagirathi-Hooghly floodplain, East India (Kastha & Khatun, 2022), Kashmir valley, India (Alam et al., 2020), Aswan, Egypt (Hamdy & Zhao, 2016) and Danang, Vietnam (Huong et al., 2013), and Manila (Murakami & Palijon, 2005), the study of land-use change was also adopted to detect the expansion of the built-up lands in the flood areas and floodplains that needs to be controlled by the policy to mitigate or manage the sprawling.

For Thailand, as same as other countries, the floodplain is a crucial space to settle and develop the communities. Lindersson et al. (2021) indicated that approximately 30 million people live in the flood-prone areas in the floodplain, which cover about 20 % of the total areas of the country. Figure 1 shows that most of the provincial cities, which are the urban centre at the provincial level of Thailand, are distributed in the floodplains, according to a floodplain map developed by Nardi et al. (2019). It implies that most of the urban centres in Thailand have the potential to be flooded. Over the past year (1985–2018), the increase in the urban areas in the floodplains in Thailand was in the top-ten ranking in terms of (1) the annual growth rate of urban exposure to flood and (2) the ratio of urban exposure to flood and the total urban expansion areas (Cao et al., 2022, pp. 4,6). In addition, Mazzoleni et al. (2021, p. 9) also indicated that the increasing rate of the built-up areas and the population in the floodplains in Thailand between 2000–2015 was high.



*Data of floodplain derived from Nardi, F., Annis, A., (2018). GFPLAIN250m. figshare. Dataset. ttps://doi.org/10.6084/m9.figshare.6665165.v1

Figure 1 The distribution of the provincial cities on the floodplain

Although the previous study on the national scale indicates the increase of built-up lands in the floodplain area of Thailand over the past time, the study about the land-use change to detect the increase of built-up lands is focused on the BMR (Davivongs et al., 2012; Durina et al., 2013; Hung & Yasuoka, 2000; Jongkroy, 2009; Satoh, 1999; Yokota et al., 2020) and regional cities such as Khon Kean, Chiang Mai, and Nakhon Ratchasima (Chotchaiwong & Wijitkosum, 2019; McGrath et al., 2017; Shummadtayar & Ongsavangchai, 2018; Thebpanya & Bhuyan, 2015;

Thongyu et al., 2014; Yongvanit & Thungskul, 2013). Few studies focus on the provincial cities, although the number of provincial cities is larger. In addition, some provincial cities also encounter the sprawl of built-up areas from previous studies, such as, Nong Khai (Keeratikasikorn, 2018; Sakayarote & Shrestha, 2019), Bueng Kan (Sakayarote & Shrestha, 2019), Nakhon Phanom (Keeratikasikorn, 2018; Praweenwongwuthi et al., 2017), Mukdahan (Suvachananonda, 2019). Furthermore, some provincial cities in of the border towns, towns along the economic corridor, tourism-based towns, and special economic zones were estimated to be the emerging urban growth centres (Hakim, 2016, pp. 39–45). According to the development of the high-speed train, scholars estimated that any provincial cities along the route will grow up in terms of economy (Isono, 2018, p. 26; Subboonrueng & Sirirat, 2020, p. 66) and the development will cause the built-up area to sprawl to the peri-urban areas responding to the economic growth in the future. Thanks to the development, the built-up lands expanded naturally to respond to the economic growth. On top of that, the areas around the train stations tend to be developed to feed the users into the speed railway and enhance the confidence of the investors, leading the investment in the high speed train to achieve the cost-effective (Subboonrueng & Sirirat, 2020, p. 67).

In the current, the Bangkok-Nong Khai railway is constructing to link with the high-speed railway network in Vientiane, Laos, as part of the Pan-Asia Railway Network (Figure 2). The Pan-Asia Railway Network is an important project of the Belt and Road Initiative (BRI) which is a megaproject of the twenty-first Century that China proposed in 2013 to promote regional economic development through infrastructure development (Huang, 2016). The five priorities of the BRI are policy coordination, facilities connectivity, unimpeded trade, financial integration, and people-to-people bond (Zhang, 2018). Based on this, the development projects under the BRI are extensive and involve various stakeholders (Jin, 2017). However, these projects were developed under the national government-to-government agreement between China and the host countries (Jin, 2017; Russel & Berger, 2019; Zhang, 2018). Given the comprehensive projects covering the multiple dimensions and areas of the BRI regions, which cover the largest areas from the western Pacific to the Baltic Sea, including two-thirds of the world's population (Baloch et al., 2019), it can be implied that the BRI is a megaproject that will unavoidably affect the world in every dimension. The development of infrastructure in the BRI regions will boost the economy (Enderwick, 2018; Zhai, 2018). At the same time, scholars indicate that urbanisation patterns will accelerate and increase the population (Jing et al., 2020; Liu et al., 2018) and areas (Apostolopoulou, 2021; Gu et al., 2020). The BRI will expand the urban area boundary and create new cities along with the areas of developed infrastructure (Apostolopoulou, 2021; Gu et al., 2020).

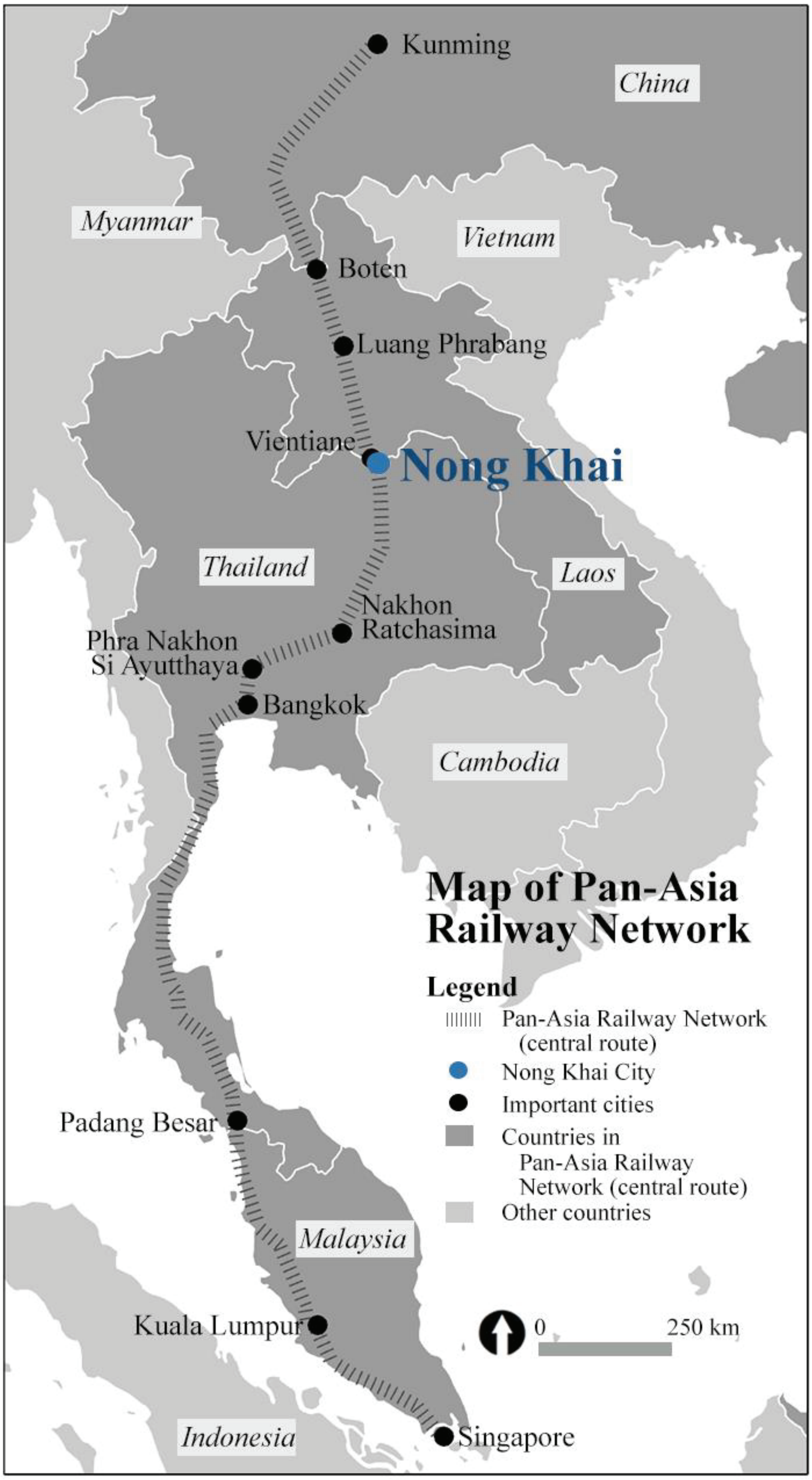


Figure 2 Map of Pan- Asia Railway network

Rich literature indicates that the High-speed railway (HSR) — the important infrastructure under the BRI's project—is crucial for accelerating economic growth and urbanisation (Heuermann & Schmieder, 2019; Ma & Liu, 2021; Verma et al., 2013). The opening of HSR has significantly promoted economic growth in the cities of the BRI by bringing in capital and foreign investment, labour, and innovation. Then, the resources will accumulate in cities and drive their economies (Li et al., 2020). In addition to economic growth, HSR also accelerates urbanisation (Momenitabar et al., 2021). Many studies indicate that HSR plays a significant role in changing the land to urban land use in China (Chen et al., 2021; Long et al., 2018; Zhu, 2021; Zhu et al., 2020) and Spain (Shen et al., 2014). Despite positive economic effects, the development of the high-speed railway network comes with some negative effects as well, such as changes in land-use types and expansion of built-up land that supports urbanisation (Shen et al., 2014). Previous studies have indicated that built-up land expansion destroys the natural ecosystem, resulting in unsustainable environments through biodiversity degradation (Hughes, 2019; Marina, 2008, pp. 73–76), pollution discharge (Dong et al., 2014) and increased flood damage (Oudin et al., 2018), eliciting social and health problems (Frumkin et al., 2004, pp. 131–135).

Although the previous documents only recorded the economic benefits of the Bangkok-Nong Khai railway (Isono, 2018; Subboonrueng & Sirirat, 2020), based on the evidence from other cities, the high-speed railway network tends to have impacts on the cities near the Bangkok-Nong Khai railway stations. Apart from connecting the infrastructures of Thailand and Laos, the high-speed railway network is expected to be a key mechanism for national and regional development (Pongsudhirak, 2019, p. 13). Consequently, the small provincial cities, especially along the HSR, should get more attention from scholars in terms of land-use change study in order to support the making of spatial plans to prevent the harmful effects of urban sprawl in the flood-prone areas due to the impending BRI development (BRI International Green Development Coalition, 2020; Zhao et al., 2021; Zhu, 2021; Zhu et al., 2020).

Although small cities are as crucial to urban systems as larger cities and are the key areas to develop the future economy (Tripathi, 2021). In Thailand and small cities worldwide, little attention has been paid to urbanisation and urban models (Bell & Jayne, 2009; Fahmi et al., 2014; Ocejo et al., 2020). Most understandings of small cities are usually derived from the generalisation of bigger cities. In fact, owing to their complexity, big and small cities do not share the same characteristics (Bell & Jayne, 2009). Thus, an understanding of big cities cannot describe the heterogeneity of small cities (Bell & Jayne, 2009; Fahmi et al., 2014). Insufficient consideration of the urbanisation of small cities has led to negligence in the policymaking relating to those cities; therefore, sustainable urban development cannot be achieved there (Wang et al., 2019). Besides

Thai academics, small cities across the world require more academics (Bell & Jayne, 2009; Yin et al., 2021) to study the land-use change and develop a suitable land-use policy that fits their contexts.

Over the last two decades that the anthropogenic activities transformed the land significantly, to support the suitable land-use policy for land management, the study of land-use change — conducted with the inventory from the remote sensing and aerial photographs (Bielecka, 2020, p. 12)— gets the attention in various dimension from the worldwide scholars ranging from the macro scale to the local scale (Bielecka, 2020; Magliocca et al., 2015, p. 212; Nedd et al., 2021). Scholars use the satellite remote sensing and aerial photographs as an inventory to identify and summarise the changes in the targeted areas (Nedd et al., 2021, p. 14). Bielecka (2020, p. 12) indicated that satellite remote sensing data and aerial photographs are crucial to describe the complex and heterogeneous land system. Although satellite remote sensing, like Landsat images, can track back the characteristics of the land uses in the past, there is a limit to the amount of the spatial data available (Magliocca et al., 2015, p. 215), especially for urban planners (Nedd et al., 2021). To develop the land-use policies, not only do the policymakers require the analysis of land-use change patterns from the satellite images, but also intense data about the ecological features of the landscape such as topography, geology, hydrology, vegetation, valuable resources, important ecological area, and the hazardous areas (Berke et al., 2006, p.149) to decrease the urbanisation effects on the environment. Based on the traditional analysis of land suitability by McHarg (1992, pp.108-109), eight main groups of ecological factors (climate, geology, physiography, hydrology, pedology, vegetation, wildlife, and land use) should be collected as the spatial data to support the land-use planning. In addition, the policymakers need to collect other data that are not related to the ecological feature such as the accessibility to infrastructure, the node of economic activities and economic information, population, planned land use and zoning, and planned infrastructure (Berke et al., 2006, pp.121, 179, 205), to detect the suitable area for urban development. Hence, to support the development of land-use policies, the policymakers need to prepare the rich spatial data from several sources to integrate into the GIS Framework which has the capability to manage and analyse the spatial data in order to recommend suitable policy for urban development.

Thanks to the technology development, spatial data is currently accessible through the local government agencies and other organisations to support urban planning and the study of land-use change such as the U.S. Department of the Interior, which provides satellite images that fulfil the limitation of aerial photos in the local areas. In addition, it provides the Digital Elevation Model (DEM), which is fundamental data to generate topography and hydrological information. Although the satellite remote sensing data can overcome the intense data requirement of the land-use policy development, other detailed socioeconomic data and topography information are also required for the development of the land-use policy in the GIS framework, especially the land-use policy to support the urban development in the floodplain areas that have encountered flood and need to delimitate the flood-prone boundary to consider the exposure, impact, and damage of flood. While developed countries like Japan and the United State of America can access the spatial data of flood-prone areas from government agencies, many developing countries don't have the information about flood-prone areas (Cotugno et al., 2021, p.1) to support the planning of land-use policies. In addition, the development of flood-prone area map for the developing countries is still obstructed due to the intense requirement of hydrological and meteorological data to create the flood-prone area map with the methods in the group of a physically based model, the traditional model to create the flood-prone map. The method requires long-period river flow and precipitation data from the gauge station and good resolution of topography and river geometry (Cotugno et al., 2021, p.1). The data to support the flood-prone area analysis is usually scarce (Kabenge et al., 2017; Lindersson et al., 2021, p. 2921; Task Force on the Natural and Beneficial Function of the Floodplain, 2002, p. 4–7; Trinh & Molkenthin, 2021; Win et al., 2020), especially for developing countries (Cotugno et al., 2021, p.1). Hence, these requirements turned out to be the major barrier to delineate the flood-prone areas to support the land-use policies in the floodplain area.

Recently, the spatial analysis under the data-scarce environment thus has gotten more attention from scholars, such as the analysis of hazard-prone areas (Aladejana et al., 2021; Dragićević et al., 2015; Lee et al., 2018), flood risk management (Win et al., 2020), flood-prone delineation and flood hazard map (Kabenge et al., 2017; Samela et al., 2017), the impact of land-use change on soil property (Mengistu & Waktola, 2016), the land-use change and ecosystem(Wangai et al., 2019), and the change of forestlands (Santos et al., 2019). Although several scholars attempt to analyse the spatial phenomenon like the flood-prone areas in the data-scarce environment, the integration of the analysis of the flood-prone areas and the suitable area analysis for urban development in the data-scarce environment into the land-use policies in order to manage the built-up area expansion is still limited. The process to develop the land-use policies in order to manage the built-up area expansion on the floodplain in data-scarce environments thus is not complete and needs evidence to fulfil the process of land-use policy.

Thailand is similar to other developing countries. The socio-economic spatial data to support the land-use policy is limited due to the undocumented information and privacy condition of the government. For example, the population data, which is fundamental data to support accurate land-use policies, is available publicly only at the sub-district level while the population data and boundaries of villages are not accessible due to privacy conditions. The economic information at the household level and the economic activities within the city boundary are also undocumented. The data about the utility network and public infrastructure, including the boundary of the conserved areas, is difficult to access. In addition, the information about the physiological features is limited, especially the feature to support the development of flood-prone maps. Although most provincial cities of Thailand are distributed on the floodplain, the boundary of flood hazards in each city is not available. To integrate the flood-prone areas into the process of city planning, the policymakers need to identify the flood-prone area to support the land-use policy of the small provincial city on the floodplain. However, it is similar to other developing countries that the hydrological and meteorological data from the gauging stations in the long-term series are scarce. In addition, the precise river section of small rivers and waterways is also limited. The scarcity of spatial data to indicate the boundary of flood-prone area and suitable areas for urban development in Thailand to support the city planning policy is still a challenge and needs evidence to support the application in the future, especially in small provincial cities which are lacking the spatial data and staff to collect the data with field survey.

To summarise, the background of the study about the built-up area expansion on the floodplain at a global scale and in Thailand reflects that in terms of the theoretical background, many previous studies about the built-up area expansion focused on the capital city and the regional cities of Thailand leading to the limited understanding of the built-up area expansion in the small provincial cities, which also encounter the urbanisation. In terms of practical background, although GIS and remote sensing technology support the study of built-up area expansion and the related policy, the policies to support the built-up area expansion of the provincial cities on the floodplain are obstructed due to the scarcity of spatial data causing the application of policies to manage the built-up areas to be limited and in need of the evidence to support the development of land-use policy in the data-scarce environment.

As mentioned above, the gaps in this study can break down into two points as follows:

(1) the understanding of the built-up area expansion in the small cities on the floodplain, which is the main topography of the provincial cities in Thailand, is limited

(2) little evidence is available when it comes to the application of GIS to support the land-use policy of the small cities on the floodplains in the data-scarce environment.

To fill the gaps, the attention to the study of land-use change in the small cities in the floodplains is required to analyse the pattern of the built-up land expansion and apply the GIS to the land-use planning in order to manage the built-up land expansion in the floodplains. Nong Khai City was selected as a representative in this study. It is a provincial city in the northeastern region located on the floodplain. Due to the location, which is the border city between Thailand

and Laos, Nong Khai city thus is the terminal station of the Bangkok-Nong Khai railway, part of the Pan-Asia Railway Network (Figure 2). As a terminal station, a small provincial city like Nong Khai is attractive because the city will grow economically (Office of Transport and Traffic Policy and Planning, 2016) from the role of the international logistics hub that connects with Vientiane Laos. Although no study has analysed the patterns and influence of urban expansion in Nong Khai City due to the BRI, existing studies show that it is experiencing urban expansion, even without the HSR construction (Keeratikasikorn, 2018; Saiyarod, 2018). In addition, some studies mentioned earlier also claim that there is a relationship between HSR and built-up land expansion. Hence, it can be inferred that after HSR is available, Nong Khai City will unavoidably encounter urban expansion. Like other provincial cities in Thailand, Nong Khai City is a small city with few lessons about land-use changes. Most previous studies (Boonkrajangsopee, 2009; Klinchat, 2003; Suvathi, 1995) have concentrated on settlement development or built-up land expansion before and after the Thai-Lao Friendship Bridge's construction. Although Nong Khai City was merely one part of the study areas in provincial- and regional-scale studies over the past three years, the time period for these studies extends into the 2010s (Keeratikasikorn, 2018; Sakayarote & Shrestha, 2019). The understanding of built-up land expansion in Nong Khai City still is limited.

Because Nong Khai City is encountering the expansion of the built-up areas, and the expansion keeps increasing due to the development of HSR, it is necessary to track the expansion of the built-up lands in Nong Khai City and provide the recommendation to manage the expansion of the built-up lands in the floodplain in the future. Hence, Nong Khai City is an interesting case suitable to be a representative of the small provincial cities in Thailand. In addition, at the macro scale, the case study in Nong Khai City is suitable for the small cities in BRI that may encounter urbanisation in the future.

1.2 Problem statement and objective

As mentioned in the introduction, the crucial limitations consist of two parts: (1) the understanding of the expansion of the built-up areas in the small cities on the floodplains in Thailand and (2) little evidence on the application of GIS to support the land-use policy of the small cities on the floodplains in the data-scarce environment. Based on these gaps, two research questions (RQ) were asked to shape the dissertation structure by focussing on Nong Khai City as follows:

RQ1: How have the built-up lands of Nong Khai City changed?

RQ2: How can GIS be applied to develop a suitable policy to manage the built-up area expansion in the data scarce environment?

To answer the questions, the main objectives of this dissertation are:

(1) to clarify the patterns of the built-up land expansion in Nong Khai City, which is a small provincial city on the floodplain, from past to the future.

(2) to apply the GIS technique to develop the land-use policies in the data-scarce environment in two dimensions: (1) the flood-prone area analysis and (2) the analysis of the suitable areas for urban development and the evaluation of the impact of land-use policies in order to manage the built-up area expansion in the flood-prone area and the least suitable area for urban development.

Chapter 2-7 states the sub-objectives responding to the main objectives as shown in Table 1.

Table 1

Objectives of the study

Research Question	Main objectives	Sub objectives	Chapter
(RQ1) How have the built-up lands of Nong Khai City changed?	(Objective 1) To clarify the patterns of the built-up land expansion in Nong Khai City, which is a small provincial city on the floodplain, from past to the future.	• To describe the pattern of settlement and land-use of north-east in premodern time, when no mapmaking or developed survey methods were available, through *Nirat Nongkhai* and related historical documents	Chapter 2
		• To analyse and categorise the provincial cities in Thailand based on the patterns of the urban population changes as well as the urban population concentration and its changes.	Chapter 3
		• To clarify built-up expansion patterns and demonstrate the driving factors of built-up land expansion of Nong Khai City during the 1997–2017	Chapter 4
		• To predict the expansion of the built-up lands in Nong Khai City between 2027–2037 under the different scenarios	Chapter 7
		• To analyse the expansion of the built-up lands in Nong Khai City between 2027–2037 in flood-prone areas and the least suitable areas for urban development	Chapter 7
(RQ2) How can GIS be applied to develop a suitable policy to manage the built-up area expansion in the data scarce environment?	(Objective 2) To apply the GIS technique to develop the land-use policies in the data-scarce environment in two dimensions: (1) the flood-prone area analysis and (2) the analysis of the suitable areas for urban development and the evaluation of the impact of land-use policies in order to manage the built-up area expansion in the flood-prone area and the least suitable area for urban development.	• To create the flood susceptibility map (FSM) of Nong Khai City in support the land-use policy of the small provincial city on the floodplain in the data-scarce environment. Under the main purpose, this chapter consists of three objectives: (1) To clarify the effects of the conditioning factors of flooding in Nong Khai City, (2) To implement the statistical modelling methods to create the FSMs of Nong Khai City, and (3) To compare the performance of each model from AUC and create the FSMs	Chapter 5
		• To assess the land suitability for urban development in Nong Khai City using AHP in order to determine the suitable and non-suitable areas to support the land-use policy planning of urban development in the future.	Chapter 6
		• To evaluate the impact of land-use policies from chapter 5 and 6 in order to manage the built-up area expansion in the flood-prone area and the least suitable area for urban development in the future.	Chapter 7
		• To recommend the land-use zoning policy of Nong Khai City based on the best scenario	

1.3 Thesis structure and methodology

The dissertation is divided into eight chapters, as shown in Figure 3. Each chapter responds to the research questions and the main objectives with different methodologies.

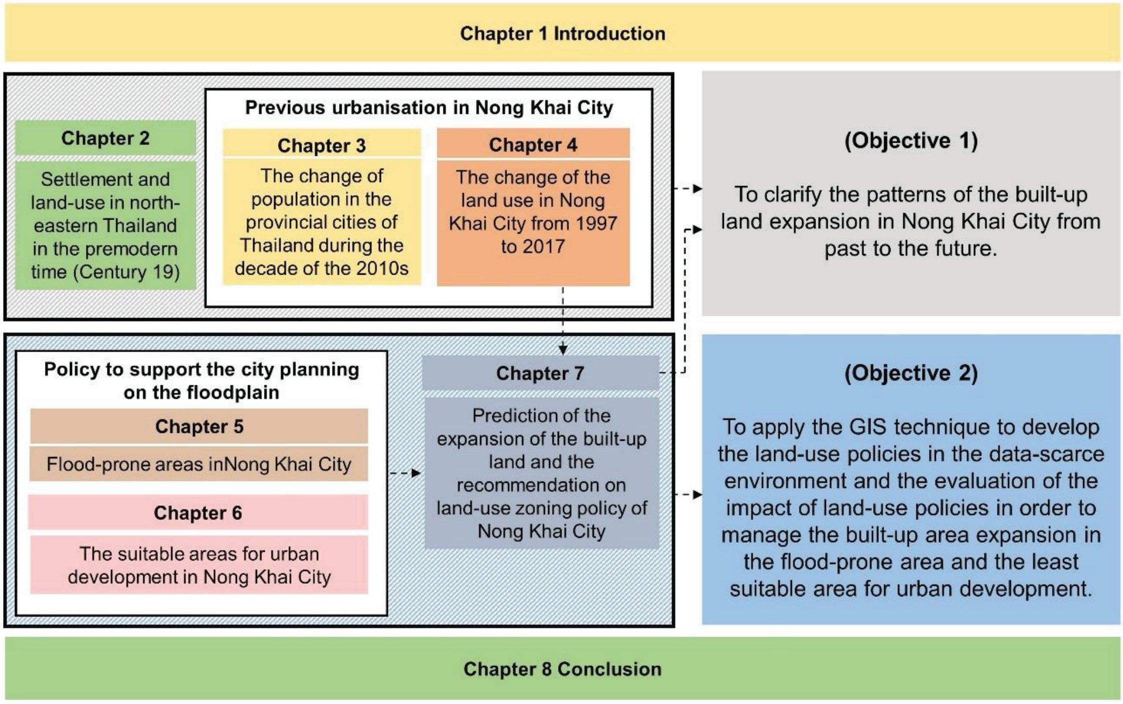


Figure 3 Structure of dissertation

From Figure 3, this dissertation consists of four groups. The first group is chapter 1 introduction. In this chapter, the gap of the study was reviewed to form the research questions and objectives. Then the main objectives and sub-objectives in each chapter were pointed out and the information of Nong Khai City was presented.

The second group consists of Chapters 2-4. The chapters in this group aim to respond to the first research question: how have the built-up lands of Nong Khai City changed? The study of Chapters 2 and 4 concentrated on the land use in the past. ***Chapter 2 'Settlement and land-use in north-eastern Thailand in the premodern time (Century 19)'*** was analysed with a narrative approach and conceptual cross-section to present the settlement and land-use patterns in the northeastern region in the premodern time when there is no data from the remote sensing and scientific surveys which are crucial to the land-use study. Although *Nirat NongKhai*, the main resource in this chapter, did not recorded the data on settlement and land use in Nong Khai City, the finding from the interpretation of *Nirat Nongkhai* was discussed with other historical documents to construct the knowledge of settlement and land use of Nong Khai City in the overview. Then, the urbanisation of Nong Khai City was clarified in terms of the built-up area expansion to support the understanding of built-up area expansion of the small provincial city. The land-use of Nong Khai City in the past was analysed from the data from the satellite remote sensing to identify the patterns of the built-up land expansion from 1997 to 2017 in Chapter 4 **'The change of the land use in Nong Khai City from 1997 to 2017: patterns and driving factors of the built-up land expansion as a representative of the small provincial cities in the China's Belt and Road Initiative.'** In this chapter, the supervised classification with the maximum likelihood classifier (MLC) algorithm was performed to classify the satellite images from Landsat in 1997, 2007, 2017 to produce the land-use maps. Then the combine function was used to determine the expansion of the built-up lands. To understand the change of the built-up lands, the logistic regression was adopted to analyse the driving factors of the built-up land expansion between 1997–2007 and between 2007 to 2017.

Although this study concentrates on the change of the built-up lands which is a physical term, the change of the urban population, which is part of urbanisation, was presented in ***Chapter 3 'The change of population in the provincial cities of Thailand during the decade of the 2010s.'*** to provide the understanding of built-up lands as an urbanisation process. In this chapter, the changes in the urban population in the provincial cities of Thailand were analysed and categorised into the groups of provincial cities, based on the indices of the population change patterns. The changes of the population in the provincial city of Nong Khai was analysed and categorised with other provincial cities. In addition, the population in the peri-urban area of Nong Khai City was analysed with the population in the provincial city, which was assumed as the core area, to determine the urbanisation stage.

The third group covers the information of Chapters 5-7 that were studied to respond to the second research question: how can GIS be applied to develop a suitable policy to manage the built-up area expansion in the data scarce environment? In general, to manage the built-up area expansion, the land-use policy should provide the information about the suitable area that the urbanised areas are welcomed or restricted. In addition, for the floodplain area the land-use policy should consider the decrease of the sprawl of the built-up lands in flood-prone areas to reduce the exposure to flooding. Based on these conditions, the information to support the policies to manage the built-up area expansion was studied in two dimensions in Chapters 5-6 by considering the data-scarce environment.

Due to the limitation of flood-prone map that is an important tool for support the built-up area expansion on the floodplain. ***Chapter 5 'Flood-prone areas in Nong Khai City'*** thus was assigned to identify the flood-prone areas in Nong Khai City by producing flood susceptibility maps (FSMs). Seven models — four standalone models of the statistical modelling method and three ensemble models — were adopted. Their performances to generate the FSMs were assessed, and the best model was selected to create the flood susceptibility map of Nong Khai City. In addition, not only did the flood-prone areas should be considered in the policy to manage the built-up area expansion, but the built-up areas should also be designated in a suitable area to mitigate the effect on the environment and provide accessibility. ***Chapter 6 'The suitable areas for urban development in Nong Khai City'*** was analysed to determine the suitable and non-suitable areas for urban development in Nong Khai by using AHP.

While Chapters 5-6 identify the flood-prone areas, the suitable areas, and non- suitable areas for urban development to support the land-use policy of Nong Khai City, ***Chapter 7 'Prediction of the expansion of the built-up land and the recommendation on land-use zoning policy of Nong Khai City'*** was studied to evaluate the impact of the policies from chapters 5-6 on the expansion of the built-up area by comparing with the expansion of the built-up area in the same trend without the policy. So, in this chapter, the boundary of flood-prone areas from chapter 5 and the boundary of the suitable areas and non-suitable areas for urban development from chapter 6 were derived and integrated to create the scenario and predict the built-up area in 2027-2037. The decision Forest Machine Learning (DF Machine Learning) and Markov Chain were selected to predict the built-up area expansion on the Land Change Modeler. To evaluate the impact of the policy, the flood-prone and the least suitable areas for urban development were used to prove the suitability of the built-up land expansion in each policy. Then, the best policy to control the built-up area in flood-prone areas and the least suitable area for urban development was selected to make the recommendations for land-use policy zoning in the last steps.

In addition, Chapter 7 does not only respond to research question 2 which focuses on the land-use policy to manage the built-up area expansion. The prediction of built-up areas in the normal scenario without the policy also answers research question 1. The result of the expansion of built-up areas in chapter 4 was integrated with the built-up area expansion in 2027 and 2037 to explain the expansion of the built-up lands of Nong Khai City from the past to the future which is the research question 1.

Finally, in ***Chapter 8 'Conclusion',*** the finding from chapters 2-7 were summarised and the future research direction was provided.

1.4 The significance and originality of the study

Floodplain is a fundamental topography to settle and develop the urban areas. Most of the provincial cities are distributed on the floodplains which are likely to encounter floods. Over the past few years, the built-up areas in many provincial cities in Thailand have been expanding into the peri-urban areas and increased the exposure to floods unavoidably. However, the study of the built-up lands in the floodplain areas — in which the built-up area changes are tracked and the exposure of flood is investigated to see the potential loss and damages — focuses only on the BMR and regional cities while the study on the small provincial cities that also encounter the expansion of the built-up lands is limited. The limitation of the case study on the small provincial cities causes the lack of knowledge about the urbanisation or the change of built-up areas and affects the planning to manage the built-up areas in the peri-urban areas although many small provincial cities tend to grow up in the future.

Although the current knowledge about land-use changes and the application of GIS to support the urban planning in terms of the land-use policy development to manage the sprawl of the built-up lands in the unsuitable area was applied from the worldwide cases, the analysis under the data-scarce environment is still a challenge. Most small cities and areas in the developing countries are typically lacking the spatial information to support the urban planning which requires a number of data to respond to the complex urban system, especially in the case of the cities on the floodplains that needs to consider the flood hazard and requires the complex data to generate a flood susceptibility map.

Based on these situations, the dissertation fulfils the understanding of the built-up land expansion and the application of GIS to create a flood susceptibility map and a suitable area for urban development in the data-scarce environment. In terms of theoretical framework, the study of built-up areas of Nong Khai City was clarified as the representative of a small provincial city. Based on the patterns of built-up area expansion of Nong Khai City, the model of the built-up area expansion in a small provincial city on the floodplain was developed to fulfil the understanding of built-up area expansion in the small city. It was categorised into three stages to explain other small provincial cities on the floodplain. Here, two small provincial cities on the floodplain along the Mekong River were selected to support and validate the model, emphasising the originality of this study in terms of a theoretical framework.

In terms of practical framework, the methodologies to create flood-prone areas and suitable areas for urban development were provided, and their performances to support the land-use policy were proved in the data-scarce environment. For the flood-prone area analysis, based on the data-scarce environment that the hydrological and meteorological data are not available due to the lack of gauging station, this study adopted the statistical model that require less data from gauging station. To extends the previous study, Modified Frequency Ratio (MoFR), the popular model to analyse the landslide-prone area, was adopted to compare the performance for identifying flood susceptibility with the other traditional statistical model for flood susceptibility areas such as Frequency Ratio and Weight of Evidence. Although the MoFR does not achieve the highest accuracy, the difference in the best model from other previous studies confirms that in order to apply the statistical modelling to create a flood-prone map that is a suitable method for a data-scarce environment, policymakers should compare the potentials of the models before creating the last flood-prone map. For the analysis of the suitable area for urban development, although AHP was performed worldwide to support urban planning, the method still has the limitation in the practical term due to the mixture of spatial characteristics in each suitability level. This study extends the performance of the AHP by integrating the grouping analysis to categorise the suitable areas based on the spatial characteristics. The zones of the suitable areas with the spatial characteristics help the policymakers to easily assign a suitable policy for each zone. In addition, it also helps the policymakers to identify the suitable areas and non-suitable areas for urban development from a vague suitability level like the marginally suitable area for urban development.

Because previous studies concentrate on delimitating the boundary of flood-prone areas and suitable areas for urban development, the application of these boundaries to urban planning in order to manage the built-up area expansion is limited. The integration of policies from the analysis of flood-prone areas and the suitable area for urban development as the scenario to predict the built-up area expansion in a data-scarce environment thus extended the findings of the previous studies. It helps the policymakers to understand the role of each boundary to control the expansion of the built-up areas. While the land-use policies of Thailand focus on the control the built-up areas through the rural and agricultural lands with flexible restriction policy and less concentration on flood hazards, the result from the implication of these policies on the built-up area expansion reveals that in order to manage the built-up area expansion in the floodplain area, the land-use policy of the small provincial cities in Thailand should be adjusted by integrating the restriction of built-up areas in the flood-prone areas and the support of built-up areas in suitable areas for urban development together with the policy to discourage the development of the built-up areas in the non-suitable area for urban development.

To summarise, in terms of practical framework, the originality of this study is the attempt to provide the methods to create the land-use policy for a small provincial city on the floodplain in a data-scarce environment. To support the suitable method for the analysis in the data-scarce environment, this study attempts to decrease the limitations by comparing various statistical methods to create the flood-prone maps. At the same time, this study also develops the capacity of the existed methodology to create policies. The extension of AHP performance by integrating the grouping analysis to categorise the areas in each suitability class based on the spatial characteristics making the policymaker easily develop the land-use policy is one of the originalities in the practical framework of this study. Furthermore, the originality of this study also occurs in the planning process. This study offers the evidence for the planning process of the small provincial cities by integrating the policy from the flood-prone area analysis and the suitability area analysis into the prediction of built-up areas to evaluate the suitable policy for built-up area expansion.

The significance and originality imply that this study is the scientific evidence to support the urban planning of small cities on the floodplain. The policymakers in the small cities on the floodplains can use the methodology in each chapter as a guideline in the planning of land use in floodplain areas with spatial limitations. Not only does the scientific information in this study contribute to the small cities on the floodplains in Thailand, but it is also a valuable reference for other small cities in the BRI region that will encounter rapid urbanisation due to infrastructure development.

In addition, to clarify the significance of this dissertation, the findings in some chapters were published in the academic journals to extend the knowledge from the academic perspective. The information of some chapters was published in the creditable journals as shown in Table 2.

Table 2

List of publications

Chapter	Publication	Significant of the study
Chapter 2	Bamrungkhul, S. & Tanaka, T. (2022). Reinterpreting Nirat Nongkhai: an historical account of settlement and land use in north-eastern Thailand during the nineteenth century. *Landscape History, 43*. https://doi.org/10.1080/01433768.2022.2064124	• Providing the understanding of the settlement and land-use patterns in the Northeastern region of Thailand in Nineteenth century that fulfil the gap in the landscape history of North-eastern, Thailand
Chapter 3	Bamrungkhul, S. & Tanaka, T. (2022). Until the wilting day: an analysis of urban population changes in provincial cities in Thailand from 2010 to 2019. *Journal of Asian Architecture and Building Engineering*. https://doi.org/10.1080/13467581.2022.2077736	• First scientific evidence clarifying the phenomena of shrinking and stagnant cities in Thailand • Require the policymakers to consider the shrinking cities in the trend of urbanisation.
Chapter 4	Bamrungkhul, S. & Tanaka, T. (2022). Patterns and Driving Factors of Built-up Land Expansion in Small Provincial City in the Belt and Road Initiative: Case Study of Nong Khai City, Thailand. *GeoJournal*. https://doi.org/10.1007/s10708-022-10681-w	• Describe the change in built-up areas and land-use change in Nong Khai City, which is a small provincial city, based on the information from the quantitative approach.

Table 2 (continued)

Chapter	Publication	Significant of the study
Chapter 6	Bamrungkhul, S. & Tanaka, T. (2022). The assessment of land suitability for urban development in the anticipated rapid urbanization area from the Belt and Road Initiative: A case study of Nong Khai City, Thailand. *Sustainable Cities and Society, 83*. https://doi.org/10.1016/j.scs.2022.103988	• Apply grouping analysis to extend the performance of AHP to clarify the suitable areas for urban development in the conditions of a data-scarce environment. • Raise the importance of policy to conserve cultural assets as a crucial part to detect the suitable area for urban development.

1.5 Target area

Nong Khai City and its surrounding region is a provincial city lying along the Mekong River in the northeastern region of Thailand. Nong Khai City locates on the floodplain. The entire area comprises flat plains and natural levees, with elevations ranging from 107 to 210 metres on average. At the beginning of the 19th Century, the city was dense along the Mekong River, but the transportation network development connecting to other areas transformed the urban morphological pattern into a ribbon settlement, particularly after construction of the Thai-Lao Friendship Bridge in 1994 (Klinchat, 2003). At that time, the buildings in the city began to sprawl into peri-urban areas. Most urbanisation occurred near the main transportation network (Boonkrajangsopee, 2009; Klinchat, 2003).

Besides being a significant trigger of built-up land expansion, transportation convenience owing to the Thai-Lao Friendship Bridge impacted the local economy. After the bridge was completed, the city became the international centre of trade, transportation and inventory (Haddad et al., 2006, pp. 17–18). Trade volume at Nong Khai Border Checker rose from about US$245.27 million in 2003 to about US$1.88 billion in 2017 (Bank of Thailand, 2022). Trade's significance also was reflected in the export value at Nong Khai Border Checker, accounting for the highest share of 41.72 % of the total cross-border export value to Laos in 2017 (Department of Foreign Trades, p. 24). Thus, after the bridge was completed, Nong Khai City was not only a local economic hub, like other provincial cities, but also an international economic and trading centre connecting Thailand and Laos. OECD (2018, pp. 58,64) indicates that Nong Khai had an advantage in terms of trading and capital via its proximity to Laos. Nong Khai had the highest average growth rate of productivity in the Northeastern region during the 2001–2015. The city's economic growth was reflected through the monthly average income of people in Nong Khai Province, which increased from US$336.69 per month in 2002 to US$648.08 in 2017 (National Statistical Office, 2022). In the future, the Bangkok-Nong Khai railway's importance should increase dramatically. Nong Khai City will grow economically and become an international gateway for the high-speed railway. According to estimates from the Office of Transport and Traffic Policy and Planning of the Ministry of Transport (2016), construction will increase long-term gross provincial product in Nong Khai Province to as high as US$2.23 billion by 2052.

As shown in Figure 4, Nong Khai City and its surrounding areas comprise eight subdistricts with an area of approximately 189.57 km^2. According to the Thesaban Organisation Act 1953 which determines the urban areas in Thailand, the provincial city of Nong Khai, designated from the boundary of Thesaban Muang Nong Khai, covers about 4.50 km^2 containing two sub-districts (Nai Mueang and Mi Chai subdistricts) and some parts of six sub-districts. Its core city is in the Nai Mueang subdistrict, comprising the original community and public amenities. Other subdistricts surrounding it serve as peri-urban areas that support the growing number of government offices, accommodations, trading areas, train stations and the Thai-Lao Friendship Bridge.

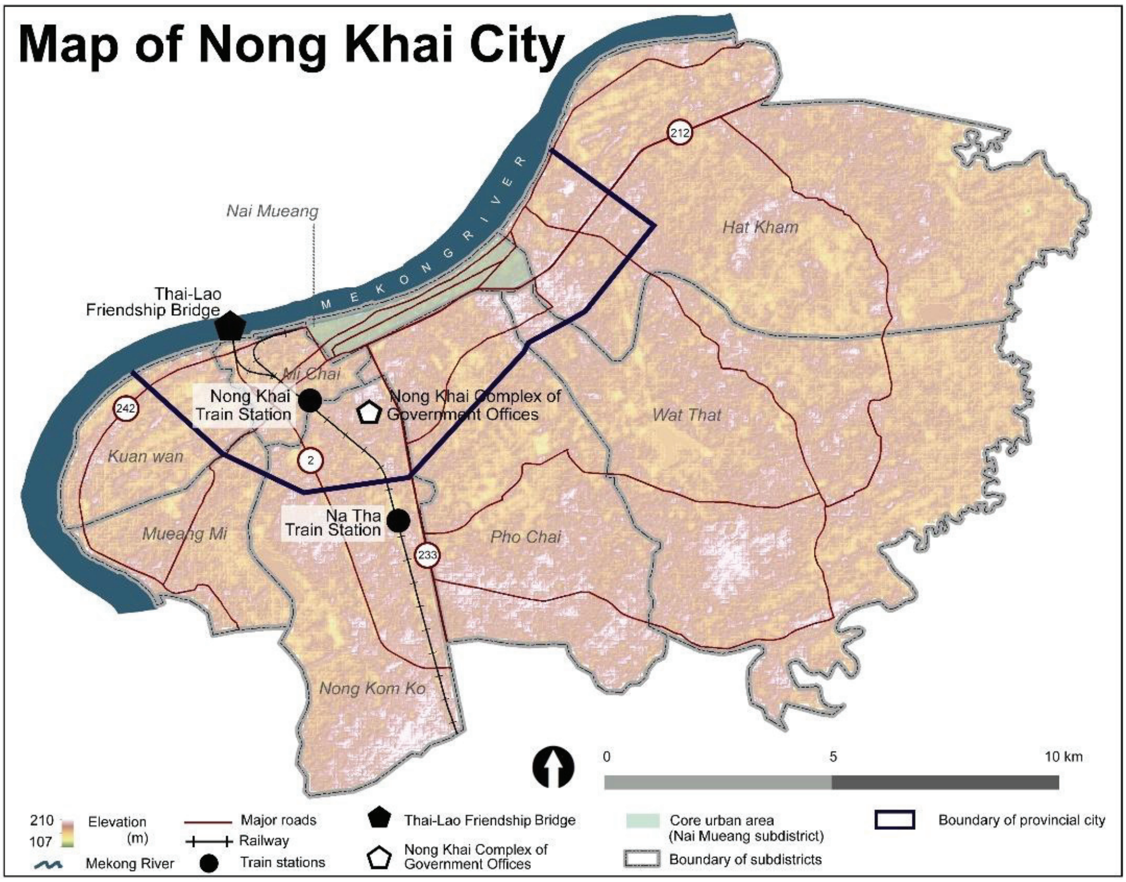


Figure 4 Study area

During the 1997 and 2007 period, Nong Khai City's population increased from 83,696 to 87,246, then to 90,968 in 2007 and 2017, respectively. Regarding population-change patterns within a subdistrict, the Nai Mueang subdistrict's population decreased from 23,894 in 1997 to 17,383 in 2017. However, the surrounding subdistrict's population increased from 58,802 in 1997 to 73,585 in 2017. The population distribution pattern indicates that Nong Khai City has been influenced by suburbanisation, with its population increasing in peri-urban areas, while the core city's population decreased. The population increase in the peri-urban areas mainly occurred in the Nong Komko subdistrict, the site of the Nong Khai complex of government offices and Khon Kaen University (Nong Khai campus). The population in Nong Komko subdistrict increased from 8,428 in 1997 to 12,432 in 2017.

To sum up, more than two decades after the construction of the Thai-Lao Friendship Bridge, Nong Khai City developed into a provincial city that is important in terms of trade and transportation between Thailand and Laos. During this period, there has been built-up land expansion and population growth in surrounding areas.

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Chapter 2

Settlement and land-use in north-eastern Thailand in the premodern time (Century 19)

Contents

2.1 Introduction

Currently, there is little understanding of the landscape and settlement pattern characteristic for the north-east of Thailand in the nineteenth century. The region included the inner areas of the country and was considered terra incognita by both foreigners and Siamese people, especially when compared with regions located in coastal areas or near the Chao Phraya Delta (Kennedy, 1970, p. 319; Terwiel, 1989; Winichakul, 2009, pp. 113–115, 119–120). These regions, including their landscape and settlement patterns, were described in numerous historical documents and foreigners' travel journals. However, the specifics about the north-eastern region that were recorded in historical documents and legends were considering politics and government. As for historical maps, which represent an important database for studying landscape and settlement changes in the past (Kinda & Uesugi, 2010), no information about this region appeared on maps from the earlier period, such as *Carte du Royaume de Siam et des Pays Circonvoisins*, a classical Thai map made in 1686. The same goes for maps from later periods, such as Pieter Van der Aa's 'From the Shores of Gujarat, Malabar, Bengal and Malacca, to the Kingdom of Siam and China in the East' made in 1707, and Jacques Bellin's *Le Petit Atlas Maritime* made in 1764. A few historical maps showed information about space in the north-east. Some of the examples are Francois Valentijin's *De Groote Siamse Rievier Me-Nam, ofte Moeder der Wateren in haren loop met de in vallende Spruyten Verbeeld* published in 1724–1726; the maps in the royal map collections (*i.e.* Khmen Nai Ni, Southern Isan and Khmer, and Isan), which were presumably drawn during the period from the late eighteenth century to the mid-nineteenth century (Phasuk & Stoot, 2004, pp. 32, 50); and the strategic map from the reign of Phrabat Somdet Phra Ramathibodi I, presumably developed during the mid-nineteenth century (Phasuk & Stoot, 2004, pp. 202–203). These historical maps are not presented in terms of Buddhist cosmography and sacred topography, which are pre-modern Thai frameworks on space (Winichakul, 2009, p. 20). Instead, they demonstrate spatial information based on reality, contributing to a rougher understanding of the landscape and settlement patterns in the north-east (Kennedy, 1970, pp. 316–318, 321–322; Phasuk & Stoot, 2004, pp. 132–135). However, the information in these maps was imprecise because of limited scale and technologies at that time, and the ambiguous purpose of mapmaking (Kennedy, 1970, pp. 320–322; Terwiel, 2017, p. 90). Thus the maps from royal map collections, compared with other historical maps, provide more information about the north-east landscape and community. They detailed the trees, topography and communities' names. Despite this, they still exhibit some limitations, such as the map writing on a large scale, and rather ambiguous pictograms, so it is not possible to be certain whether the specific geographical features were truly useful or merely and generally served as decoration (Ginsburg, 2004, p. 46).

Later, in the late nineteenth and early twentieth century, Siam adopted a scientific map-making method, and foreign surveyors were more interested in this region. However, it is irrefutable that information from the new maps and survey reports could not provide a deeper understanding of the past landscape (Moore, 1988, pp. 24–26). The knowledge and understanding of the settlement patterns of the north-east in the past became more evident during and after World War II, when field surveys began to take place, and aerial photographs were applied to explore and gain a better understanding of the topography and settlement patterns. It is undeniable that the survey results further expanded the knowledge about the settlement and the land uses in the north-east in the mid-twentieth century, with the changes triggered by transportation and regional development, especially the rice field expansion in the north-east. Moreover, the information from the surveys became a significant database for scholars to better understand the patterns of the ancient settlements in the north-east in the first millennium A.D. (Moore, 1988, pp. 26–34; Supajanya & Vanasin, 1986).

However, there is not much information about the landscape and settlement patterns in the nineteenth century. The lack of information and limited resources for studying this area have created an important gap in the landscape history of north-eastern Thailand.

Travel journals and cultural literature have long been used by humanists and sociologists to study the interrelationship between humans and the environment, as well as geographical phenomena such as landscapes, settlement patterns, and land use types (Hones, 2018, pp. 146–147; Komeie, 2010, pp. 225–226; Terwiel, 1989, p. 14; Wright, 1926, pp. 477–480, 485–486). This is because they provide the information necessary to understand the environment of a city, geographical phenomena, landscapes, and society, especially during a period when no map making or developed survey methods were available (Goodchild & Gong, 2014, p. 13; Komeie, 2010, p. 223). Travel journals and cultural literature are thus parts of the resources that scholars have always used to study and reconstruct the topography, landscape and human settlement in each period.

Depending on the authors' writing style and techniques, landscape information may appear explicitly in the text or may be implicitly demonstrated in the context setting. For this reason, in some cases, an analysis of landscape components, such as information about settlement and land use, is similar to a setting analysis (Lando, 1996, p. 4). Setting is a crucial component in the literature, and its role is not just a backdrop (Houston, 2019, p. XIV), but also a good source of information about the history, topography, people, and cultures mentioned in the piece (Jeremiah, 2000, p. 25). It implies both the location and time; for location, it includes a geographical location, social environment, landscape, and weather conditions (Kennedy & Gioia, 2007, pp. 112–113;

Risley, 1978, p. 23). Accordingly, an analysis of the setting and activities described in the literature offers useful insights into the context of a particular landscape.

Nirat is a form of ancient Thai literature that presumably has existed since the early sixteenth century (Chitakasem, 1971, p. 141). It is mostly used to describe a poet's emotions, as well as the events that he saw on a long journey (Damrongrachanuphap, 1963, p. 86). However, from the nineteenth century, poets tended to treat *nirat* as a journal of events, social contexts, and the environment rather than a description of their feelings (Chitakasem, 1971, pp. 165–167). As a result, not only is it aesthetically, but also socially valuable. It can be regarded as an ancient travel journal reflecting topography, settlement, social context, and the economy of a particular time (Thai Government's Fine Arts, 1985, p. 25).

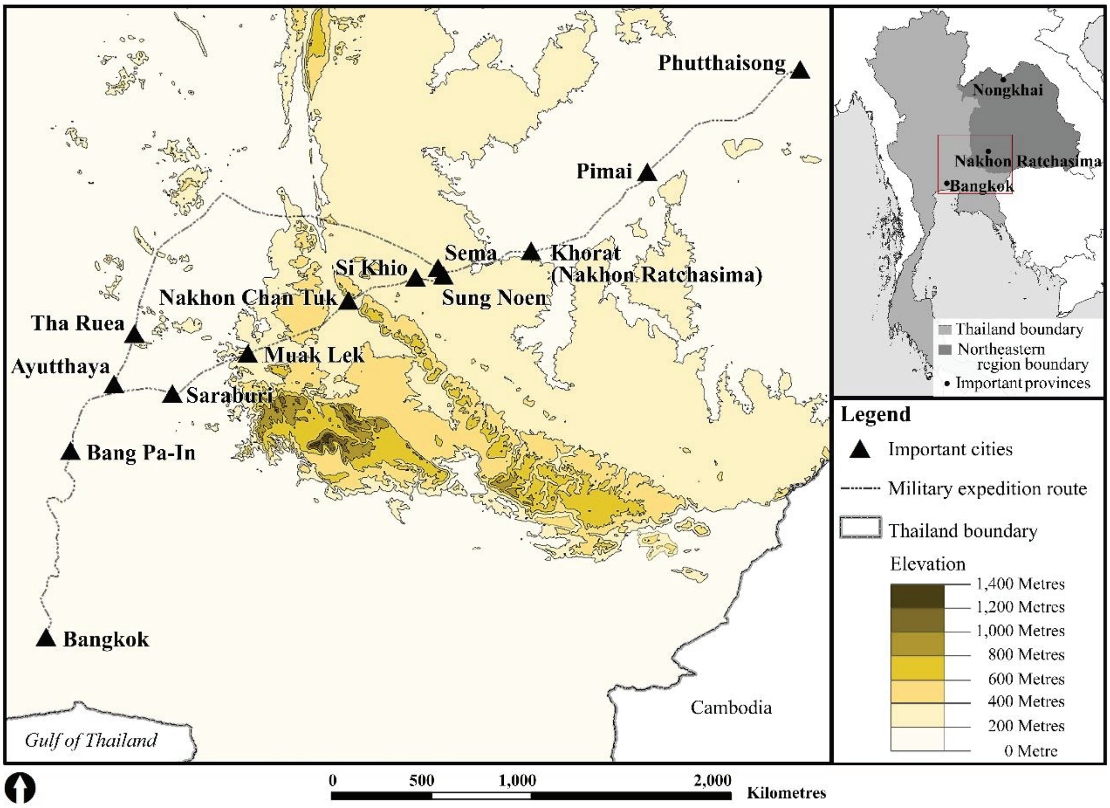


Figure 5 Route map of the military expedition in *Nirat Nongkhai*

Nirat Nongkhai (a poetic travel journal of Nongkhai) was written by Luang Phatthanaphongphakcli (Tim Sukhayang) in 1875 when he was on a military expedition from Bangkok to Nongkhai to subjugate the *Haw* (Chinese Yunnanese bandits) in 'Haw wars' (see detail in Forbes 1988). Although the destination was Nongkhai, *Nirat Nongkhai* was placed in Phutthaisong City (located in Buriram province in the present) because the war against the Haw ended while the army was still on its way (see Figure 5). Owing to the shift from subjective romanticism composition style towards the style of realism (Phumisak, 2018, p. 175), this piece of literature is of historical value. The poet was more likely to narrate the historical events at that time than describe his own feelings, so *Nirat Nongkhai* could be regarded as an archive of the events that occurred during the expedition (Phatthanaphongphakcli, 1955, p. 1). It is frequently analysed and presented as a piece of historical literature demonstrating pre-modern Thai politics (Chonlaworn, 2018, pp. 108–109; Phumisak, 2018, pp. 182–183; Reynolds, 2006, pp. 83–84).

Furthermore, as previously mentioned, *Nirat Nongkhai* is valuable considering other dimensions as well, especially the social dimension. In addition to military expedition related events, the poet provided knowledge of geography, society, lifestyle, and life in general (Phatthanaphongphakcli, 1955, p. preface; Reynolds, 2006, p. 86). Although Phumisak (2018, pp. 194–204) interpreted that the tough geographic features and landscape characteristics through settings had some underlying meaning and political purposes, it is undeniable that the poet's elaborated description painted vivid pictures of the north-eastern topography, landscape and settlement in the nineteenth century. However, there are few analyses of *Nirat Nongkhai* in the social dimension, especially an analysis of its background setting, which reflected the information about landscapes, settlements and land use in the north-east of Thailand during the nineteenth century.

This chapter employed traditional methods of the landscape history circle — narrative approach and conceptual cross-section — to analyse and interpret *Nirat Nongkhai* in terms of the settlement and land use in north-eastern Thailand, an area described in the *Nirat Nongkhai* 1955 edition, which was examined, organised, and revised by the Office of Literature and History under the Fine Arts Department. Scholars generally use this version in their research (Phatthanaphongphakcli & Siworaphot, 2016, pp. 6–14). The chapter is structured into six sections as follows. The objective of this chapter is provided in the first section. Then, the topography of the north-east is described, and following that is the detail about the settlement in north-eastern Thailand. These are divided into two parts based on the topography zones: (1) the plateau and (2) the Khorat marginal highland. Then, the details of the five land-use patterns — forestlands, built-up lands, water bodies, unused lands, and agricultural lands — are presented. After that, the discussion is presented in two parts. First, it is the discussion about the settlement and land use of the north-eastern region in the nineteenth century based on *Nirat Nongkhai*. The second part is the discussion about the finding from *Nirat Nongkhai* and the settlement and land-use patterns of Nong Khai City in the premodern time. Lastly, the conclusion is presented.

2.2 Objective

To describe the pattern of settlement and land-use of north-east in premodern time, when no mapmaking or developed survey methods were available, through *Nirat Nongkhai* and related historical documents

2.3 Topography of north-eastern Thailand

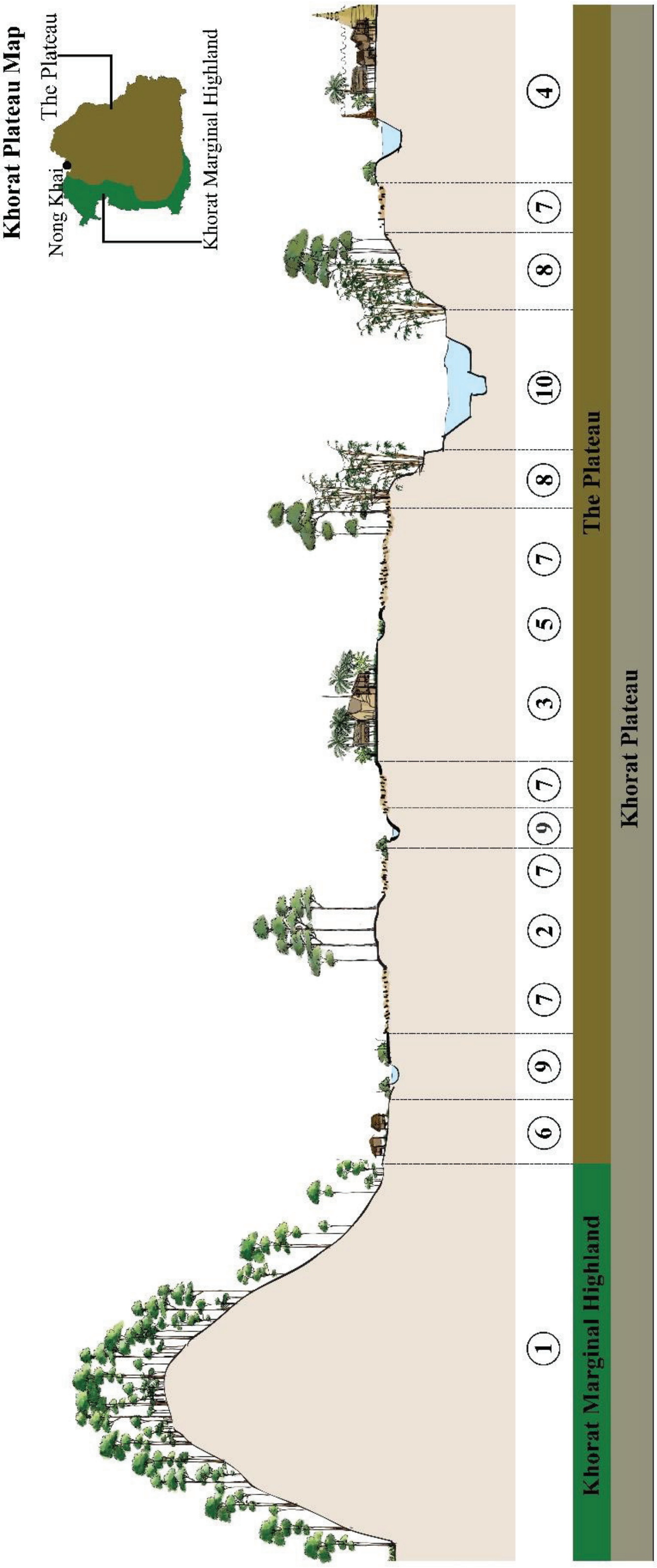
The topography of north-eastern Thailand is unique. It differs from the topography of other regions of Thailand or South-east Asian countries. The region is dominated by a large, broad, and flat sandstone plateau with incised valleys. The plateau is called the Khorat Plateau, and it can be divided into two zones: (1) the plateau and (2) the Khorat marginal highland.

The plateau covers most of the north-eastern areas. It is composed of plains, low hills, and intermittent lakes, as shown in the topographic model (Figure 6). The plains on the plateau are called *thung* in Thai. According to the geographic conditions, the thung on the plateau is arid and unsuitable for cultivation (Figure 7). Most of the thung areas were abandoned, leaving lands or grassy plains unused throughout the year. The flatness of the thung on the plateau was mentioned several times in *Nirat Nongkhai*. One example is when the army passes Thung Samrit:

> Walking into Thung Samrit and looking around, we were in the midst of a flat thung. There were rows of trees at the furthest distance. Standing in the middle of the thung, strong winds caused blowing sand and dust (Phatthanaphongphakcli, 1955, p. 80).

The Khorat marginal highland is an area full of mountain ranges and covering the western part of the north-eastern region. According to *Nirat Nongkhai*, this area was generally comprised of mountain ranges alternating with ledges, deep gorges, and narrow streams scattered across the moist and evergreen forests (Phatthanaphongphakcli, 1955, pp. 30–33). *Nirat Nongkhai* frequently mentions steep and high mountain ranges in this area:

> When our army reached Khao Yai, which blocked our way, we had to circumvent and went along the narrow mountain walkway, leading to the altitudinous mountain. . . . The walkway was so steep that the elephants had to lean against the mountain while walking. When we looked around, we could see mountainous terrain alternating with flat land. After going past the peak of the mountain, the elephants could walk normally through forest areas and streams (Phatthanaphongphakcli, 1955, pp. 39–40).



Legend

	Physical Feature	Toponym	Land Use Type		Physical Feature	Toponym	Land Use Type
1	Mountain ranges	Dong, Khao	Forestlands	6	Plain	-	Built-up lands
2	Low hill	Khok	Forestlands	7	Plain/ Floodplain	Thung	Unused lands
3	Low hill	Khok, Noen, Don	Built-up lands	8	Natural levee	Noen	Forestlands
4	Low hill	-	Built-up lands	9	Reservoir	Sra, Pru, Kut, Nong	Water bodies
5	Low hill	Don	Agricultural lands	10	Waterway	Lam, Nam, Wang	Water bodies

Figure 6 Conceptual section of the topography and settlements in the north-eastern region as described in *Nirat Nongkhai.*

Figure 7 The physical characteristic of northeastern *thung* in 1940 was a large but poor flatland mostly covered with grass. (Photograph by Robert Larimore Pendleton)

2.4 Settlement in north-eastern Thailand

According to *Nirat Nongkhai*, there were settlements on both the plateau and the Khorat marginal highlands. The details of the settlements in both zones are as follows.

2.4.1 Characteristics of the settlement on the plateau

Settlements on the plateau were island villages that spread out over low-hill areas called *khok*, *noen*, and *don* in Thai. Flat areas around the foothills were rice fields, large unused lands and forestlands, respectively, as shown in Figure 8.

Nirat Nongkhai indicates several times that the villagers chose to settle in the low-hill areas of the plateau, as in 'In Sikhio City . . . we found Laotian houses, closed cattle pens, and clean temples. . . . It was quite surprising to see a city on a don' (Phatthanaphongphakcli, 1955, p. 40), and 'Crossing Lam Takhong and reaching Song Noen, it was pleasant to see monasteries, temples, and hundreds of Laotian houses' (Phatthanaphongphakcli, 1955, p. 42) and 'The army stopped for a break at *Tambon* (sub-district) Nong Sakae, which was located on a khok in the middle of a forest'(Phatthanaphongphakcli, 1955, p. 79). This information is consistent with Phrayaphetpanee (1924, p. 5), which stated in *Chotmaihet Ruangmonthon Nakhonratchasima Putthasakkarat 2467* 'Archive of Monthon Nakhon Ratchasima' of 1924 that the villagers preferred building their houses on low hills and thus grew rice on the wet flat lands. Wide lowlands between the low hills are called *thung*.

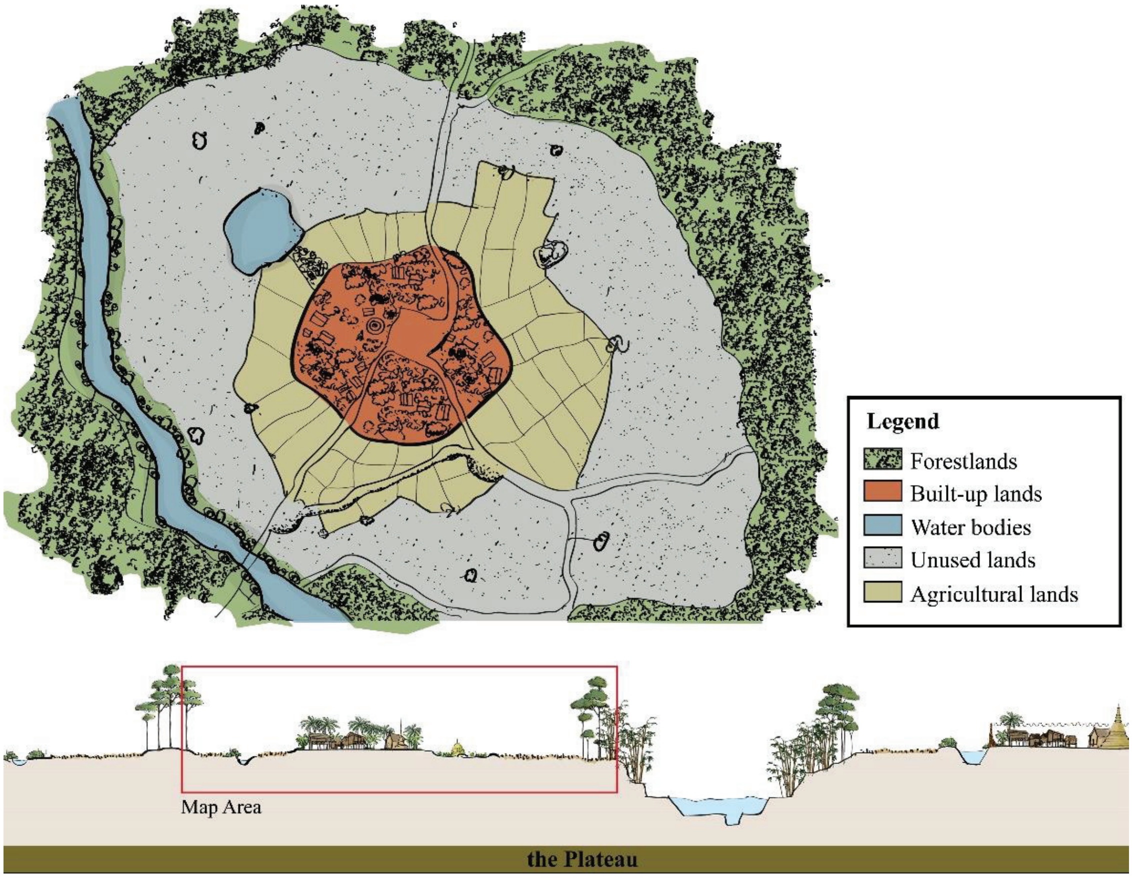


Figure 8 Typical settlement layout on the plateau

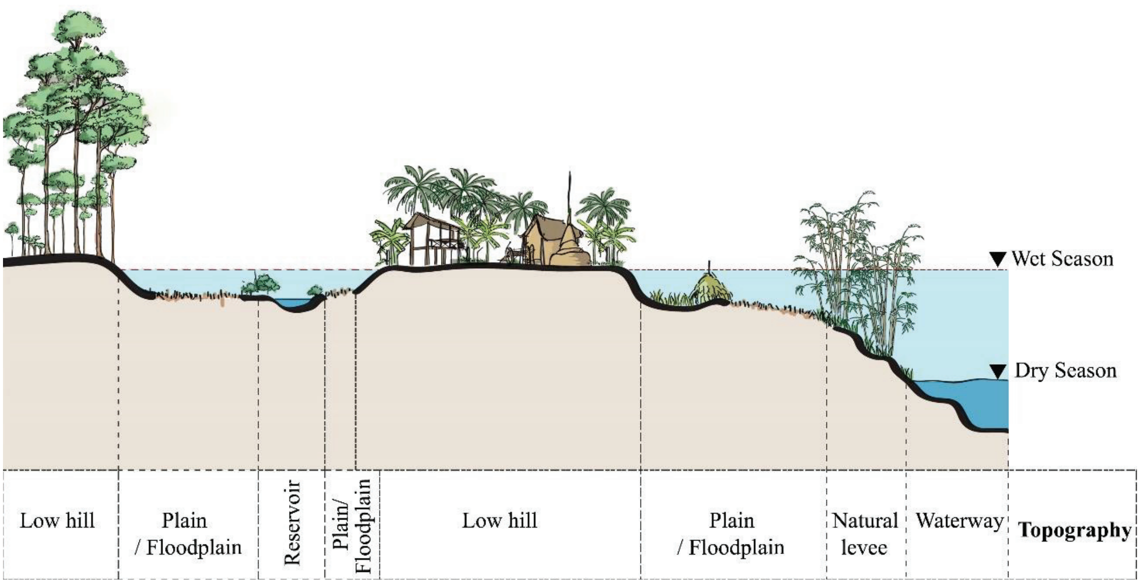


Figure 9 Conceptual section of the community settlements on the plateau during the rainy and dry seasons.

The main reason for the settlements to be located in the low-hill areas of the plateau is that the general topography of the plateau is a floodplain and is likely to encounter severe flooding. Therefore, settlement was impossible (Figure 9). The plateau, as a floodplain, also appeared in the Khorat City map created in 1899. The map (Figure 10) illustrates that the plains along the Mun River were floodplains (Service géographique de l'Indochine, 1899).

Regarding horizontal dispersion, the communities on the plateau were often scattered along watercourses or large water resources, and there were plenty of communities along the Mun River, as the main river in the area that did not dry up seasonally. Phatthanaphongphakcli illustrated this point: 'Leaving Nakhon Ratchasima, we headed to a forest and found numerous communities along the way' (Phatthanaphongphakcli, 1955, p. 78). This is however different from the other areas. The poet (Phatthanaphongphakcli, 1955, p. 83) also mentioned many settlements near the Mun River, such as Ban Tapo, Ban Wang Hin, and Ban Sala Huk. Most of them were places where the army had set up camps during the expedition.

Clustered communities along the Mun River, as described in *Nirat Nongkhai*, were also emphasised in Etienne Aymonier's survey journal *Voyage dans le Laos*. The journal that was reported through a map (Figure 11) shows that there were as many as forty-three villages along the Mun River from Khorat City to Phutthaisong City (Aymonier, 1895, pp. 208–209).

In addition to settlements along the Mun River, there were settlements near other water resources on the plateau. *Nirat Nongkhai* reports that 'We stopped at Lad Buakao to have lunch. There was a large lake with beautiful lotuses and fish swimming in the clear water' (Phatthanaphongphakcli, 1955, p. 40) or 'At Ban Keantao, there was a big lake presumably called Nongbuaban' (Phatthanaphongphakcli, 1955, p. 94) or 'At Sra Khut, there was a *sra* [pool], as suggested by its name. The sra was strangely large and, despite the dry season, it had enough water for villagers to catch fish or use it in their daily lives' (Phatthanaphongphakcli, 1955, p. 35).

By analysing village names and geographic terms in *Nirat Nongkhai* related to water resources, the names of many villages had water resource related toponyms, mostly referring to intermittent lakes. The villages were often located near water resources or waterways, mainly because most areas of the plateau in summer were arid. The events in *Nirat Nongkhai* occurred during the dry season, and *Nirat* captured the drought in the inner areas of the plateau, which was situated between Khorat City and Nongkhai City. Phatthanaphongphakcli noted that 'It was bone dry all the way from Nongkhai. Not even a single drop of water could be found in the canals or swamps. The plains were the wide areas of thung with no trees to provide' (Phatthanaphongphakcli, 1955, p. 76) Prince Damrongrachanuphap (2012, p. 458) also mentioned the drought within the plateau in his Phutthaisong City inspection record: 'In a dry season, there were only clumps of grass on the thung. Cracked lands appeared everywhere, making the journey difficult, not to mention the torrid heat'.

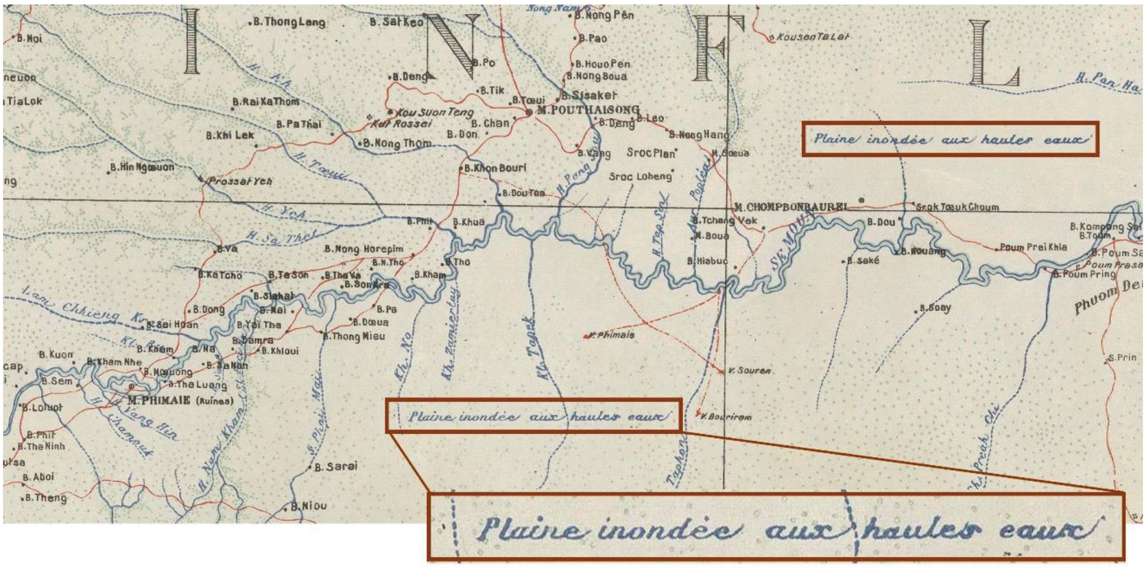


Figure 10 Khorat City map from 1899, showing the plains along the Mun River as 'Plaine inondée aux hautes eaux' or floodplains (in the square box). Source: Adapted from Indo-Chine Service Géographique, Korat (Hanoi: Service géographique de l'Indochine, 1899), http://1886.u-bordeaux-montaigne.fr/items/show/70021 (last accessed 26 April 2020).

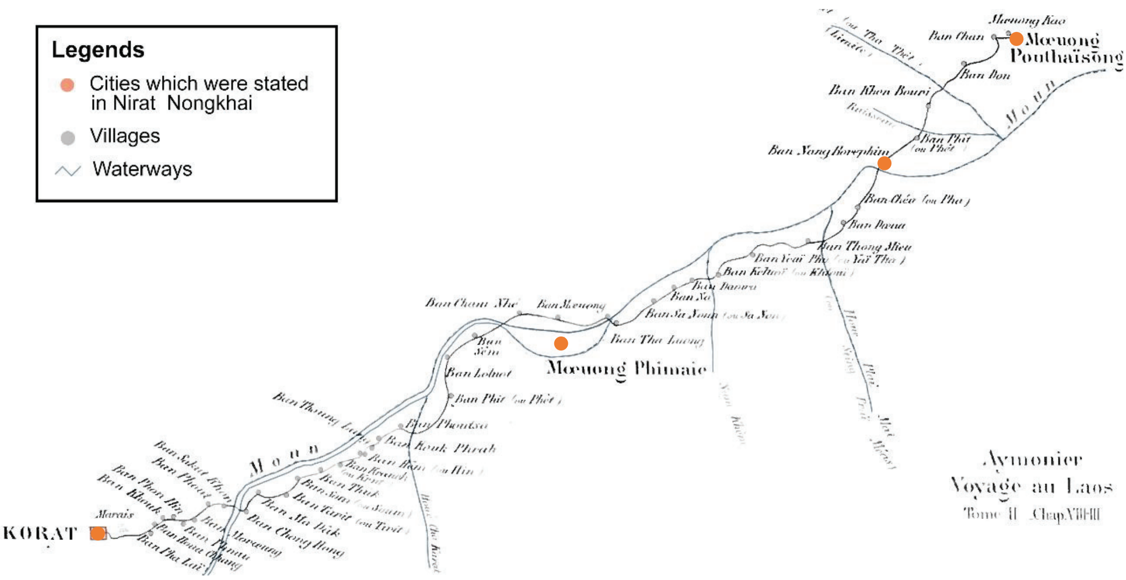


Figure 11 Numerous villages along the Mun River between Khorat City and Phutthaisong City in Etienne Aymonier's map (Source: Adapted from Voyage dans le Laos (Aymonier, 1895))

Most communities in the north-east belonged to Laotians (Phatthanaphongphakcli, 1955, pp. 36, 42, 85, 87, 94) who were native inhabitants originally living in Lao Kingdom of Lan Xang and then who then migrated into the area in the fourteenth century. Their numbers grew rapidly in the eighteenth century (Fukui, 1993, pp. 27, 33). Laotians in the north-east comprise many subgroups, such as Lao wiang, Phu thai, Puan, and Song (Ouyyanont, 2017, p. 303). However, there might be different ethnic groups in communities near a trading area or a large city such as Khorat. Chinese people were among those who made a living in a trading area and thus settled nearby (Cummins & Wood, 1969, p. 3; McCarthy, 1900, p. 27). The evidence of their settlements according to *Nirat Nongkhai* were Chinese architectural structures called *tuk din* [earthen buildings] situated side by side in a market (Phatthanaphongphakcli, 1955, p. 51). Moreover, there are other races living in Khorat, such as Thais and Mons (Phatthanaphongphakcli, 1955, p. 59). According to McCarthy's record (1900, p. 27), 800 Chinese people settled in Khorat City during the reign of King Chulalongkorn. However, the Thai census of 1904 indicates that a total of 2,431 Chinese people and 2,259 Mons lived in Monthon Nakhon Ratchasima (Grabowsky, 1996, pp. 64–65).

Laotians who settled on the plateau led different lives compared to the Siamese. This can be seen in *Nirat Nongkhai*, which describes the food culture in detail. For example, Laotians liked glutinous rice wrapped in banana leaves and often ate it with rock salt (Phatthanaphongphakcli, 1955, pp. 42–43). Rock salt was a common seasoning in the north-eastern region because the soil in the deeper layers was mixed with it. In the rainy season, the ground water dissolved the salt and brought it to the surface. When the sun heated the ground in the summer season, a tiny layer of salt would emerge, making the surface of the ground appear white (Pendleton, 1962, p. 44).

In addition to eating it with glutinous rice, salt was an important ingredient for North-Easterners, who used it to preserve food. They used it to produce *pla ra* (*i.e.* fermented fish). Phatthanaphongphakcli described an event when the local villagers prepared food for the army: 'Every one of them made the dishes as best as possible. The prepared foods were glutinous rice, pla ra, boiled vegetables, and pumpkin' (Phatthanaphongphakcli, 1955, p. 93).

2.4.2 Characteristics of the settlement on the Khorat marginal highland

The Khorat marginal highland is located at the western and southern margins of the Khorat Plateau. Most of the area accommodates high mountains and dense forests. Compared to the plateau, there were fewer settlements there (see Figure 6). Villages in this area belonged to the Laotians. They were small and located in the open lands near the forest edges (Phatthanaphongphakcli, 1955, pp. 33, 36, 38).

2.5 Land use pattern in north-eastern Thailand

According to an analysis of *Nirat Nongkhai* considering the settlements in the north-eastern region, the topography, human activities and land use patterns in north-eastern Thailand during the nineteenth century can be classified into the following five types: forestlands, built-up lands, water bodies, unused lands, and agricultural lands.

2.5.1 Land use pattern of forestlands

Land use of forestlands appeared on both the plateau and the Khorat marginal highlands. Due to their different geography, these two zones had distinct patterns of forestland use.

The forests on the plateau were distributed around river levees and hillocks over the thung areas. This type of forest was called *pa khok* [small hilly forest]. The distribution of forests across thungs was described in the *Nirat Nongkhai* several times: 'Walked a long distance across a wide thung, and then went into *palamo* [scrub forest]'(Phatthanaphongphakcli, 1955, p. 84), and 'Walking across a thung and into a forest, we continued to walk and would soon go through a sakae [*Combretum quadrangulare* Kurz] forest' (Phatthanaphongphakcli, 1955, p. 85), and 'After leaving a thung, we entered a forest in the evening' (Phatthanaphongphakcli, 1955, p. 92). The alternation between forests and thungs corresponded with McCarthy, who stated that Khorat city 'was very flat, with sparse (McCarthy, 1900, p. 30). This pattern of forests near rivers alternating with hillocks amid thungs remained for a long time despite the construction of the railways and roads in the northeastern region. Robert L. Pendleton's aerial photographs taken in 1951 and Williams-Hunt's photographs taken in 1946 showed the distribution of forests on the river levees on the plateau (Figure 12 and Figure 13), among the unused lands.

Considering the plants mentioned in *Nirat Nongkhai*, it could be assumed that the forests on the plateau were teng rang forests, deciduous dipterocarp forests, and scrub forests. This was in line with a travel note from the late nineteenth century which states that 'The trail, as one may call it – for there is no pretence at road making – winds through open jungle . . . and mostly mai rang, mai teng, and mai yang, as they call the Siamese resinous trees of the Dipterocarpus genus' (Black, 1896, p. 438). *Nirat Nongkhai* mentions many plants in the forests on the plateau — for example, sakae, rang, bamboo, and over forty kinds of small plants that Thai people generally call *wan*, such as *wan arthit* (*Manthus multiflorus* Martyn), *wan kangkok* (*Gerbera piloselloides* Cass.), and *wan kip rat* (*Angiopteris evecta* G. Forst. Hoffm). Given the foliage of the trees in the Isan map from the royal collections (Phasuk & Stoot, 2004, pp. 130–131, 136), there is consistency with the content of *Nirat Nongkhai*. Specifically, bamboo appeared over large areas.

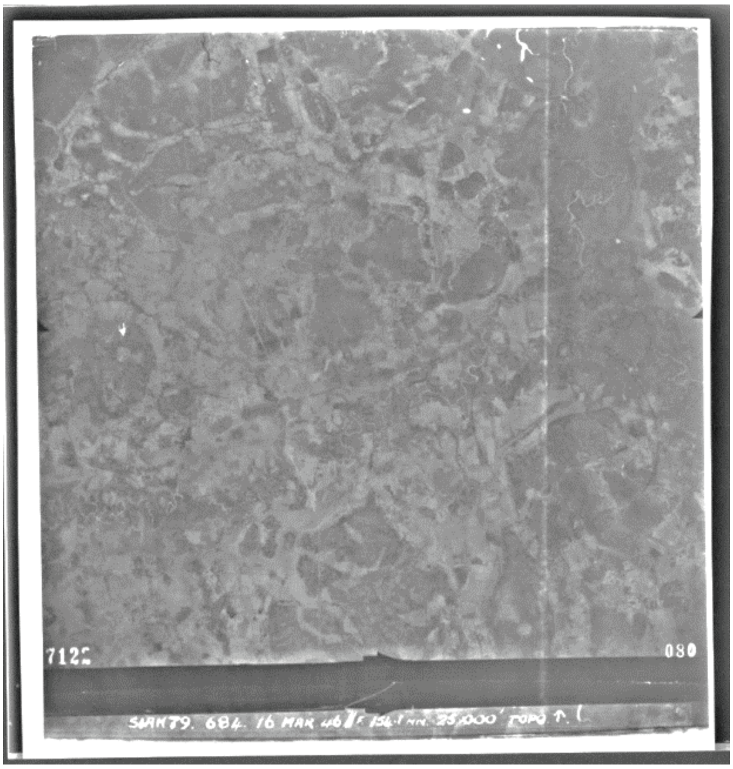


Figure 12 An aerial photograph taken at Phimai City in 1946 from the Williams–Hunt Collections showing *Pa Khok* (in dark-coloured areas) dispersed over the areas of *thung* (in light-coloured areas) (Source: Digital Archive from Chulachomklao Royal Military Academy (CRMA), Thailand)

Figure 13 The eastern areas of Nakhon Ratchasima in 1951 near the Phimai ruin. The photo shows the forest alongside the waterway and the forests dispersed over the areas of *thung* (source: Robert Larimore Pendleton)

The land uses of the forestlands in the Khorat marginal highland, as shown in *Nirat Nongkhai*, involved the forest in the western area of the region. The Thai people typically called this area 'the Dong Phraya Yen Forest' or 'the Dong Phaya Fai Forest'. *Nirat Nongkhai* further reveals that the forest in this area was very thick, rich in plants and animals. The thickness of the forest obstructed the military expedition and transportation linking the north-eastern to the central region of Thailand at that time.

The thickness of Dong Phraya Yen was described in several sections of *Nirat Nongkhai*: 'After elephants carried us wading through the stream, we arrived at Dong Phraya Yen Forest, which was thick and dead. There were high yang trees everywhere' (Phatthanaphongphakcli, 1955, p. 29), 'High and large trees were dense covering the mountain fully. If the soldiers had been ordered to clear the way, thousands of them would have been wasted' (Phatthanaphongphakcli, 1955, p. 31), and 'To leave the central Dong Phraya Yen, we had to walk through the forest so full of thick trees that the sunlight rarely passed through' (Phatthanaphongphakcli, 1955, p. 35). Owing to its thickness and density, the forest was bountiful and abundant in plants.

An analysis of plants in *Nirat Nongkhai* showed that Dong Phraya Yen was home to over sixty genera and seventy species as the setting and many plants could be found in a dry evergreen forest and a mixed deciduous forest, as shown in Table 3.

Table 3

The example of plants in *Nirat Nongkhai*

Common Name	Scientific Name	Common Name	Scientific Name
Demee	*Cleidion javanicum* Blume	Prayong	*Aglaia odorata* Lour.
Kankrao	*Fagraea fragrans* Roxb.	Sadaochang	*Acrocarpus fraxinifolius* Wight ex Arn.
Khanang	*Homalium tomentosum* Vent. Benth.	Sai	*Ficus annulata* Blume
Krang	*Ficus altissima* Blume	Somsiao	*Bauhinia saccocalyx* Pierre
Kritsana	*Aquilaria crassna* Pierre ex Lecomte	Takhian	*Hopea* sp.
Makham	*Tamarindus indica L.*	Yang	Dipterocarpaceae
Payom	*Shorea roxburghii* G. Don		

2.5.2 Land use pattern of built-up lands

In *Nirat Nongkhai*, the buildings were for daily life, used in defence, or local religious celebrations. They can be classified into the following five types: (1) city walls, moats and glacises; (2) archaeological sites; (3) religious sites; (4) residences; and (5) shops.

2.5.2.1 City walls, moats, and glacises

City walls, moats, and glacises are elements of a city. Their main purpose involved both ecological and political activities (Moore, 1988, pp. 8–9,143). Today, the development of road networks in cities, as well as urbanisation, has transformed or demolished walls, moats and glacises of ancient cities. The details in *Nirat Nongkhai* played a significant role in testifying that these city components existed before urbanisation.

The communities mentioned in *Nirat Nongkhai* that had these elements were Khorat City, Old Khorat City, Ban Nang Or, and Phutthaisong City. The size and form city walls, moats and glacises depended on the size and significance of the individual city. Most of these cities were surrounded by earthen ramparts and moats, which served as city walls. However, Khorat City was different in that it had brick city walls with a fortress. According to *Nirat Nongkhai*, 'the long-established big city of Phutthaisong looked strong and stable with the earthen rampart as its city wall, and it was surrounded by moats' (Phatthanaphongphakcli, 1955, p. 86). Ban Nang Or was also described as an old city with earthen ramparts and moats (Phatthanaphongphakcli, 1955, p. 84). In addition, Old Khorat City was briefly mentioned as 'an old city with a big and high earthen rampart as its city wall, . . . and the city entrance was in the west' (Phatthanaphongphakcli, 1955, pp. 93–94).

Compared to other cities, Khorat City and its city wall, moats, and glacises are described in detail:

> Khorat was a big city surrounded by a strong eight-metres-high wall. Entrances were installed on all four sides of the wall. Unlike other cities, battlements surmounted these entrances. The moats and glacis were adjacent to the wall. The outer glacis was two and a half metres high (Phatthanaphongphakcli, 1955, p. 51).

The appearance of the wall in the *Nirat Nongkhai* — surrounding Khorat, with an entrance on each side — was consistent with the description in many documents before the nineteenth century and in the late nineteenth century. For example, Jean Baptiste Pallegoix (2009, p. 43) said that Khorat City 'was surrounded by a striking wall that was built on the high lands.' McCarthy (1900, pp. 25–26) mentioned the four city entrances surrounded by a 6 metre-wide moat. Furthermore, Aymonier (1895, pp. 112–113), who showed the details of Khorat City and nearby communities, demonstrated that the city wall and entrances were similar to the description in *Nirat Nongkhai*.

Considering the characteristics of the city walls, moats and glacises, most of the moats in the nineteenth century served to mark territories and were used in defence. Moreover, these elements existed only in cities with legends or a long history. This finding is in compliance with Elizabeth Moore's study (Moore, 1988, pp. 3–6), which points out that a moat was an important element for identifying the ancient settlement associated with the civilisations that existed in the north-east areas.

2.5.2.2 Archaeological sites

The archaeological sites were the built-up land use types found in ancient cities. This was the physical evidence confirming the long settlements of the communities in the north-eastern region. In *Nirat Nongkhai*, there were two communities of this kind: Ban Nang Or and Phimai City. The archaeological site in Ban Nang Or was small and made of stone. Villagers believed that it was the loom mentioned in a local legend (Phatthanaphongphakcli, 1955, p. 84). In contrast, the archaeological site in Phimai City was gigantic, elegant, made of laterite, and associated with the Khmer civilisation (Phatthanaphongphakcli, 1955, p. 81). The description is as follow:

> The stone castle stood tall and wide with impressive tympanums. Its stone wall was engraved with flowery patterns, and its balusters were made exquisitely. A secondary castle was linked to the main one. The corridor had a stone roof. A stone wall surrounded the castle. The porticos were attached to all four directions of the castle. A subordinate building, called the Tim Dap, was also located within the area. Enclosing the archaeological site, the outermost wall was a strong earthen rampart. A stone road connecting to the eastern portico led to Khmer (Phatthanaphongphakcli, 1955, pp. 81-82).

2.5.2.3 Religious sites

Religious sites were built to honour the local beliefs of Buddhism and sprits. The ones in *Nirat Nongkhai* can be classified into three categories: temples, city pillar shrines and spirit houses. The temple is a religious site of Buddhism. This Buddhist place of worship was commonly found in communities. The components of each temple varied. Some temples had vihara, aka monasteries. Some had pagodas, while others had pavilions (Phatthanaphongphakcli, 1955, pp. 42, 52, 92). A temple had a boundary divided by wood fences (Phatthanaphongphakcli, 1955, p. 40). Spirit worship was a particularly important for locals in north-eastern Thailand. The religious sites associated with this belief generally came in two forms: (1) a city pillar shrine that was built in a community like Khorat City, the administrative centre at that time; and (2) a spirit house or a tutelary spirit house, which was often established near the forest edges (Phatthanaphongphakcli, 1955, pp. 29, 33, 39). The spirit house came in various styles, and new designs were welcome (Phatthanaphongphakcli, 1955, p. 37).

2.5.2.4 Residential buildings

The houses in both the forest edge communities and the plateau communities were located side by side along the pathway. Phatthanaphongphakcli (1955, p. 40) indicated that they were built in the Laotian style. The houses were *ruan kruang phuk* made of bamboo and built by tying each of their structures together. Their roofs were made of vetiver or cogon grass. Barns and 160 to 200 metre-wide cattle pens were also placed in proximity (Phatthanaphongphakcli, 1955, pp. 40, 74), so that they would not be raided at night. Moreover, the houses were surrounded by trees such as areca palms, coconut trees, and edible plants such as vegetables, banana trees, chilies, and pumpkins (Phatthanaphongphakcli, 1955, p. 45). All of these were reflected in the photos captured by Robert L. Pendleton (1943, p. 34) in the mid-twentieth century. The photos showed that the houses in the north-eastern region were *ruan kruang phuk*. Their surroundings were full of trees from the palm family. This characteristic was also recorded by McCarthy, who wrote that Phimai City 'had a cosy appearance in the deep shade of fruit trees and palms' (McCarthy, 1900, p. 30). Considering the evidence in *Nirat Nongkhai* and other sources, it can be assumed that the communities in the north-east at that time must have been encircled by such dense trees that it was hard to see the houses (Phatthanaphongphakcli, 1955, p. 38).

2.5.2.5 Shops

The shops were found in trading areas, such as the Po Klang area (Figure 14 and Figure 15). In *Nirat Nongkhai*, they were depicted as rows of attached earthen buildings with red wooden doors; the roofs were made of earth and covered with vetiver. The earthen building was an architectural structure for Chinese merchants who sold commodities. The goods sold included fruits, food, supplies, and utensils (Phatthanaphongphakcli, 1955, p. 51).

Figure 14 Williams Hunt's aerial photograph of the Po Klang area in 1946 showing rows of attached buildings along the street (red rectangular border) (Source: Adapted from the Digital Archive from Chulachomklao Royal Military Academy (CRMA), Thailand)

Figure 15 Shops in the Po Klang area (source: National Archives of Thailand)

2.5.3 Land use pattern of water bodies

The land use of water bodies in *Nirat Nongkhai* occurred on both the plateau and the Khorat marginal highlands. However, there was not much significant land use of this kind in the Dong Phraya Yen Forest. The assumption was that the water bodies were forest streams with stones and that they did not dry up all year long, even in the dry season. It was presumed that they would overflow during the rainy season (Phatthanaphongphakcli, 1955, pp. 15, 20, 30–31). As Phatthanaphongphakcli (1955, p. 31) described, 'It was difficult to travel. If we had come in the rainy season . . . the water would have been higher than our height.'

In contrast, there were numerous bodies of water on the plateau, dispersed over the flat areas of the thung. *Nirat Nongkhai* mentions many bodies of water. An analysis of the toponym in the water bodies' name reveals two forms of water bodies on the plateau: waterways and reservoirs, as shown in Table 4.

Table 4

Demonstrating the association between the names of water bodies on the plateau and their physical characteristics

Type	Toponym	Meaning	Place names
Waterway	Lam	Stream, brook, Channel	Lam Takhong, Lam Chiangkrai and, Lam Sathaek
	Nam	River	Nam Mun
	Wang	Deep Channel	Wang Hin and Wang Long
Reservoir	Sra	Pool	Sra Khut, Sra Krabaek and, Sra Thammakhan
	Pru	Swamp	Pru Nokyung
	Khut	Oxbow lake	Khut Phaknam
	Nong	Lake	Nong Rongrua, Nong Sakae, Nong Huaimu, Nong Changnam, Nong Tabaek and, Nong Buaban

The important waterways on the plateau included a large river called Mun, which was potable and never dried up, even in the dry season (Phatthanaphongphakcli, 1955, p. 77). It was home to aquatic animals, as Phatthanaphongphakcli (1955, p. 81), reported that standing near the edge of the Mun River, one could see the wide and clear watercourse full of fish and crocodiles. As mentioned above, many communities settled a longside the river. Other important water bodies on the plateau were Lam Takhong, Lam Chiangkrai, and Lam Sathaek. Nevertheless, the deeper layers of soil on the plateau were mixed with salt; some streams were brackish and could not be consumed (Phatthanaphongphakcli, 1955, p. 80).

Nirat Nongkhai recorded events during the summer, so the poet found only a few reservoirs dispersed over the areas. The reservoirs with water for domestic consumption were large, such as

Sra Khut, Nong at Latbuakao, Nong Sakae, Nong Changnam, and Nong Buaban. Small reservoirs were nameless and had little water or had dried up; some that still had enough water were, unfortunately, not suitable for drinking. The dryness of small reservoirs and the condition of their whereabouts are depicted in *Nirat Nongkhai*:

> The army took a break at Wang Long. The reservoir had enough water, but it was too smelly to consume. Fortunately, there was another reservoir that was 2 m deep and 2 to 2.5 m wide. Its water was slightly white but still consumable for long distance travellers. . . . In the dry season, most of the water resources dried up, so it was difficult to find water. Everyone had to fill his flasks with water and not be careless; otherwise, he could become gravely dehydrated (Phatthanaphongphakcli, 1955, p. 95).

As a result, in some cases, the land use of water bodies inseparably overlapped the land use of unused lands. Phatthanaphongphakcli (1955, pp. 76–77) placed considerable emphasis on drought on the plateau, especially in areas far away from the Mun River. This is because drought affected the military expedition. The troops had to travel along the Mun River, which was filled with water all year long, rather than along Khok Luang, whose reservoirs were completely dried up. This was consistent with Black, who pointed out that during the trip from Khorat City to Nongkhai City, 'We suffered greatly from heat and want of water' (Black, 1896, p. 441). The shortage of water in *Nirat Nongkhai* might have been a result of less rain in the dry season. Old, yet accessible, north-eastern climatological data showed that during the dry season (November–May), the evaporation rate on the plateau was high, and there was little or almost no rain, especially from December to February (LaMoreaux et al., 1958, pp. 9–11). Accordingly, reservoirs on the plateau dried up.

In summary, water bodies on the plateau were both qualitatively and quantitatively limited, especially during the dry season. The limitation was a significant condition affecting the land use patterns of unused lands and agricultural lands in the nineteenth century.

2.5.4 Land use pattern of unused lands

Unused land was common on the plateau. Some unused areas overlapped with dried water bodies or agricultural land in the summer. In *Nirat Nongkhai*, the unused lands were reflected by the vastness and emptiness of 'thung', which appeared as a setting context of the military expedition and as a part of an important place's name, such as Thung Chaiwan and Thung Samrit.

Regarding *Nirat Nongkhai*, thung was often a large unused land alternating with a forest or a community settling on a low hill. It was mentioned several times when the poet discussed the military expedition: 'Leaving Phimai City, we entered a forest and traversed a wide and flat thung before going through another forest' (Phatthanaphongphakcli, 1955, p. 83), and 'Walked across a wide thung for some time and then got into palamo' (Phatthanaphongphakcli, 1955, p. 84). This type of thung was an arid grassland without trees (Phatthanaphongphakcli, 1955, pp. 77,80). Prince Damrongrachanuphap gave an interesting opinion about the main reason why the areas of thung in the north-east were unused:

> The flat areas on the plateau were severely flooded during the rainy season, whereas cultivation was impossible in the summer because of drought. Villagers had no choice but to leave them unused until they were covered in grass (Damrongrachanuphap, 2012, pp. 407, 458).

In addition, the quality of the soil on the plateau might have played a major role in the large amount of unused land. Phatthanaphongphakcli (1955, p. 35) stated that soil was red in some areas, and pitch black or bright yellow in others. Considering this text with the quality of the soil series surveyed and discovered by the Office of Soil Resources Survey and Research (2013), we found that the lots of the soil series — in the area where the army went on an expedition — were similar in colour to the soil mentioned in *Nirat Nongkhai*. For example, the soil series of Sikhio, Chok Chai, and Sung Noen are red; the soil series of Pak Thong Chai, Korat, and Huai Thalaeng are yellow; the soil series of Kantara Wichai and Chan Tuk are black and grey. In addition, the quality of the soil series was mostly low, with only a few soil series being of moderate quality. This was in line with Carl C. Zimmerman (1934, p. 281), who indicated that many areas in the region were not suitable for growing rice. Consequently, before agricultural technologies and irrigation systems were developed, the land in the region was unused.

Apart from the low quality of soil, Phatthanaphongphakcli (1955, p. 35) implied another problem when he said that the soil in some areas was pure white. It can be inferred that the 'white soil' is the soil with salt crust. Such soil would be bad for cultivation. Although agriculture is not possible, another economic activity emerged in the region, producing salt in salt fields. It was a primary household industry in the region (Yankowski & Kerdsap, 2013, pp. 232–233, 242). As a result, unused lands — besides being deserted grasslands — in some areas became salt fields. The land use of unused lands continued to remain as Robert L. Pendleton's photograph showed that there were thungs alternating with forests and communities in 1940 and 1948 (Figure 16).

Figure 16 A salt field in 1940 in the east of Khorat City. The soil in the salt field turned white because of salt crystals (Source: Robert Larimore Pendleton)

2.5.5 Land use pattern of agricultural lands

Although the areas in the north-east were mostly unused, Phatthanaphongphakcli (1955, p. 42) revealed a few details about the agricultural land use; most of it included rice fields on don, also called *nadons*. It can be assumed that the scarcity of details about agriculture was because military expedition took place in the summer, when the areas on the plateau were not suitable for cultivation. Most of these areas were dried grasslands rather than agricultural lands. Regarding the agricultural lands in Monthon Nakhon Ratchasima, Prince Damrongrachaunphap said:

> Despite the large size of thung in Monthon Nakhon Ratchasima . . . any agricultural activity is impossible due to the lack of water in the dry season and floods in the rainy season. That is why they were abandoned and became mere grasslands (Damrongrachanuphap, 2012, p. 407).

However, it is very likely that there were not many agricultural lands at that time. According to the statistical data on the principal crop between 1938 and 1939, the cultivated areas on the plateau covered only 6.88 % of all the areas, although the market economy had already expanded owing to the Bangkok–Khorat railway. In total, 98.97 % of the cultivated areas were rice fields (Pendleton, 1943, p. 26).

In addition to rice fields, there were few details on other types of agricultural areas, but it could be inferred from the plants and food described in the *Nirat Nongkhai* that villagers might have at least small gardens in the area of their houses for growing plants such as chillies, pumpkins, coconut trees, areca palms, and Palmyra palms.

2.6 Discussion

2.6.1 Settlement and land-use of north-eastern region in the nineteenth century

The settlements and land use were influenced by geographic conditions. *Nirat Nongkhai* clearly shows that in the nineteenth century, the north-eastern people settled mainly in rural areas. This is because the region had a limited connection with Bangkok due to geographic conditions. *Nirat Nongkhai* clearly describes the hardships of travelling from Bangkok to the north-eastern region. There were mountain ranges separating the central region from the north-east. There were no connecting roads between the two regions. Travellers needed to trudge through dense forests, which used to be habitats of wild animals and the source of malaria. Phatthanaphongphakcli (1955, pp. 25, 93) noted that over 120 soldiers died during the military expedition, mostly because of malaria. James Fitzroy McCarthy (McCarthy, 1900, p. 25), who had surveyed Siam for mapmaking since 1881, wrote the following:

> The forest known as the Dawng P'ia Fai, or the forest of the Lord of Fire, is known for its deadly fever. There, hundreds of Chinese labourers were buried during the construction of the railway, and hundreds more will be buried before it is completed.

Moreover, they could only take a trip in the dry season because some areas on the mountain ranges were flooded at times. *Nirat Nongkhai* does not fail to describe this hardship as it records the environment on Dong Praya Fai mountain in the raining season: 'It is said that the pathway called Praya Fai is full of mire and mud; it's flooded and cut off' (Phatthanaphongphakcli, 1955, p. 17).

All these factors contributed to the difficult and time-consuming transportation and communication between the north-eastern region and other regions. One of the limitations of this work is that it does not indicate how long it took to travel from Bangkok to the north-east. However, according to other travel journals kept around or in the same period of time, it took between six and thirteen days to reach Khorat City from Bangkok (Black, 1896, p. 440; Pallegoix, 2009, p. 43). Not surprisingly, the north-eastern society at that time was relatively closed and separated from other regions.

Geographic factors were not only barriers to the isolation of the north-eastern region, but also had a significant impact on settlement patterns and land use in the nineteenth century. The soil in most areas of the north-east was poor. In addition, the severity of natural disasters, such as droughts and floods, resulted in empty and unused land.

To prevent destitution caused by geographic factors, most Laotian communities were dispersed as island villages. The low hills spreading across the flat area were vital areas for settlements and other land uses, especially agricultural and forestlands, because they were higher than the flood level in the rainy season. The settlement pattern of island villages in the North-East, which was dispersed across low hills, differed from the settlements on the plains in the central region and other regions. Considering the accessibility of resources and the convenience of trading, they were typically established alongside the rivers (Zimmerman, 1934, pp. 27–28), as shown in Figure 17. However, these community settlements, like the communities in the central region of the country, still regarded temples as the centre of their activities.

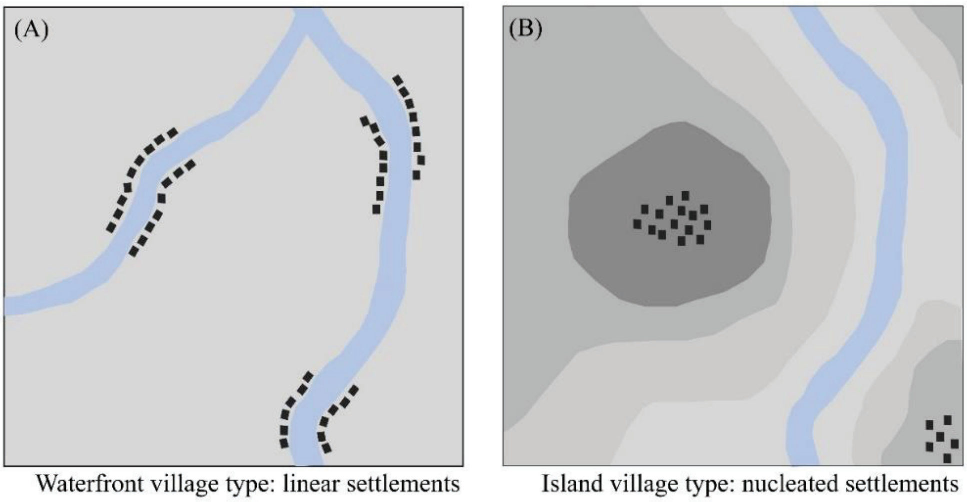


Figure 17 Typical settlement in the central region (A) and the north-eastern region (B) of Thailand

Despite the lack of evidence showing the continuity of the settlement in the north-east from a prehistoric period, the settlement patterns in this area demonstrated in *Nirat Nongkhai* were similar to a moated settlement, which was a pattern present in the north-eastern region in the prehistoric period. The settlement in that period was also restricted by geographic conditions related to flooding and drought (Moore, 1988, p. 92; Scott & O'Reilly, 2015, p. 1136). Communities were in the low hill areas and were surrounded by agricultural lands and moats (Moore, 1988, pp. 19–20, 66, 85–17). Moreover, there were nearby water resources, densely located along the Mun River (Moore, 1988; O'Reilly & Scott, 2015, p. 17), similar to the settlement pattern in *Nirat Nongkhai*.

The patterns of settlements and land use under these geographic conditions began to transform with the construction of the Bangkok–Khorat railway in the early twentieth century.

This railway was the first regional railway of the Siamese government and part of the Siam transportation reform. It is undeniable that the railway construction became the key pathway leading Siam and its north-eastern society into modernisation later (Pugh, 1929, p. 4).

The Bangkok–Khorat railway did not abruptly affect the general landscape of the north-east. The changes in landscapes, settlements, and communities occurred slowly, starting from the areas around the railway stations. Prince Damrong's record of changes after the Nakhon Ratchasima railway construction explains the changes after two years of the Bangkok–Khorat railway's availability. According to the record, this railway transformed the architectural structures and the patterns of the settlements in the north-east, as the houses and buildings expanded along the railway stations (Thai Government's Fine Arts, 1968, p. 173).

The comparison between the information from *Nirat Nongkhai* and subsequent historical documents in the previous section reveals that the settlement patterns of the areas farther from the railway stations were similar to those in the late nineteenth century. Moreover, the settlement patterns and land use did not change until transportation networks, railways and roads spanned across the region. The convenience of transportation development encouraged more cultivation in Isan (Andrews, 1937, pp. 40, 43). When railways were extended to other provinces in the north-eastern region, evidence shows that rice fields in this region increased from 3,900,000 km^2 kilometres during 1920–1924 to 12,000,000 km^2 in the 1940s (Ouyyanont, 2017, p. 313). A market economy brought about cultivated fields, while the Bangkok–Khorat railway and other related transportation network development brought about the expansion of the settlements along the transportation routes and into the railway cities (Yongvanit & Thungskul, 2013, p. 18).

Although the patterns of the settlements had changed, with the expansion of city areas around train stations, the construction of the transportation network, and the expansion of agricultural areas into thung that used to be empty unused areas, the droughts and the poor soil in north-eastern Thailand remained. Unfortunately, the stereotype about its destitution remained as well. The stereotype and the impact of geographic limitations on settlements and land use began to decrease when the system was developed and agricultural technologies were introduced into the region. There was a transformation in land use; the vast arid grasslands became the essential agricultural areas of Thailand, as statistics show that the planted areas and the harvested areas of rice in the north-east were the greatest in the country (Office of Agricultural Economics, 2020, p. 5).

2.6.2 Settlement and land-use patterns of Nong Khai City in the premodern time based on the findings from the interpretation of *Nirat Nong Khai*

Although the settlement and land-use description in *Nirat Nong Khai* was not recorded in Nong Khai Province, the comparison with many historical documents and the previous studies confirm that the settlement and land-use patterns of Nong Khai City in the premodern time are similar to the description in *Nirat Nong Khai* as follows:

1) Patterns and structure of typical settlement are similar.

Although Nong Khai City is located on the natural levee along the Mekong River while most communities on Korat Plateau are on the low-hill areas, both settlements still share some characteristics. Their communities cluster on the areas that are higher than the surrounding plains, and the land uses there are *thung* which are vast empty lands, agricultural lands, water bodies, and forestlands on small hills, as shown in Figure 8.

The information about the settlement structure of Nong Khai City in the past was mentioned in a record of Prince Damrongrachanuphap during his visit in Monthon Nakhon Ratchasima, Monthon Udon, and Monthon Isan in 1906. The record stated that Nong Khai City was located on a levee which was a high land. The inner areas that were far away from the river were cultivable marshes (Damrongrachanuphap, 2021, p. 164). However, the land use was not limited to agriculture because some areas alternated between thung or a large unutilised plain and forests. Herbert Warington Smyth (Smyth, 2019, pp. 283–-284) recorded the landscape and environment in Siam between 1891–1893 and vividly described the land use of the area behind the levees as follows:

> In Nong Khai…above the ship was the slope along the river where one could see a vast lowland in the south. We saw a bunch of sugar palms (Borassus flabelliformis) standing solemnly on deserted vast lands…The forest edge was somewhere behind, not too far nor too close…

The vastness of thung alternating with the forests in Nong Khai City recorded by Herbert Warington Smyth is similar to the land uses in Thung samrit where there is an alternation of thung and forests as described in *Nirat Nong Khai* (see more details in 2.3 Topography of north-eastern Thailand).

In addition to the shared land-used characteristics like the combination of thung, agricultural lands, and forests, the topography of the areas around Nong Khai City is similar to that of other cities mentioned in *Nirat Nong Khai*; they are low hills and intermittent lakes. Prince Damrongrachanuphap's (2021; 139) narration of his journey before entering Nong Khai City reflected the mixed topography of the surroundings of Nong Khai City. He recounted that

> ...in the morning...travelled across Huai Tad, Huai Yang, and Huai Kongsi before climbing up Kok Sang Hin and down to Thung Kam Kae, Thung Huai Kae, and Thung Ranam until we reached Nong Khai City at 5 a.m. ...

As mentioned above, the settlements on the low hills in northeastern region may be related to floods. Figure 18 is a geomorphological survey map of the Mekong River basin indicating area subject to flooding made by Masahiko Oya in 1967. It shows that the settlement in Nong Khai City is on natural levee (yellow), the area Oya claimed that it would only face extraordinary flood. In contrast, the surroundings of Nong Khai City are backswamp which can encounter regular floods. That is to say, despite not being on a low hill, the location of Nong Khai City is still higher than the surrounding areas as it is located on a natural levee. This characteristic is possibly associated with the prevention of floods shown through the settlement patterns mentioned in *Nirat Nongkhai*. Moreover, the map reveals that although Nong Khai City is located along the Mekong River, there are other waterbodies nearby as well. This is consistent with *Nirat Nongkhai* which remarked that the cities in northeastern region are mostly found near water resources.

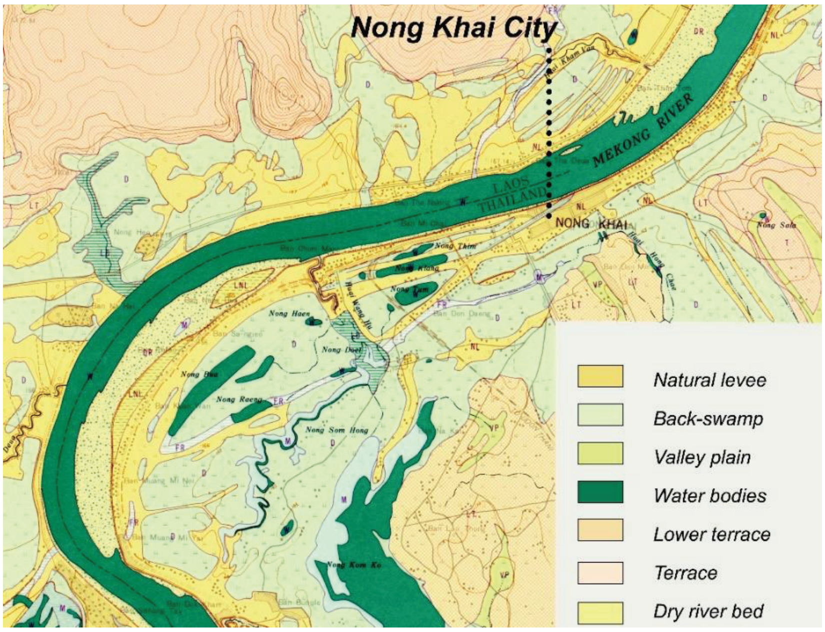


Figure 18 A geomorphological survey map of the Mekong River basin indicating area subject to flooding (Source: National Research Institute for Earth Science and Disaster Resilience, https://ecom-plat.jp/suigai-chikei/index.php?gid=10066)

2) Pattern of built-up lands is similar.

The pattern of the built-up lands in Nong Khai City is similar to the pattern in *Nirat Nongkhai*. Smyth (Smyth, 2019, p. 290) wrote that Nong Khai City, full of banana tress and arecas palms, lies along the Mekong River and there are many temples in its communities. Likewise, the communities in *Nirat Nongkhai* represents the communities in the north-east at that time which must have been encircled by such dense trees that it was hard to see the houses (Phatthanaphongphakcli, 1955, p. 38) and the houses were surrounded by trees such as areca palms and edible plants. The temples are the centres of the communities.

The houses are also in accord with the description of the houses in *Nirat NongKhai* which stated that the houses in the northeastern communities are *ruan kruang phuk*. Prince Damrongrachanuphap (2021, p. 151) briefly described that

> ...most houses in Nong Khai City were elevated houses with roofs made of bamboos, vetiver, and wooden tiles. On the ground under the elevated houses was a space for weaving. The houses were located on the roads that led to the agricultural lands.

For shops, in Nong Khai City the shops were one-story building located along the major roads (Damrongrachanuphap, 2021, p. 151). Because the city beat Vientiane in being the important commercial hub of the region (Chomphoonuch, 2006, pp. 40,97) there were around 30 shops on a main street (Smyth, 2019, p. 291). Although no evidence confirmed whether the shops were *tuek din* like those in *Nirat Nongkhai*, most of them belonged to the Chinese just as what appeared in the literature (Damrongrachanuphap, 2021, p. 140).

In conclusion, the records about the settlement pattern of Nong Khai City reveals that Nong Khai City in the past was located on natural levee which was higher than the surrounding flat areas consisting of agricultural lands, deserted lands, and small hills which contained forests and waterbodies. The marshes around the city cannot avoid floods while the houses in the city were elevated houses located along the roads and surrounded by trees. The Chinese shops in the city spread across main streets due to the role of the city as a commercial hub. Boonkrajangsopee (2009, p. 33) pointed out that even though the commerce was thriving later in Nong Khai City, houses can still be seen on the main roads. Despite that, the houses and the settlement area of Nong Khai City began to expand towards east and south in 1994 due to the development projects of the government sector, such as Thai–Lao Friendship Bridge and Nong Khai Government Administrative Centre.

2.7 Conclusion

A land-use change is a dynamic phenomenon caused by multi-factors. The understanding of the settlement and land-use patterns in each period is thus the crucial information for the study of land-use changes to construct a land-use policy in the future. That is the reason why the current studies of land use are strongly related to surveying technology since this type of technology is essential for accessing and collecting spatial information about the settlement and land use. The development of the surveying technology, remote sensing (RS), and geographic information systems (GIS) over the years has contributed to a major advance in research on land use and settlement (Alam et al., 2020; Sohl & Sleeter, 2012, p. 226). Although these technologies have the capability to capture the historical land cover data, they can't access sufficient land-use information in the past period when no mapmaking and developed survey methods were available. To understand the settlement and land-use patterns in the past, scholars can only use the information from other historical documents such as historical maps, paintings, and travel journals including literature to identify the patterns of the settlement and land use during the targeted period.

Owing to the limitations of the sources about the settlement and land use in pre-modern time to describe the patterns of the settlement and land use of the north-east in pre-modern time when no mapmaking or developed survey methods were available as the chapter objective, in this chapter, *Nirat Nongkhai* and other historical documents from surveyors were used as the main sources. *Nirat Nongkhai* is an 1875 Thai poem that can also be regarded as a travel journal kept during the military expedition. The poet recorded what happened along the way in detail and used a realistic composition style. Not only did the literature provide the information about political history, but its settings and context also revealed clearer knowledge of the north-eastern landscapes, settlements and land uses under tough conditions. For this reason, *Nirat Nongkhai* became a valuable piece of Thai literature as historical evidence.

Nirat Nongkhai shows that the geographic conditions played a prime role in constructing the settlements and land-use patterns of the north-east region in the nineteenth century. The communities were the island villages; clustering on the low hills to avoid floods during the rainy season. The surrounding areas were the low hills with the forestlands, waterbodies and the plains used as agricultural lands and unused lands. Although the water bodies were distributed over the plain, due to the soil quality combined with the severity of natural disasters in terms of floods and drought, most flat areas remained unused and dry grasslands locally known as *thung*.

Although the settlement and land-use description in *Nirat Nongkhai* was not recorded in Nong Khai, the comparison with many historical documents and the previous studies confirm that the settlement and land-use patterns of Nong Khai City in the pre-modern time were similar to the description in *Nirat Nongkhai*. Nong Khai City settled on the natural levee that was higher than the surroundings to avoid floods, and its location was near the water bodies and waterway. Nong Khai City's surrounding areas were plains with agricultural and unused lands. The city was dense with trees and located along the Mekong River with residential and shops along the main roads. Like other Thai communities, temple was the centre of Nong Khai City's communities. These settlement patterns remained until 1994 when the built-up areas of Nong Khai City began to expand towards the east and south due to the development projects of the government sector, such as the Thai–Lao Friendship Bridge and Nong Khai Government Administrative Centre.

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Chapter 3

The change of population in the provincial cities of Thailand during the decade of the 2010s

Contents

3.1 Introduction

Population change is a process and output of natural increase and migration (Martinez-Fernandez et al., 2012, p. 214; National Research Council, 2003, p. 89). It is a phenomenon that is closely related to the urbanisation process (Champion, 2001, pp. 147–148; Dyson, 2011, pp. 47–48; Kabisch & Haase, 2011; Turok & Mykhnenko, 2007, p. 167). The number of population changes is a crucial variable which urban planner usually used to determine the urban development policies because it reflects the status of the cities: growing cities, stagnant cities and shrinking cities (Turok & Mykhnenko, 2007; Wiechmann & Wolff, 2013).

Previously, scholars attempted to suggest that the urbanisation process of the macro-scale areas like country and continent affects the population change in the micro-scale, causing its pattern not to be homogenous; there is not just a growth pattern. It consists of the growing cities and the shrinking cities suggesting the parallel mode (Alves et al., 2016, p. 28; Hattori et al., 2017, p. 131; Oswalt, 2008, p. 3; Turok & Mykhnenko, 2007, pp. 169–170; Wiechmann & Wolff, 2013, p. 7). Recently, the information of the United Nations (2019, p. 73) indicates that there were 94 shrinking cities between 2015–2020. Until 2030, 5 % of the cities worldwide will encounter a population decline. In the future, the process of growth and shrinkage will reach a balance, and the population shrinkage in the city will be a common phenomenon (Oswalt, 2008). Thus, shrinking cities and growing cities are unavoidable, global phenomenon.

The latest study of Moreno et al. (2021) which explored the global population changes found that despite the increase in population in the metropolitan areas between 2000–2015, about 22% of the metropolitan areas around the world shrank and stagnated. 45% of them were in the more developed countries while 26% were in Asia, especially in the less developed countries. However, the antecedent studies only focused on more developed countries such as the European countries, Australia, the United States and Japan (Alves et al., 2016, p. 21; Cunningham-Sabot & Fol, 2007; Hattori et al., 2017; Mallach et al., 2017; Martinez-Fernandez et al., 2012; Pallagst, 2010; Wang et al., 2020, p. 2; Wiechmann & Wolff, 2013).

There are numerous shrinking cities in Japan, especially in the small and local cities outside metropolitan areas. In contrast, the suburban cities surrounding the major cities and the cities in the new town development project have a higher rate of population growth thanks to immigration (Mallach et al., 2017, p. 103; Martinez-Fernandez et al., 2016, pp. 13–14, 16). Wang et al. (2020, pp. 4, 9–11) indicate that 503 of 790 cities between 2000–2010 were shrinking cities. The declining birth rates and the strict regulation of overseas immigration are the main driving factors affecting the pattern of population change in the cities across Japan (Martinez-Fernandez et al., 2016, p. 13).

For the European countries, there are studies classifying cities into clusters based on population changes as well. The analyses on the *shrinking city* distribution have been widespread since early 2000 (Martinez-Fernandez et al., 2016). Several studies indicate that the number of shrinking cities has risen across European countries in recent years (Turok & Mykhnenko, 2007, pp. 168–170; Wiechmann & Wolff, 2013). The cities in the United States were also studied like this (Fol & Cunningham-Sabot, 2010; Morrill, 2012). They have been classified as shrinking and growing cities. The latest data from the population division of the U.S. Census (2020) revealed that between 2010–2019, 132 out of 719 cities with over 50,000 people encountered the population decline. The population change was related to suburbanisation and deindustrialisation associated with migration (Fol & Cunningham-Sabot, 2010; Martinez-Fernandez et al., 2016).

The group of more developed countries mentioned earlier and some cities in the group of less developed countries were also classified as the shrinking cities (Fol & Cunningham-Sabot, 2010, p. 6; Oswalt, 2008). The examples are India (OECD, 2020, p. 101), Iran (Hajian Hossein Abadi & Khavarian-Garmsir, 2021), China (Long & Gao, 2019), Sri Lanka, Cuba, the Republic of Korea (United Nations, 2019, p. 73), and the countries in the central Asia (Restrepo Cadavid et al., 2017, pp. 11–12).

Although there have been indications of shrinking cities globally, most studies focused on big cities resulting in the lack of the change information in small cities which accounts for the most part of the city system. The previous studies found that the medium and small cities have also encountered the population shrinkage (Fol & Cunningham-Sabot, 2010, p.13; Hajian Hossein Abadi & Khavarian-Garmsir, 2021; Mallach et al., 2017, p.103; Tong et al., 2020). Moreover, the studies about big cities may mean that the population decline in medium and small cities will be overshadowed by the rapidly growing big cities (Long & Gao, 2019). Despite being studied widely in more developed countries, shrinking cities in more and less developed countries have both similar and different patterns and contexts as stated by several studies from less developed countries (Cunningham-Sabot et al., 2013; Hartt, 2017). The differences appear in the patterns of the shrinking cities in more developed countries as well (Buhnik, 2010, p.151; Mallach et al., 2017, p.103). For example, Long & Gao (2019) indicate that although the population of the biggest cities and the developed coastal cities in China showed an increase population between 2000–2010, the township population had decreased from 39,007 to 19,882. However, the proportion of depopulation is lower than the developed countries and despite the shrinking cities, the economy still is growing. For small cities, Tong et al. (2020, pp. 11–12) who compared the shrinkage of the small cities in China and the developed countries found that the small cities in China are different in many aspects ranging from the causes the characteristics of the cities, the economic structure, and the policy of administrative boundary. Or in the case of Iran, Khavarian-Garmsir et al. (2018) showed that a shirking city is a consequence of the government policy, the external factor and the condition of housing sector investment.

Although there are studies about urban population change worldwide, unfortunately, the insight from small cities (Grossmann & Mallach, 2021) and the cities in less developed countries leave a big gap for the academic circle related to urban planning. This is because different contexts between less developed countries and more developed countries need different policies to manage the cities. The study of Guan et al. (2021, p.15) reveals that although China has shrinking cities like the western countries, its capital transfer is slower than population transfer, so the related government office should support the traditional industries and the high-tech industry. As a result, it is essential to study about the patterns of population change phenomenon in less developed countries. That helps fulfil the background experiences related to the city patterns, which are sensitive to the time and the context of a country.

Thailand is among the less developed countries. Over the past years, due to the increasing urban population, Thailand has encountered rapid urbanisation (United Nations, 2019, p. 22). The urban population is growing within the *Thesaban* [municipality] boundary, the urban area unit of Thailand. According to the Thesaban Organisation Act 1953, the Thesaban boundaries are divided by the population size and income. They are categorised into three types (excluding Bangkok and Pattaya city, which are the special urban settlements in Thailand): Thesaban Nakhon (City-municipality) with a population of over 50,000, Thesaban Muang (Town-municipality) with a population of over 10,000, and Thesaban Tambon (Subdistrict-municipality).

Although the laws designated Thesaban areas as urban areas of Thailand, urban areas, in general, refer to the provincial cities. They are the centres of the provinces in many aspects ranging from administrative, settlement and economic to social aspects. When the transportation and the industries were undeveloped, the population changes within the provincial cities occurred naturally due to the limitation on mobility. Later, the National Economic and Social Development Plans and the urbanisation caused the development of the transportation and the economic areas, resulting in more internal immigration into the economic or peri-urban areas (Ratniyom, 2017, pp. 76–78). The population sprawled into other areas, both provincial cities and other types of cities, causing the population in the provincial cities to change dynamically.

Despite such a situation and just as many countries, the population changes within the provincial cities of Thailand vary; few studies on urban area classification based on population change were conducted. Like many other countries worldwide, shrinking cities have not been mentioned much in the Thai academic context and Thai urban policies (Long & Gao, 2019; Long

& Wu, 2016; Martinez-Fernandez et al., 2016, p. 5). The city management of Thailand has only been based on a pro-growth policy, although the population of Thailand was predicted to be shrunk by 2050 (Jarzebski et al., 2021, p. 4). The prototype policy based on the pro-growth policy is not a panacea that can respond to every pattern of population change in the city and is not sustainable. The incorrespondence leads to problems in many dimensions (Heeringa, 2020), especially infrastructure redundancy, public utilities, city-area deterioration and liquidity in a city.

Within this context, this study aims to explore the patterns of the urban population change in Nong Khai City and other provincial cities in Thailand by (1) analysing the patterns of changes in population and urban concentration in the provincial cities and (2) categorising provincial cities into clusters to lay a foundation for generating sustainable provincial city management frameworks. The finding will be one of the important case studies providing insights about the cities of less developed countries which need more attention and evidence. Furthermore, this study will offer more bodies of knowledge about city patterns based on the population change at the national level. It presents the urban situations in Thailand influenced by the concept of pro-growth strategies. The influence is not limited to the growing cities; the shrinking and stagnant cities are also affected. The involved departments should adjust the paradigm used for city planning to correspond with the actual population change.

This chapter is structured into six sections as follows. The first section is the objective. Then, the data and methodology are introduced. This section provides information about the study area, population data, supplementary data, and the methodologies that were performed to determine the patterns of the population change and classify the clusters. Following that are the results, which are divided into two parts. Part 1 of the spatial distribution of the population in the provincial cities describes the patterns of the population changes based on three indices and discusses the statistical data from the previous studies. Part 2 is about the cluster profile. In this part, the characteristics of each cluster are briefly described. Then, the discussion is presented in two parts. First, the patterns of population changes in this study are discussed using the previous studies to identify the characteristics of the population change patterns in the provincial city in Thailand from 2010 to 2019. Second, the population change of Nong Khai City is also discussed in this part to provide an understanding of the urbanisation in Nong Khai City in terms of the population. Afterwards, the brief city management approaches based on each cluster are presented in the last part of discussion. Next, conclusion is presented following by the limitations and brief direction of the research.

3.2 Objective

1) To describe the patterns of the urban population changes in Nong Khai City and other provincial cities in Thailand by analysing and categorising them based on the patterns of the urban population changes as well as the urban population concentration and its changes.
2) To recommend the policies to manage the land use in Nong Khai Provincial City and other cities in terms of population change, in order to support the policies on the built-up land expansion.

3.3 Data and methodology

3.3.1 Study area: Provincial cities in Thailand

The study area covers every Thesaban that is a provincial city. Based on the number of provinces in Thailand in 2019, there are 76 provincial cities, excluding Bangkok, the capital city. The number increased from 75 provincial cities after the establishment of Bueng Kan Province in 2011. At present, there are 22 Thesaban Nakhon and 54 Thesaban Muang across the country, as shown in Figure 19.

In this study, the names of the provincial cities are put after their Thesaban. We will use abbreviations for each type of Thesaban: TN is for Thesaban Nakhon; TM is for Thesaban Muang; TT is for Thesaban Tambon.

3.3.2 Data

The data used in this study consist of two parts.

3.3.2.1 Population data

Because of the limitation to access the population data about the birth, death and migration at the provincial city level, we decided to use the total population to clarify the patterns of population changes. Every piece of data was from 2010 to 2019, except the data of Bueng Kan Province, which was from 2011. The data at the provincial city level were retrieved from the Bureau of Registration Administration's website (http://stat.dopa.go.th/stat/statnew/), and the data at the province level were from National Statistical Office's website (http://statbbi.nso.go.th/staticreport/page/sector/th/01.aspx).

3.3.2.2 Supplementary data

We applied some socioeconomic statistics to define and describe the characteristics of the cluster profiles. The main supplementary data consists of two parts. The first part is the data of Gross

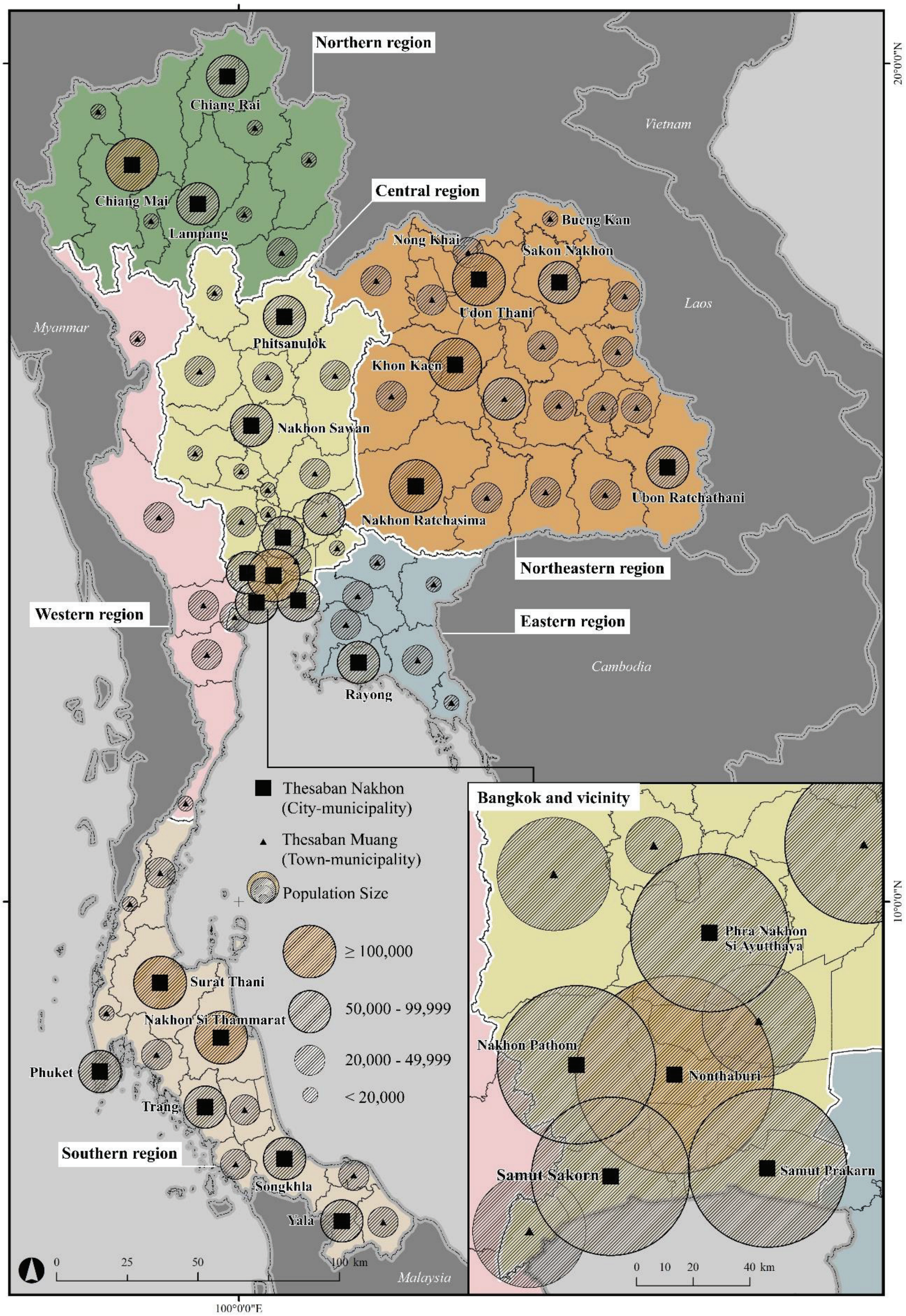

Figure 19 Map illustrating the provincial cities in 2019

Provincial Product (GPP). It was retrieved from the National Economic and Social Development Council's website (https://www.nesdc.go.th/nesdb_en/ewt_w3c/ewt_dl_link.php?filename=national_account&nid=4317).

GPP is an index to determine the structure of economy and the function of the province based on the economic activities. It consists of 19 sub-sectors, revealing the economic activities. In this study the GPP is the major GPP among the highest GPPs of sub-sectors. Only 5 sub-sectors were indicated as the main GPPs: accommodation and food services, agriculture activities, manufacturing, mining and electricity supplies, and wholesale and retail trade. Although GPPs were generated from the entire province, not only the provincial city, under the limitation of information at provincial city GPPs can provide the overview about the economic activities in and outside the provincial cities to support the population change pattern. In the provincial cities, GPPs usually respond to economic activities in the group of service based on the context such as wholesale and retail trade, administrative and support service activities, and education. Scholars usually indicate the relationship between the economic structure and the population change pattern. (Barreira et al., 2017, p. 865; Guan et al., 2021; Tong et al., 2020)

The second part is the number of Thesaban. It was retrieved from the Department of Local Administration's websites (http://www.dla.go.th/upload/service/2011/9/156.pdf and http://www.dla.go.th/work/abt/). The data about the number of Thesaban in each level presents the other urban area outside the provincial cities that is related to the urban concentration and the role of an urban settlement centre.

3.3.3 Methodology

The methodology consists of two parts, as shown in Figure 20. The first part is the content analysis. The patterns of the population changes in the provincial cities were analysed based on three indices at this step. Then, in the second part, the cluster analysis was performed to divide the groups of the provincial cities by using the characteristics of the population change patterns deriving from the first step.

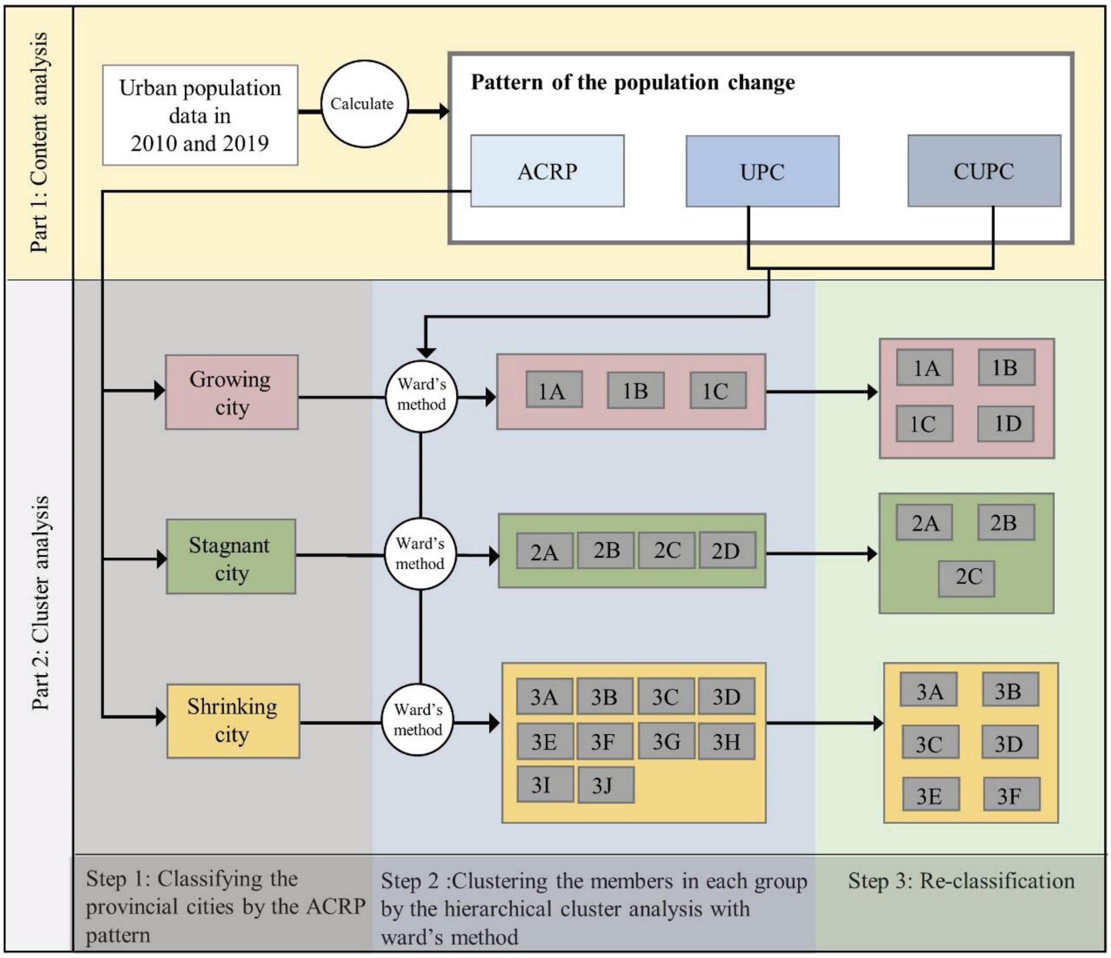

Figure 20 Research methodology flow chart

3.3.3.1 Content analysis

This aims to clarify the patterns of the provincial city population in the aspect of the population changes, the urban population concentration, and its changes. The content analysis with descriptive statistic consists of three parts: ACRP, UPC and CUPC.

3.3.3.1.1 The patterns of the annual change rate of the population (ACRP)

The population changes are associated with the urbanisation stage. The population changes, both growth and depopulation, reflect the city's character and are related to the urban services. Many methods were used to determine the change rate of population in the target area such as the change rate in exponential formula (Peterson, 2017) and the linear growth formula (Guan et al., 2021; Morrill, 2012; Sun et al., 2020).

In this study, ACRP was analysed based on the linear growth formula that is easy to understand and interpret. In addition, to diminish the influence of the time difference between TM. Bueng Kan and other provincial cities, ACRP was analysed as the annual change rates. It was calculated by a simple formula frequently used by previous scholars (Kabisch & Haase, 2011), as shown below:

$$ACRP = \frac{(P_{b+n} - P_b)}{P_b} \times \frac{1}{n} \times 100 \quad (3.1)$$

Where P_b is the population in the beginning time, P_{b+n} is the population in the end time, and n is the number of periods.

In this study, there are three patterns of ACRP. 1) the population changes with the growth rate of (ACRP ≥ 1). 2) the population changes with the decreased rate of (ACRP ≤ -1). 3) the population changes with the static rate of (ACRP ≥ -1 and ACRP ≤ 1).

3.3.3.1.2 The urban population concentration (UPC)

The UPC is an index of the urban population's spatial distribution patterns at the province level. It reflects the urban settlement concentration in the provincial cities revealing the role of an urban settlement centre. It also reflects the urban settlement density in the provincial cities. This index was inspired by and adjusted from the urbanisation rate commonly used to calculate the proportion of the urban population to the total population in the target area (Champion, 2001; National Research Council, 2003, p. 82). We modified it by changing the divider from the total population to the total urban population in the province to reflect the urban population concentration at the local level, as shown in formula (3.2)

$$UPC = \frac{P_{pc}}{P_p} \times 100 \quad (3.2)$$

Where UPC is the urban population concentration, P_{pc} is the number of populations in the provincial city, and P_p is the urban population in the province.

Because the divider was changed into the total urban population, UPC can reflect the role of the urban settlement concentration of the provincial city at the province level. In order to analyse the pattern of the UPC, we applied the normal distribution concept to classify the patterns into three groups:

(1) The city has a high UPC compared with other cities in the province. It is a city with a value equal to or greater than the mean value of 50%. (The range of all plus the standard deviation from the mean of 50%).

(2) The city has a general UPC compared with other cities in the province. It has a value of 15.90–50%. The cut point at 15.90 was determined by the range of minus one standard deviation from the mean.

(3) The city has a low UPC compared with other cities in the province. It has a value of less than 15.90%, which is the value next to minus one standard deviation from the mean.

3.3.3.1.3 The changes in the urban population concentration (CUPC)

CUPC shows how the provincial city lost or gained the role of an urban settlement centre in terms of the urban population change. The CUPC was calculated via the formula below:

$$\text{CUPC} = UPC_{b+n} - UPC_b \qquad (3.3)$$

Where UPC_{b+n} is the urban population concentration in the end time, and UPC_b is the urban population concentration in the beginning time.

To clarify the patterns of CUPC, we categorised their patterns into three types:

(1) The city has a value over 1.0, indicating that it gains the role of the urban settlement centre from the increasing urban population concentration at the province level owing to the immigration or the shrinking urban population outside the provincial city.

(2) The city has a value less than -1.0, indicating that it is losing the role of the urban settlement centre from the decreasing of urban population concentration at the province level owing to the increase in population outside the provincial city or the population decline in the provincial city.

(3) The city has a value between -1.0 and 1.0, indicating that the change of city role as the urban settlement centre is static. The change of urban population concentration maintains a balance between the provincial cities and the urban areas outside during the time.

3.3.3.2 Cluster analysis

In urban studies, cluster analysis is a traditional methodology applied for classifying cities. Clusters of the cities with high homogeneous characteristics help planners quickly identify the proper policies to solve the city problems. This study attempts to categorise the provincial cities regarded as urban settlements in Thailand into clusters based on their population change patterns deriving from the content analysis. The categorisation has three stages, as shown in Figure 20.

In the first stage, we classified the provincial cities into three clusters based on the ACRP pattern: the growing city, the stagnant city, and the shrinking city. In the second stage, the UPC in 2019 and the CUPC during the 2010s were the variables used to classify the clusters on IBM SPSS Statistic 27. The hierarchical cluster analysis with the Ward's method, a commonly used method (Rogerson, 2010, p. 306), was applied with two indices to classify the cities in each cluster.

Ward's method is a statistical technique use to perform to classify the city or spatial cluster (Oke et al., 2019; Omurbek et al., 2021; Salazar et al., 2020). It divides the groups of members based on the size of an error sum-of-squares criterion (Everitt et al., 2011, p. 77). Generally, in the Ward's method algorithm, every member begins as its own cluster. Then a pair of clusters is merged by minimizing the increase in the total within-cluster error sum of squares. This process continues until only one cluster remains (Everitt et al., 2011, p. 77; Rogerson, 2010, p. 305). Scholars regard Ward's method as the outperform technique to compose the cluster (Blashfield, 1976; Oke et al., 2019). The process of Ward's method is simple and there's no need to specify the number of clusters before analysis. In addition, it is suitable to compose the sample through the continuous data (Everitt et al., 2011, p. 258). From this advantage, the Ward's method was performed in this study to classify the clusters of the provincial cities that the value of indices is the continuous data.

After the classification in the second stage, there are 17 sub-clusters. The last stage is re-classification. The descriptive statistical analysis of the cluster indicates that a few members of different clusters have a similar pattern of the variables. To make each cluster more homogeneous, the re-classification was done repeatedly by considering the patterns of each member's overlapping variables and then grouping some provincial cities with a similar pattern together. Finally, 13 sub-clusters were created within the three main clusters that were classified in the first step.

3.4 Results

3.4.1 Spatial distribution of the population in the provincial cities

3.4.1.1 The size of the provincial city population and their changes

In 2019, there were 3,341,093 inhabitants in 76 provincial cities. The population sizes of the provincial cities are different. TM. Bueng Kan was the smallest in the population size; there were only 4,494 inhabitants. TN. Nonthaburi was the biggest in the population size with 254,375 inhabitants. According to the number of the population in the provincial cities, there is no provincial city which has more than 300,000 inhabitants. It indicates that although the provincial cities are the core areas of the urban settlement in the provinces, no city reaches the standard of United Nation which identified a city from the population of at least 300,000 inhabitants (United Nations, 2019, p.55). All provincial cities in Thailand are only the urban settlement according to the United Nation's standard.

The analysis of the provincial city population distribution divided by geographical regions, as shown in Figure 19 and Figure 21, indicates that the inhabitants of the provincial cities were dense in the central and north-eastern regions with a similar ratio, followed by the southern, the northern, the eastern and the western regions. The main reason is that more provincial cities with the largest number of inhabitants—TN. Nonthaburi, TN. Nakhon Sawan, TN. Nakhon Ratchasima, TN. Udon Thani, TN. Khon Kaen, TN. Nakhon Si Thammarat and TN. Surat Thani—distributed in the central, northeast and southern regions. Moreover, the number of

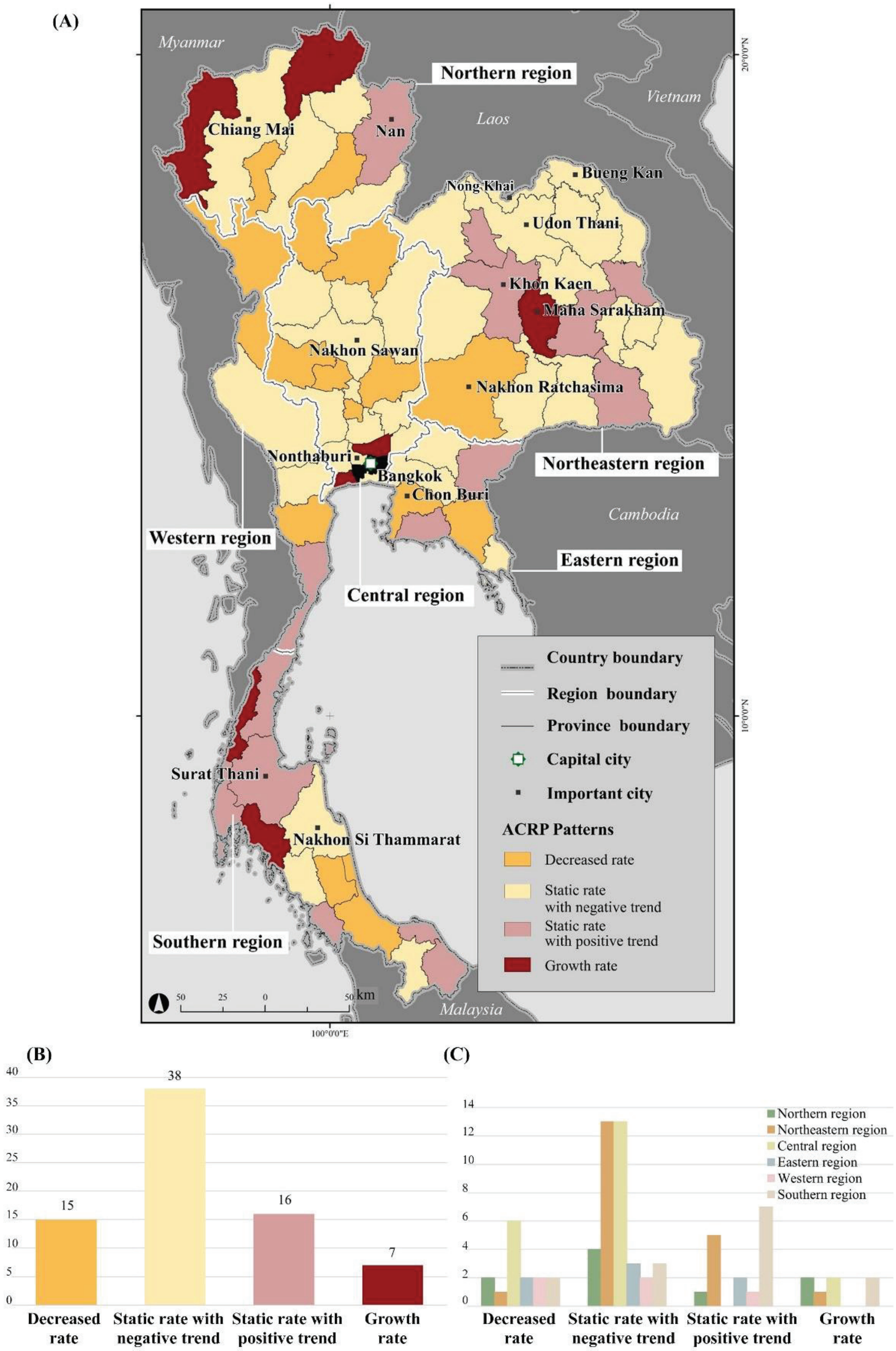

Figure 21 The spatial distribution of the ACRP patterns; (A) The distribution map shows the pattern of ACRP; (B) The number of the provincial cities, divided by ACRP patterns; and (C) The number of the provincial cities, divided by the geographical regions and ACRP

provincial cities in the central region was the highest, making up 21 cities, followed by north-eastern regions with 20 cities. The southern, northern, eastern and western regions had only fourteen, nine, seven and five cities, respectively. That's why the number of provincial inhabitants in the central and northeast regions was higher than in other regions.

The population in the provincial cities at the country level in 2019 was slightly lower than in 2010 with -0.26 as the average of ACRP at the country level. Precisely, 47 provincial cities have the values lower than that. TM. Maha Sarakham hit the highest ACRP with a growth rate of 2.88. In contrast, TM. Chon Buri hit the highest ACRP with a decreased rate of -1.74. Although many studies showed the correlation between the population size and the change rate by indicating that the cities with low population often encountered the population decline while the cities with high population often encountered the population growth (Park & Heim LaFrombois, 2019, p.245; Sun et al., 2020) , the analysis of the correlation revealed that there was no significant correlation. TM. Maha Sarakham which had the highest population increase rate ranked twenty-ninth in 2010 in terms of the population size while TM. Chon Buri which had the lowest population increase rate ranked thirty-ninth. After looking at the change rate of the top 10 biggest cities in terms of population in 2010, nine cities are stagnant cities with low population changes. Also, Nakhon Ratchasima which was the second biggest cities ranked eleventh in terms of the population decrease rate. The fluctuation in the population sizes and the population change rates is similar to the study of Merino & Prats (2020, p.6) in the 2010s which focused in the municipalities in Spain between 2012–2016 and found that the growth cannot be determined by the previous size.

Considering the patterns of the population changes, Figure 21 (B) indicates that 54 cities were stagnant cities. 16 cities in this group changed with the positive trend while the populations in 38 cities changed with the negative trend. Besides, 15 cities were shrinking cities, and only seven cities were growing cities. Regarding the stagnant cities changing with negative trends and shrinking cities, we found that 53 provincial cities in 2019 experienced a decrease in the population. This contrasts with the trend of the urban population in Thailand, which increased during the 2010s, as shown in Figure 22. It reflects that the population outside the provincial cities has been increasing. The increasing number of the local Thesaban might have been the result of the decentralisation policy and could have been a significant factor in the population growth outside the provincial cities.

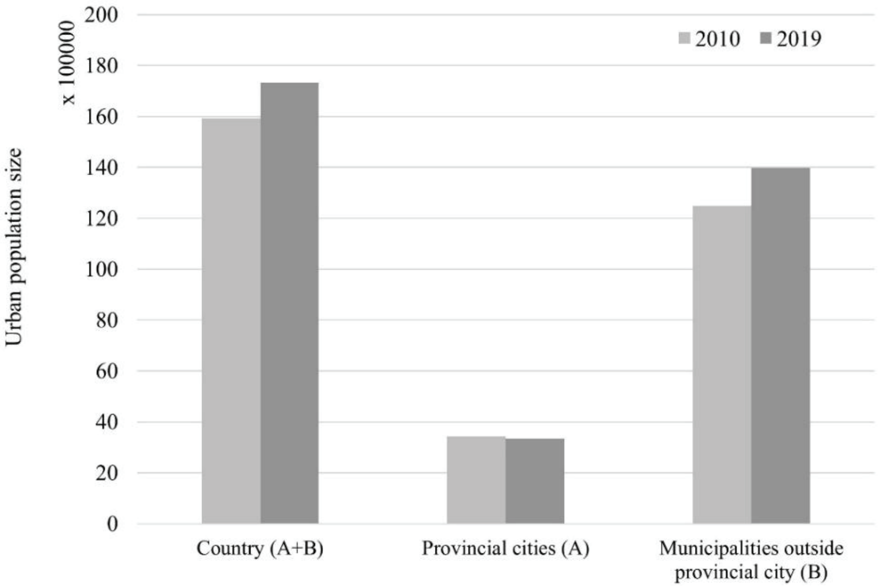

Figure 22 The urban population changes between 2010–2019

According to the spatial distribution analysis at the regional scale, as shown in Figure 21 (C), most of the provincial cities in every region were stagnant cities which changed with a negative trend. There were two exceptions. In the western region, the stagnant cities which changed with negative trend accounted for an equal number of the shrinking cities. And for the southern region, most provincial cities were stagnant cities which changed with a positive trend. It is noteworthy that there were no provincial cities in the western region and the eastern region containing only the growing cities.

3.4.1.2 The urban population concentration and its changes

At the country level, the average UPC value in 2019 was 24.28. As shown in Figure 23, there were only four provincial cities—TM. Samut Songkhram, TM. Nakhon Nayok, TM. Ranong and TN. Trang—in which their population accounted for more than 50% of the total population of their provinces. TM. Samut Songkhram hit the highest proportion with 71.95%. Given the GPPs and the structure of each province, the four provincial cities were in the provinces with the agricultural economy and the lower number of Thesaban other than the provincial cities. Consequently, their provincial cities have high population and are the sources of economic activities and public facilities.

In the five provinces with the lowest UPCs which were TM. Chonburi, TM. Pathum Thani, TM. Bueng Kan, TM. Lamphun, and TM. Buriram, the population in TM. Chon Buri was

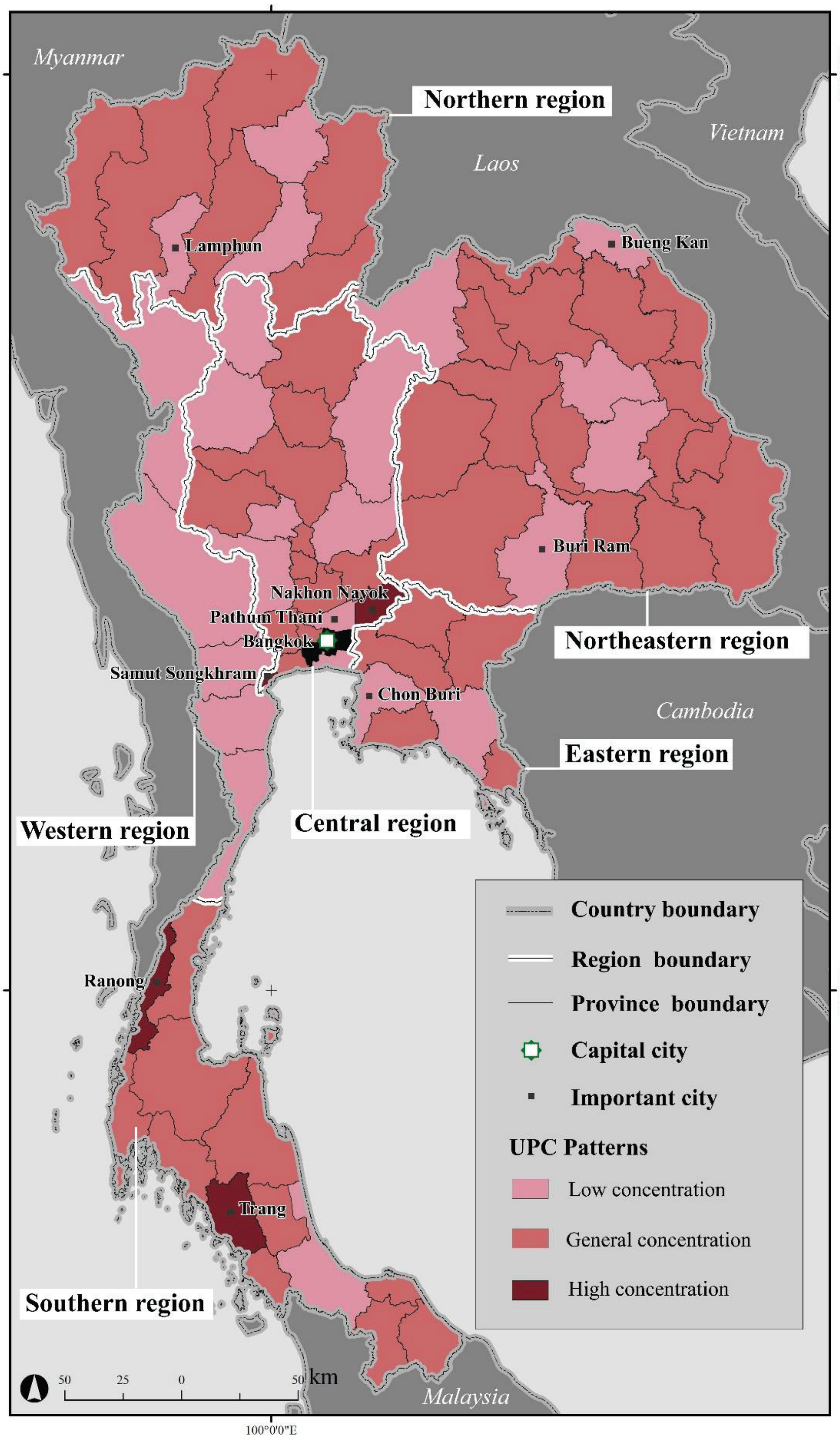

Figure 23 The spatial distribution map of the UPC patterns

the lowest with the ratio of 2.45% of the total urban population of the province. All the provincial cities were only TM. Which have average population. Considering the economic structures at the province scale through GPPs and the number of Thesaban, three provincial cities (TM. Chonburi, TM. Pathum Thani, TM. Lamphun) were located in the provinces with the manufacturing economy and consisted of many Thesaban, resulting in low concentration of urban population because of the concentration outside the provincial cities, especially in the industrial areas which provided higher employment opportunity. For TM. Bueng Kan, and TM. Buriram, although their economy wasn't based on manufacturing like the three provinces, the province that TM. Buriram belonged to show the high number of Thesaban outside the provincial cities, causing the low urban concentration. TM. Bueng Kan emerged later when it was upgraded to TT due to the city hall located there, so there is still no sign of high population concentration.

According to the regional level, 48 provincial cities are generally the centres of the urban population in the provinces with UPC Value between 15.90–50.00%. Most provincial cities in this group are in the north-eastern region, followed by the central region and the southern region with the same number. In contrast, 24 provincial cities are less dense in terms of the urban population in the provinces. They have an urban population lower than 15.90% of the total provincial urban population. The provincial cities in this group distributed in every region, mostly the central region, followed by the western region and the north-eastern region with the same number. Notably, every provincial city in the western region was less concentrated. This resulted from the dense urban population in the industrial or commercial areas outside the provincial cities.

At the same time, there were two provincial cities in the southern and central regions in a highly concentrated pattern (UPC ≥ 50%). In contrast, the northern, north-eastern, eastern and western regions had no provincial city housing more than 50% of the total urban population of their provinces.

The UPC decreased at the country level with an average rate of -1.13 during the 2010s. TM. Nong Khai hit the highest change rate at 16.15%. In contrast, TN. Phitsanulok hit the most remarkable change rate at -8.53 due to the increasing population in the outskirt area.

According to the regional level, only six provincial cities, distributing in four regions except for the western and eastern regions, showed the growth rate. Precisely, 38 provincial cites showed a decreased rate. Most of these provincial cities were in the central and southern regions, respectively. 32 provincial cities showed the static rate, and most members of this group were in the north-eastern region, as shown in Figure 24.

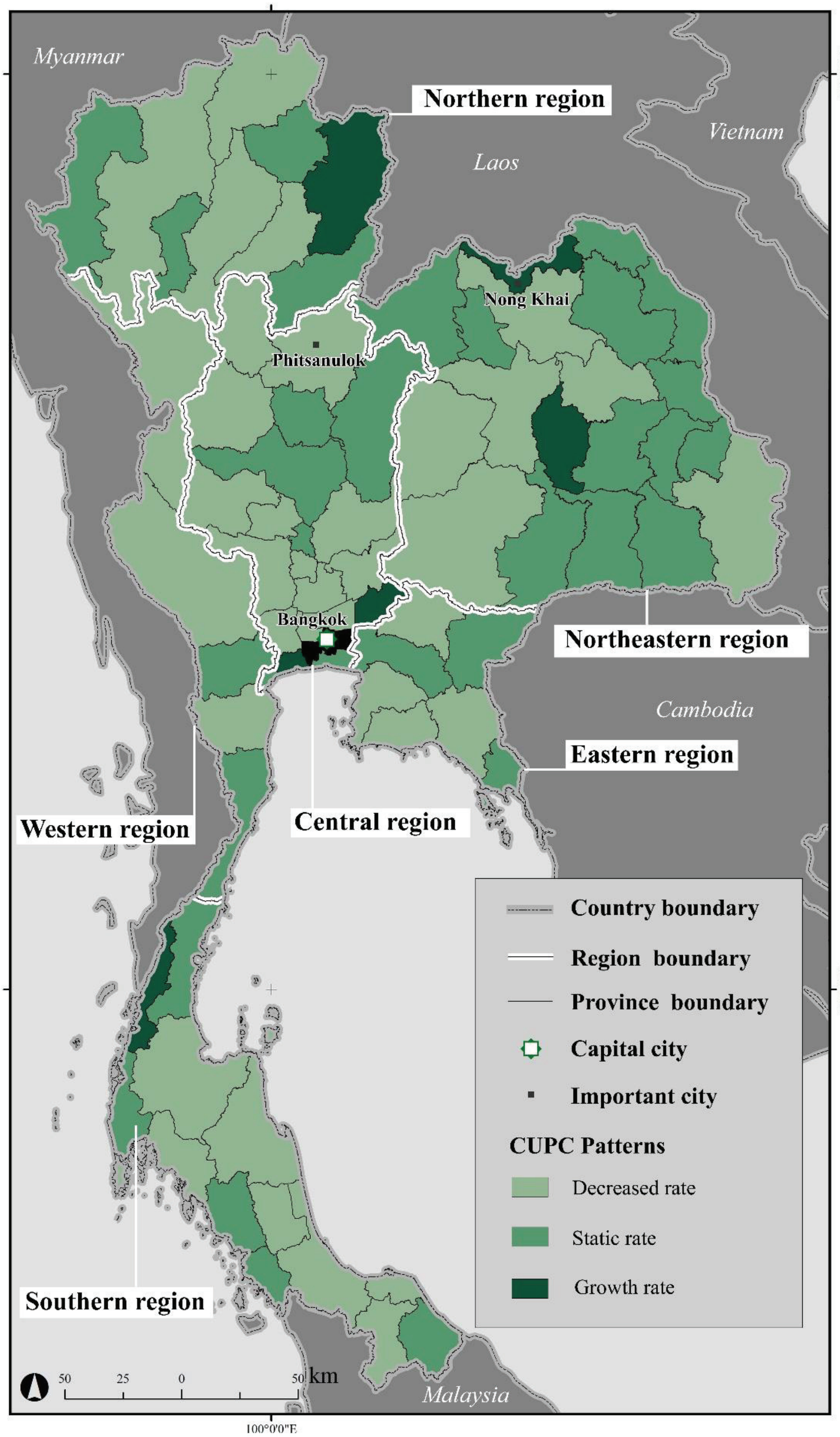

Figure 24 The spatial distribution map of the CUPC patterns

The decrease of the UPC, which was the primary pattern, indicated that most provincial cities were losing the roles as urban settlement centres and were replaced by neighbour cities or district cities owing to the process of suburbanisation and the decentralisation policies from the central government that attempted to spread the development from the core area. The urban system tended to change the provinces from containing only one settlement centre in each provincial city to multi-settlement centres in a province. For eastern and western regions which didn't see the increase of UPC in any province, the economic structure based on GPP values indicated that their economy didn't depend on the agriculture, so the urban population concentrated in the industrial, commercial and tourist areas outside the provincial cities, especially in the eastern region whose industries were invested and developed because of the Eastern Seaboard policy and the Eastern Economic Corridor in the 2010s. The policies led to the agglomeration of the technology and industries, followed by the increase in the employment rate (Tontisirin & Anantsuksomsri, 2021, pp. 1–4) and the population outside the provincial cities. The consequence was the decrease in UPC values.

TM. Nong Khai hit the highest change rate. The decrease in urban population was mainly caused by the political conditions. Although the urban population outside the provincial city decreased like other provinces whose UPC increased, the establishment of Bueng Kan in 2011 took the urban population of about 80,000 from Nong Khai Province causing the UPC of TM. Nong Khai to hit the highest change rate.

3.4.2 Cluster profile

According to the cluster analysis, the ACRP pattern was used to categorise the provincial cities into three groups: the growing city, the stagnant city, and the shrinking city. Then, the hierarchical cluster analysis with Ward's method was adopted to categorise the provincial cities in each group based on the UPC and CUPC. The UPC and CUPC in each group were considered and re-classified by merging the members whose UPCs and CUPCs show similar characteristics into the same group. Finally, the provincial cities were grouped into 13 sub-clusters. Each sub-cluster has its own statistical characteristics with three variables, as shown in Figure 25.

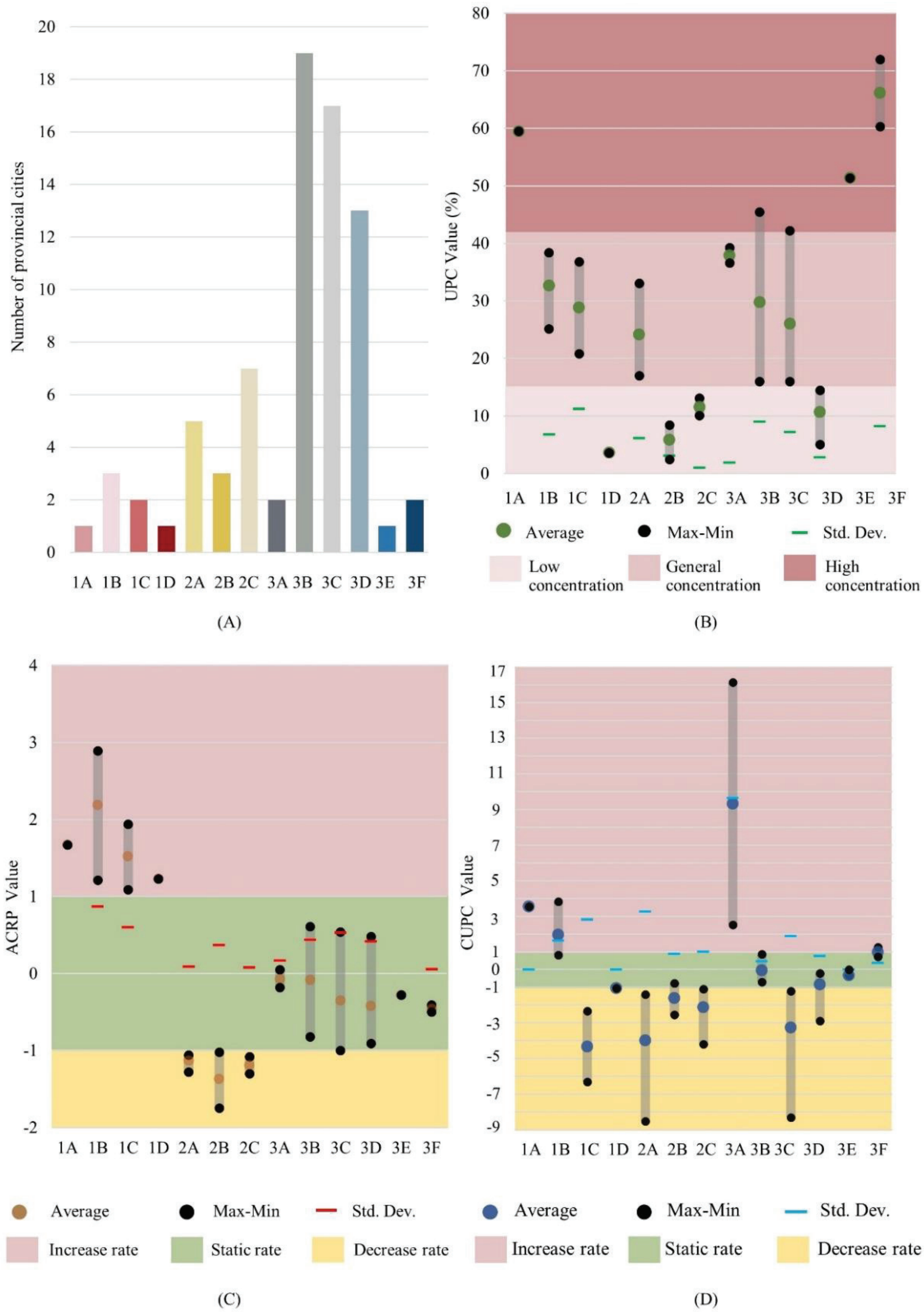

Figure 25 Statistical profile of the variables in each sub-cluster; (A) the distribution of provincial cities in each sub-cluster, (B) the statistical profile of UPC in each sub-cluster, (C) the statistical profile of ACRP in each sub-cluster, and (D) statistical profile of CUPC in each sub-cluster.

Figure 26 and Table 5 indicate that each region has a different sub-cluster distribution pattern. The number of provincial cities in each region's main and secondary sub-clusters is extremely close, except the north-eastern region, where it's obvious that sub-cluster 3B is the main and sub-cluster 3D is the secondary. Both sub-clusters have similar city profiles; the only difference lies in the UPC. The value of UPC is higher in sub-cluster 3B, which is also the main for the eastern region. The number of eastern provincial cities in this sub-cluster is close to sub-cluster 3C, which is the main for other regions.

Although sub-cluster 3C isn't the largest, most cities in the northern, central and southern regions (or three out of six regions) are in this cluster. The members of sub-cluster 3C from each region are mostly regional cities or Thesaban Nakhon. Despite being the main sub-cluster for those regions, sub-cluster 3C doesn't have much more members than secondary sub-clusters. For example, the nearly equal number of other northern provincial cities are in other seven sub-clusters. Another example is the southern region, where sub-cluster 3B is its secondary sub-cluster and mostly shelters small cities. The central region has a different pattern. It has both sub-cluster 3C and 3D as the main sub-clusters, and these two have an equal number of members. Note that sub-cluster 3D is the main for the western region.

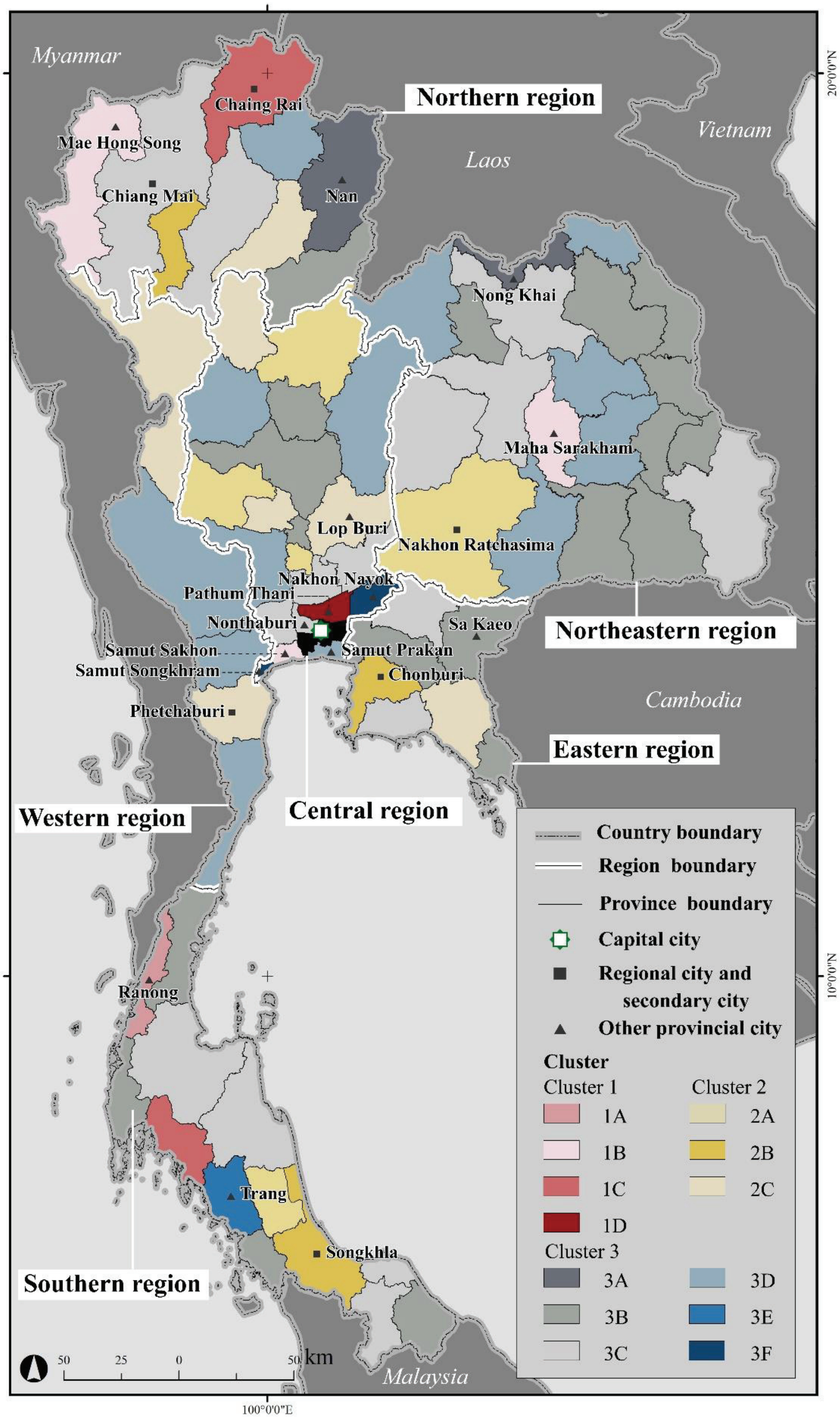

Figure 26 Cluster profile distribution map

Table 5

Distribution of provincial cities divided by clusters and regions

Region	Cluster 1				Cluster 2			Cluster 3					
	A	B	C	D	A	B	C	A	B	C	D	E	F
Northern	-	1	1	-	-	1	1	1	1	2	1	-	-
North-eastern	-	1	-	-	1	-	-	1	8	4	5	-	-
Southern	1	-	1	-	1	1	-	-	4	5	-	1	-
Central	-	1	-	1	3	-	3	-	3	4	4	-	2
Western	-	-	-	-	-	-	2	-	-	-	3	-	-
Eastern	-	-	-	-	-	1	1	-	3	2	-	-	-

Table 6

Information about the population and supplementary data of the provincial cities

Sub-Cluster	No.	Provincial city	Region	The pattern of population change			Number of Thesaban			Main GPP**
				ACRP	UPC	CUPC	TN.	TM.	TT.	
1A	1	Ranong	Southern	1.67	59.47	3.55	0	2	10	AG
1B	1	Maha Sarakham	Northeastern	2.89	38.36	3.81	0	1	18	AG
	2	Samut Sakhon*	Central	2.48	25.15	1.22	2	2	11	MA
	3	Mae Hong Son	Northern	1.21	34.49	0.81	0	1	6	AG
1C	1	Chiang Rai*	Northern	1.09	20.83	-2.33	1	0	72	AG
	2	Krabi	Southern	1.94	36.79	-6.32	0	1	14	AG
1D	1	Pathum Thani	Central	1.23	3.60	-1.05	1	10	18	MA
2A	1	Nakhon Ratchasima*	Northeastern	-1.08	20.02	-1.96	1	4	85	MA
	2	Phitsanulok*	Central	-1.17	33.07	-8.53	1	1	24	AG
	3	Phatthalung	Southern	-1.06	25.28	-6.37	0	1	48	AG
	4	Uthai Thani	Central	-1.09	25.56	-1.63	0	1	13	AG
	5	Ang Thong	Central	-1.28	17.01	-1.40	0	1	20	MA
2B	1	Songkhla*	Southern	-1.33	8.44	-2.53	2	11	35	MA
	2	Chon Buri	Eastern	-1.75	2.45	-1.52	2	10	36	MA
	3	Lamphun	Northern	-1.02	6.73	-0.76	0	1	39	MA
2C	1	Lop Buri	Central	-1.27	10.87	-2.05	0	3	20	MA
	2	Chai Nat	Central	-1.24	12.18	-1.10	0	1	38	AG
	3	Chanthaburi	Eastern	-1.08	10.10	-1.49	0	5	42	AG
	4	Phrae	Northern	-1.17	12.40	-1.59	0	1	25	AG
	5	Tak	Western	-1.13	11.30	-4.19	1	1	17	AG
	6	Sukhothai Thanee	Central	-1.30	10.77	-2.40	0	3	18	AG
	7	Phetchaburi	Western	-1.14	13.11	-2.00	0	2	13	MA
3A	1	Nong Khai	Northeastern	-0.18	39.23	16.15	0	2	17	AG
	2	Nan	Northern	0.05	36.57	2.51	0	1	18	AG
3B	1	Nakhon Sawan*	Central	-0.82	42.42	-0.33	1	2	18	AG
	2	Sakon Nakhon*	Northeastern	-0.14	26.41	-0.32	1	0	65	AG
	3	Sing Buri	Central	-0.59	32.30	0.18	0	2	6	AG
	4	Trat	Eastern	-0.37	18.04	-0.70	0	1	14	AG
	5	Chachoengsao	Eastern	-0.12	24.55	-0.61	0	1	33	MA
	6	Sa Kaeo	Eastern	0.49	20.85	0.46	0	3	13	AG
	7	Surin	Northeastern	-0.28	41.91	0.11	0	1	27	AG
	8	Si Sa Ket	Northeastern	0.37	23.73	0.77	0	2	35	AG

Table 6 (Continued)

Sub-Cluster	No.	Provincial city	Region	The pattern of population change			Number of Thesaban			Main GPP**
				ACRP	UPC	CUPC	TN.	TM.	TT.	
	9	Yasothon	Northeastern	-0.17	37.10	0.00	0	1	23	AG
	10	Amnat Charoen	Northeastern	-0.24	39.44	-0.20	0	1	23	AG
	11	Nong Bua Lamphu	Northeastern	0.21	19.40	0.55	0	1	23	AG
	12	Pichit	Central	-0.75	15.95	-0.28	0	1	14	AG
	13	Nakhon Phanom	Northeastern	-0.27	30.53	0.02	0	1	21	AG
	14	Mukdahan	Northeastern	0.33	45.44	0.05	0	1	24	AG
	15	Uttaradit	Northern	-0.61	21.04	-0.69	0	1	25	AG
	16	Pangnga	Southern	0.61	31.00	0.87	0	2	13	AC
	17	Chumphon	Southern	0.08	34.24	0.12	0	2	26	AG
	18	Satun	Southern	0.38	37.13	-0.59	0	1	6	AG
	19	Narathiwat	Southern	0.38	24.47	-0.10	0	3	13	AG
3C	1	Nonthaburi*	Central	-0.27	32.73	-8.31	2	10	10	WR
	2	Rayong*	Eastern	0.54	17.72	-2.87	1	2	27	MA
	3	Ubon Ratchathani*	Northeastern	-0.99	19.29	-3.72	1	4	54	AG
	4	Khon Kaen*	Northeastern	0.06	22.55	-4.52	1	6	77	MA
	5	Udon Thani*	Northeastern	-0.54	26.16	-1.81	1	3	67	AG
	6	Chiang Mai*	Northern	-0.99	18.84	-4.67	1	4	116	AG
	7	Lampang*	Northern	-0.94	19.71	-1.22	1	3	39	ME
	8	Nakhon Pathom*	Central	-0.83	25.57	-6.15	1	5	20	MA
	9	Nakhon Si Thammarat*	Southern	-0.62	34.56	-2.39	1	3	50	AG
	10	Phuket*	Southern	0.47	28.80	-3.35	1	2	9	AC
	11	Surat Thani*	Southern	0.50	29.97	-2.42	2	3	35	AC
	12	Phra Nakhon Si Ayutthaya*	Central	-0.62	15.95	-1.57	1	5	30	MA
	13	Yala*	Southern	-0.38	42.22	-3.07	1	2	13	AG
	14	Saraburi	Central	-0.43	26.09	-1.24	0	4	34	MA
	15	Prachin Buri	Eastern	-0.78	27.19	-2.16	0	1	12	MA
	16	Chaiyaphum	Northeastern	-0.38	20.28	-4.25	0	1	35	AG
	17	Pattani	Southern	0.28	34.82	-1.75	0	2	15	AG
3D	1	Samut Prakan*	Central	-0.54	7.66	-0.61	1	7	14	MA
	2	Buri Ram	Northeastern	-0.77	7.66	-0.73	0	3	60	AG
	3	Bueng Kan	Northeastern	-0.54	5.00	-0.33	0	1	17	AG
	4	Leoi	Northeastern	-0.42	12.98	-0.63	0	2	27	AG
	5	Roi Et	Northeastern	0.48	13.83	-0.29	0	1	72	AG
	6	Kalasin	Northeastern	-0.76	11.36	-1.06	0	2	77	AG
	7	Phayao	Northern	-0.77	8.07	-0.23	0	2	33	AG
	8	Kamphaeng Phet	Central	-0.19	14.50	-1.44	0	3	22	MA
	9	Petchabun	Central	-0.66	12.21	-0.22	0	3	22	AG
	10	Ratchaburi	Western	-0.35	11.92	-0.39	0	5	31	ME
	11	Kanchanaburi	Western	-0.91	12.22	-1.64	0	3	46	MA
	12	Suphan Buri	Central	-0.42	11.08	-2.90	0	2	44	AG
	13	Pachuap Khiri Khan	Western	0.34	10.64	-0.36	0	2	14	MA
3E	1	Trang*	Southern	-0.28	51.37	-0.32	1	1	22	AG
3F	1	Nakhon Nayok	Central	-0.41	60.32	1.25	0	1	5	AG
	2	Samutsongkham	Central	-0.50	71.95	0.73	0	1	8	AG

* Thesaban Nakhon

** Main GPP = Main economic activities of Gross Provincial Product, AC = Accommodation and food services, AG = Agriculture activities, MA = Manufacturing, ME = Mining and electricity supplies, WR = Wholesale and retail trade

3.4.2.1 Cluster 1: growing cities

Cluster 1 is a group of growing cities. It consists of seven provincial cities, as shown in Table 6. Most provincial cities are located in the northern region, central region and southern region with a similar number. Based on the characteristics of UPC and CUPC, cluster 1 can be classified into four sub-clusters.

3.4.2.1.1 Sub-cluster 1A and Sub-cluster 1B

The profiles of sub-cluster 1A and sub-cluster 1B are similar. ACRP and CUPC value of both sub-clusters are high, except the CUPC of TM. Mae Hong Son in the sub-cluster 1B which is static. The UPC value of provincial cities in sub-cluster 1B is slightly lower. Sub-cluster 1A and 1B are good representations of a *growing city* with densely settled populations and their continued population growth rates, including the urban population concentration.

The provincial cities in these clusters have one of the following characteristics. First, some provincial cities are located in provinces with limited settlement areas, such as TM. Ranong and TM. Mae Hong Song in the provinces which the settlement areas are only 2.46% and 1.07%, respectively. Therefore, the public facilities in the provinces are in the provincial cities. Given the limited areas for settlement and the agricultural economy, there are few sources of economic activities outside the provincial cities. That is why the provincial cities become the sources of economic activities and job opportunity, appealing people to settle there.

Second, there are not many other Thesaban in the province where provincial cities are located, so the growth of the urban population outside the provincial cities is not lofty and not comparable to that inside the provincial cities. Third, some provincial cities are the centres of the industrial and educational sectors, such as TN. Samut Sakorn and TM. Maha Sarakham with huge job opportunities and economic activities. Being the sources of job opportunities and economic activities is an important factor in maintain the growing status, especially in the cities that provide employment in the secondary and tertiary sector (Barreira et al., 2017, p. 863).

The provincial cities in this group are in the agriculture-based provinces with few urban areas outside the provincial cities. They also have limited settlement areas and are the economic centres. These factors have a positive impact on their public facilities and economic strength, leading them to be the sources of economic activities and the settlement areas. The population increase due to economic strength was also mentioned in the study of Barreira et al. (2017, p.862) which indicates that the population change has a relationship with the economic strength. Job opportunities appeal people to settle in the cities. The study of Suwanlee & Som-ard (2020) also stated that the population often concentrates in the areas with the intensity of service source, industrial factor and service trades. These areas usually are parts of a district of a provincial city in Thailand according to Gravity Model concept.

3.4.2.1.2 Sub-cluster 1C

The city profile of sub-cluster 1C is similar to sub-cluster 1B, but the CUPC of sub-cluster 1C decreased. This reflects the growth of the urban population outside the provincial cities. The dispersal of the population into other urban areas in the same province makes the role of urban settlement centres in the provinces less stable. Yet, this increase is not sufficient to restructure the city system. The provincial city remains the urban settlement centre in the province, such as in the case of TN. Chiang Rai. It is worth mentioning that the small towns near the Chiang Rai border locate customs houses, which play an important role in terms of international trading. The customs houses are also a significant factor in the decrease of the UPC. In 2010–2019, the populations in TT. Mae Sai and TT. Chiang Saen changed dramatically at the rate of 43.74% and 33.18%, respectively. Although the population in the border cities increased so much that CUPC of TN. Chiang Rai became negative, the huge distance to the new economic centre and the role as a main city at microregional scale enabled TN. Chiang Rai to accumulate economic activities and become a big city which was 2.73 times more populated than TT. Mae Sai.

3.4.2.1.3 Sub-cluster 1D

Sub-cluster 1D is evidently different from other sub-clusters because its UPC value is low and likely to decrease despite the increase in ACRP. The decrease emphasises that it is no longer the main settlement area in the province and is beaten by other cities full of communities, economic growth, or industrialisation. This means that the provincial city now merely serves as the local administrative centre. There is only one member in this sub-cluster: TM. Pathum Thani.

Owing to urbanisation, the population increased in the outskirt areas of Bangkok, as seen through the high number of TNs and TMs in the outskirt areas. As a result, the population of TM. Pathum Thani made up only 3.60% of the total urban populations in 2019, and this is likely to keep declining with the rate of -1.05. Therefore, despite the increase of the population in TM. Pathum Thani, the population growth in the outskirt area of Bangkok prevents TM. Pathum Thani from keeping its role as the main urban settlement centre. TN. Rangsit connecting Bagkok and TM. Pathum Thani in the north is the biggest urban area of Pathum Thani and 3.61 times bigger than TM. Pathum Thani. It is the twelfth biggest TN in Thailand. The increase in accommodations, malls and industrial factories in the areas connecting Bangkok and Pathum Thani is an important factor that is going to deprive TM. Pathum Thani of its role as the urban settlement centre. This was illustrated in the study of Losiri & Nagai (2020, p. 38) who explored the urban expansion in BMR. The study showed that between 2011-2014 the urban areas were growing dramatically in the areas connecting Pathum Thani Province and Bangkok, especially when compared with the areas in the provincial city.

3.4.2.2 Cluster 2: Shrinking cities

Cluster 2 consists of the provincial cities whose population and UPC value decreased. This shows that these provincial cities are shrinking cities because of two significant factors. First, the city system structure in each province comprises many other cities besides the provincial cities, increasing the number of populations outside the provincial cities. This is related to the suburbanisation and the policy of decentralisation process. Second, the provincial city areas are fairly small. There are no bigger than 20 square kilometres, except TN. Nakhon Ratchasima. The emergence of shrinking cities in the small urban areas is similar to the shrinking cities in France. Most of them cover limited areas. This is consistent with the concentration of activities, population, employment, and information flow (Cunningham-Sabot et al., 2013). Besides the limitation of the areas, 10 members are the old towns. Thus, the urban area sizes were limited for the population increase both horizontal and vertical owing to the conservation policy, affecting the value of UPC. This cluster has 15 members, mostly in the central region, categorised into three sub-clusters, as shown in Table 6.

3.4.2.2.1 Sub-cluster 2A

Sub-cluster 2A comprises the provincial cities facing the population decline, but it is the only sub-cluster with the moderate UPC value. The sub-cluster 2A contains five provincial cities. The prominent factors for the shrinkage of UPC are the population decline in the provincial cities and population growth in small urban communities and the outskirts. Suburbanisation is a phenomenon occurring when the population increases in the outskirts while decreases in the core area. It also happened in many European countries (Barreira et al., 2017, p. 855; Cunningham-Sabot et al., 2013). Nevertheless, the populations in the outskirts do not increase much as it can be seen that those Thesaban around the provincial cities is small.

Another factor influencing the population growth outside the provincial cities and lessening their roles as the urban settlement centres is the population increase in the tourist and industrial areas, appealing new settlement. The increase happened for the same reason as the migration of Thais in 2010; they moved because of job opportunities. Most of these people worked in the service and industry sectors (National Statistical Office, 2020, p. 19). The industrial and tourist areas are the centres of the districts and far away from the provincial cities. For example, Nakhon Ratchasima Province contains four TM in the tourist and industrial areas.

3.4.2.2.2 Sub-cluster 2B and Sub-Cluster 2C

Sub-cluster 2B is similar to sub-cluster 2C. They face a decline in the number of populations and the UPC level. However, the UPC of sub-cluster 2B is lower than sub-cluster 2C. The CUPCs of two sub-clusters indicates that the provincial cities in these groups are losing their roles as urban settlement centres.

In the case of sub-cluster 2B, the provincial cities in this sub-cluster have two shared characteristics. First, they are small cities with no more than 10-square-kilometre areas. Second, they are provincial cities of the provinces where GPP mainly comes from manufacturing industries. The emergence of the commercial areas and industrial estates outside the provincial cities, along with the growth of economic cities, have lowered the UPC value and their provincial cities' roles as the settlement centre. For example, Songkhla Province's biggest city is TN. Hatyai, which is also the biggest regional area of Thailand. It is a crucial commercial and industrial area in the southern and Indonesia-Malaysia- Thailand Growth Triangle (IMT-GT) areas. Compared with TN. Songkhla, TN. Hatyai is 2.53 times bigger. In Chon Buri Province, the provincial city is not big, and the biggest cities are in major tourist and industrial areas such as Pattaya City, TN. Chaophrayasuren and TN. Lamchabang. The total population of these three example cities are 8.89 times much more than TM. Chon Buri. Besides the dense population in industrial areas, small Thesaban areas connected to the provincial cities have a population increase. The population growth in the economic and industrial areas causing the population decrease in the provincial cities also appears in the findings of Alves et al. (2016, p.26) which is about the population change in a city. The findings reveal that the population moves to the areas with better economic and social conditions. Cunningham-Sabot et al. (2013) indicates that the emergence of a new city due to the industry development will exclude the old economic area and result in the sluggish economy in that area.

Tong et al. (2020, p.11) stated that the population flow within the province is related to the industrial development area. However, Jilin City and the provincial cities in this group are different because the high intensity of economic activities in Jilin occurred in the core area and turning the area into a growing city while the high intensity of economic activities happened outside the provincial cities in this group owing to the development policies of the government. Therefore, the outside area became the main sources of economic activities and job opportunities whereas the core area saw the population decline.

In the case of sub-cluster 2C, its members are located in the provinces with different characteristics from sub-cluster 2B. Considering the GPP, the economic structures of their provinces are mainly related to agricultural activities, except Lop Buri Province and Petchaburi

Province, whose economic systems are related to agricultural manufacturing. The increase of population in the industrial zone is not the crucial cause like the sub-cluster 2B. The main cause of losing UPC is similar to sub-cluster 2A. It is because there is a population increase in the peri-urban areas of the provincial cities due to the suburbanisation and in the cities that are the district cities and other small cities due to the decentralisation policy.

3.4.2.3 Cluster 3: Stagnant cities

Cluster 3 consists of the provincial cities whose population changed slightly. In other words, they are stagnant cities. Most cities maintain their roles as the significant urban settlement centres of the provinces and are located in the north-eastern region. Cluster 3 is the biggest, consisting of 54 provincial cities. These provincial cities can be categorised into six sub-clusters based on UPC and CUPC, as shown in Table 6.

3.4.2.3.1 Sub-cluster 3A

The provincial cities are the moderate urban settlement centre of the provinces, with populations of more than 35% of the total urban populations of the provinces. Although the ACRP is static, the UPC seems to increase. Their two members are TM. Nong Khai and TM. Nan. One of the factors is that the provincial cities are the main sources of economic activities and services at the provincial and sub-regional level. TM. Nan has numerous tourist attractions and is capable of providing tourism facilities. Also, TM. Nan is the centre of the border town between the northern region of Thailand and Laos. In the case of TM. Nong Khai, there is a border checkpoint between the north-eastern region of Thailand and Laos, producing 59,228,510,432 Baht in import and export value, which was the second-highest in 2019 (Ministry of Interior, 2019, p. 10). According to the growth of both provincial cities' economic roles, the UPC of both provincial cities tends to grow, which is not surprising. The increase of UPC in this cluster is accorded to with the study of Hakim (2016, p. 39), indicating that the border towns across the Mekong subregion were new emerging urban areas.

3.4.2.3.2 Sub-cluster 3B

Sub-cluster 3B has 19 provincial cities. This is the greatest number and makes up 25% of the entire country. They have three major characteristics. First, the number of their populations doesn't change much. The highest of ACRP value is 0.61, whereas the lowest of ACRP value is -0.82. Second, they are the moderate UPC with the lowest of 15.95 % and the highest of 45.44 %. Third, the economic activities at the province level of almost all provincial cities are based on agricultural activities, except TM. Chachoengsao.

Most of the provincial cities, except TM. Sa Kaeo, are the most populated cities in the provinces. Although there are many small Thesaban in the provinces of this sub-cluster, the population changes are small, with an average rate of -0.06. As a result, the proportion of the changes outside the provincial cities is low, leading to the stability of the UPC level.

3.4.2.3.3 Sub-cluster 3C

Sub-cluster 3C consists of 17 members. ACRP and UPC are similar with sub-cluster 3B while the CUPC is slightly lower. Most provincial cities in this sub-cluster are regionally important and are designated as secondary cities. In the political dimension, a secondary city is the centre of a group of provinces. This is one of the factors causing these provincial cities to still be the main urban settlement areas of the provinces. And considering the city hierarchy, the provincial cities in this sub-cluster are different from those in other sub-clusters; most of them are TN.

Although most of the provincial cities are big cities, the city system structure of each province comprises numerous secondary and tertiary Thesaban, such as Nonthaburi Province and Chiang Mai Province (see the detail in Table 6). It results in a moderate UPC. Moreover, the population grows in the economic areas outside the provincial cities such as manufacturing industry and the mining areas. At the same time, the population in the provincial cities changes slightly, gradually decreasing in the UPC value.

The static urban population change in a big city of Thailand is different from the urban population changes in the past because most of the big cities at that time showed the high rise of population (Sun et al., 2020). The change pattern in this group implies that big cities in Thailand are stagnant cities, especially the cities in the group that contains other big cities in the same province.

3.4.2.3.4 Sub-cluster 3D

Sub-cluster 3D consists of 13 provincial cities. Like sub-cluster 3B and 3C, their number of populations does not change much, but the value of UPC is very low and gradually decreasing. The reason for this is that city structure comprises many cities in each province like sub-cluster 3C. However, while the provincial cities in sub-cluster 3C are the provincial administration centres, the provincial cities in this sub-cluster are small except TN. Samut Prakan. The population in the provincial cities is not high and there are many cities outside the provincial cities. That is why its proportion of UPC is lower than sub-cluster 3C which contains big cities.

TN. Samut Prakan has such a low UPC value that it was categorised into this sub-cluster instead of sub-cluster 3C which mostly contains big cities because its urban population concentrates in the industrial area which is the economic foundation of the province. Another reason is the population growth in the edge area of the city connecting to Bangkok. The situation is similar to TM. Pathum Thani in sub-cluster 1D except for the patterns of ACRP which is increasing in the case of TM. Pathum Thani while being static with negative trend in the case of TN. Samut Prakan.

3.4.2.3.5 Sub-cluster 3E and Sub-cluster 3F

Sub-cluster 3E is similar to sub-cluster 3F. They encounter small population changes and are highly populated, making up over 50% of the total urban populations in the province. While UPC of TN.Trang, a member of sub-cluster 3E, changes at the static rate with negative trend, the UPC of the member of sub-cluster 3F changes with the growth rate in the case of TM. Nakhon Nayok and the static rate with the positive trend in the case of TM. Samut Songkhram.

The small number of Thesaban outside provincial cities and the economic structure based on agriculture decreases the concentration of the industrial and commercial areas in other cities and enables the members of both sub-clusters to maintain the ratio of the urban population in the areas and be the centres of the provinces in many aspects ranging from the administration, industry, commerce, transportation and education.

3.5 Discussion

3.5.1 Characteristics of the population change patterns in the provincial city in Thailand from 2010 to 2019

The previous study shows that prior to the 2010s, populations grew dramatically in the urban areas across Thailand, especially in the southern and north-eastern regions (Paudel et al., 2015, p. 60; Punpuing & Ritcher, 2017, p. 113), and across some countries in the Greater Mekong Region (Hakim, 2016, p.37) . However, there is little explanation about the decrease of urban population in the provincial cities which is the parallel mode of urbanising city in the case of more developed countries. Gravity law was applied to describe the dense population in Thai city centres like the provincial cities. The density of the population was related to the accessibility to the city amenities located in the provincial cities (Suwanlee & Som-ard, 2020) .

The results demonstrate that during the 2010s, the patterns of distribution and changes in population began to alter. Only seven provincial cities were growing cities, and these provincial cities were not located only in the southern and north-eastern regions but also in the northern region and cities around Bangkok. At the same time, the results from Thai provincial cities confirm that the phenomena of shrinking cities are also the parallel mode of growing city in less developed countries as same as more developed countries. Most of other provincial cities in Thailand were likely to face stable or decreasing population along with the urban concentration decline in many clusters, especially the provinces in the central region.

Regarding this phenomenon, it could not be refuted that although the provincial cities had many public amenities, the patterns of changes in population in the provincial cities were affected by the growth of other cities. These cities were more and more important in economic and social aspects because of the decentralisation process implemented by the government. The effects on the provincial cities were particularly significant when those provincial cities were in the provinces with the economic and industrial activities that could not proceed in the provincial cities, leading them to have a low urban population in some sub-clusters and lose their roles as the urban settlement centres. This pattern of distribution was not in line with the study of Suwanlee and Som-ard (2020). The decrease of UPC reflected the fact that public amenities in the provincial cities were not the only factor in the urban concentration; another factor was the economic agglomeration within and outside the provincial cities. It was in accords with Webster & Gulbrandson (2016, p. 103), indicating that economic activities such as tourism and industries played a crucial role in supporting the urbanisation of the medium-small cities in Thailand. The economic activities in the urban areas outside the provincial cities caused the areas to grow and attract more settlements, responding to the needs of industries and services (Oontimwong, 2002, p. 113; Punpuing & Ritcher, 2017; Ratniyom, 2017, p. 76). These new communities, thus, provided basic public amenities, lessening the importance of the public amenities in the provincial cities. As a result, people did not need to settle in the provincial cities and the vicinities to access the amenities. In addition to the population growth in the industrial areas and the economic activities, the population growth in the outskirt areas was another factor in the decrease of population and the proportion of the urban population in the provincial cities, just as what had happened in more developed countries prior to 2010 due to the suburbanisation (Fol & Cunningham-Sabot, 2010, p.12).

The decreased or low UPC values of most provincial cities indicate that the provincial cities tend to lose their roles as urban settlement centres. Most people immigrate to other cities that are district cities and new economic centres. This phenomenon is different from what happened before the 2010s. At that time, the provincial cities were not only urban settlement centres but also the centres of economic, political and social activities that led to the urbanisation. The current phenomenon caused by the urban population concentration in the new economic centres outside the provincial cities, especially in sub-cluster 2B, is a significant example showing the role of globalisation in the cities at the local scale. The government encourages the economic development and foreign investment by establishing industrial estates and designating new tourist and economic areas in Songkhla, Chon Buri, and Lamphun, resulting in the population and investment shift from the provincial cities — which have the limitation on land uses and sizes — to the new areas. This leads provincial cities to encounter the shrinking city phenomenon. The government support for the industrial development responding to globalisation and resulting in an uneven spatial development is also a significant trigger for the shrinking cities in other countries such as China (Liu et al., 2020, p.9).

In addition, the globalisation triggering the shrinking cities in Thailand is consistent with the study of Fol & Cunningham-Sabot (2010) which indicates that although shrinking city was a phenomenon driven by many factors, nowadays it is undeniable that globalisation plays an important role in the phenomenon worldwide. The globalisation promotes some cities to be developed into the centres of economy, service, information, and communication. The excellent conditions in many aspects will cause the investment shift from one area to another. Attracting private investment and being the source of employment, the new area will become the growing city. At the same time, this development will lead some cities to lose their roles as the economic bases and job sources resulting in the population decline. These cities will end up being shrinking cities.

3.5.2 Population change in Nong Khai City and the surrounding areas in the last decade

Based on the boundary of the Nong Khai Provincial City, the city was indicated as a stagnant city as shown in Table 6. The population in TM. Nong Khai between 2010-2019 changed at a static rate with a negative trend while the urban population concentration (UPC) remained normal with the increase of the CUPC due to the decrease of the urban population outside the provincial city, especially with the establishment of Bueng Kan Province that caused Nong Khai Province to lose urban population in the urban areas outside the provincial city. Based on the UPC and CUPC, TM. Nong Khai was assigned to group 3A with Nan. Both provincial cities are the centres of border towns near the Mekong River in the northern and northeastern regions. Owing to the economic role of the provincial cities from the tourism and trading, the urban population changed less than other urban areas and gained the UPC from the urban areas outside the provincial cities which lost the population with the higher rate.

In this study, Nong Khai City also covers the provincial city and the surrounding areas, which were regarded as the peri-urban areas. Generally, the population in Nong Khai City changed by a static rate with a positive trend of 0.38 from 2010 to 2019 while the urban population in Nong Khai provincial cities changed by a static rate with a negative trend of -0.18. The population in the peri-urban area increased by 1.08, especially in the area of Pho Chai sub-district where the population increased by 2.20%. The contrast of the increasing population in the peri-urban area and the static population of an urban area like the provincial boundary with a negative rate implies that Nong Khai City is in the suburbanisation stage which means the population tends to sprawl in the peri-urban area.

3.5.3 Recommendations on the city management based on the clusters of the population changes

This study reveals that over the past 10 years, 90% of the total provincial cities have encountered a stable and decreasing population, and 48.68% of the total provincial cities have also encountered a decreasing UPC. These changing trends are turning most provincial cities into shrinking cities. Nevertheless, all the policies regarding the administration of the cities of the provinces revealed that the city planning aimed to utilise lands mainly to support the urbanisation as stated in almost every central city plan:

> According to ministerial regulations, central city plans ... contain policies and measures for the effective usage of lands, transportation networks and public services, ensuring that they can support the *urbanisation* in the future as well as boost and develop [the] economy...

Thus, this study proposes that the land-use management based on provincial comprehensive plans of each province, which only focus on the city growth, is not consistent with the present and future situation. This may create problems and destroy the valuable resources of the city (Liu et al., 2020, p. 9) affecting the sustainability of the cities. And the wilting day of the ones facing the population declining will come finally, especially when it is predicted that Thailand will have faced the population decline at the national scale by 2050 (Jarzebski et al., 2021, p. 4).

To sustain the provincial city management, the urban planner should not focus merely on supporting population growth. It should also consider the other population trends (Pallagst, 2010, p. 3). The study, thus, aims to propose city management approaches based on clusters.

Cluster 1: Responding to the Urbanisation Policy is a cluster containing the provincial cities that encounter population growth. If there is no systematic and cautious land management, the growth will affect the population density and the sufficiency of public utilities and public assistance, resulting in urban sprawl. Not only will the urban sprawl, triggered by the population growth, impact the environment but population overgrowth in the peri-urbans will also lead to a decrease in provincial city population, making the provincial cities eventually deteriorate (Döringer et al., 2020, p. 1964). The planners should develop the policies by applying the compact city framework, which helps control the urban sprawl and manages the cities based on compactness, density, mixed land uses, sustainable transportation, green spaces, and intensification (Bibri et al., 2020; Yeh & Li, 2000). The population increase brings the higher demand of land uses. The compactness of the cities can help us use urban areas and urban resources effectively (Shi et al., 2016). The study of Yao et al. (2022) found that the compactness of large cities will support the agglomeration economy as OECD (2012, p. 89) stated that the application of the concept of the compact city in urban policy is the main reason why the population growth is higher than the urban land expansion in some areas. This phenomenon reflected the slow rate of the built-up land expansion despite the population growth. Although, the compact city is a global paradigm of sustainable urban development, which has been globally referred to since the 1990s (Bibri et al., 2020), it has not been formally and widely reinforced, in terms of policy, in city plans of Thailand.

Cluster 2: Provincial City Redevelopment Policy is a cluster of shrinking cities. The decrease is an important factor in shrinking cities, unemployment, housing vacancy and economic decline (Döringer et al., 2020, p.1701), leading to the vital declination of communities. The provincial comprehensive plans should focus on solving shrinking cities problems by applying core redevelopment (Hartt & Warkentin, 2017), including the compact city concept (Buhnik, 2010, p. 149). This will increase the functions of the original structures of the provincial cities and bring about economic recovery. There are many measures to reinforce the core redevelopment and revitalise the shrinking city. They should be applied based on the condition of cities such as, establishing the substitute industry (Schackmar et al., 2021), supporting the tourism (Barreira et al., 2017; Hartt & Warkentin, 2017), developing the new urban facilities and services (Guan et al., 2021) and recovering the vacant house to new functions (Campos-Sánchez et al., 2019). But regarding the limitation of Thai city plans in advancing the large industries in the provincial cities, the core development on the provincial cities should focus on promoting trade and investment by building and improving commercial infrastructure to support the private investment and substitute industry that is suitable for the local context. The investment and substitute industry will create the job opportunities and then attract the new habitants (Barreira et al., 2017, p. 863). Another way is to promote their roles as tourist spots and creatively change cultural capital in the provincial cities into economic advantages. 10 out of 15 provincial cities in this cluster locate old cities with heritage buildings that illustrate the stories and the settlement development in the areas (Kirdsiri et al., 2021; Kullapat et al., 2019; Tansukanun, 2021). These cities can be developed into cultural tourist attractions. The study of Deng et al. (2021) found that despite its ineffectiveness in increasing population, the tourist industry can effectively boost the economic condition and the investment of the cities.

Cluster 3: Maintaining and Balancing their function policy is a cluster facing slight population changes. The provincial comprehensive plan should concentrate on the policies that keep a balance between urbanisation and shrinking cities. The plans should focus on maintaining and supporting the roles of the provincial cities, especially the economic role, to support the economic growth in the cities. This can be done by increasing employment in these areas to slow down the internal migration, which can weaken the provincial cities. At the same time, the areas should be managed to prevent the cities to sprawl into the peri-urbans.

3.6 Conclusion

Population change is an important indicator of city status and can guide urban planning. Based on population changes, each city is categorised as “a growing city,” “a stagnant city,” or “a shrinking city.” Although shrinking and stagnant cities are common, city planning based on the pro-growth paradigm often omits them, causing negative impacts on the performance of urban policy, especially in less-developed countries. From the investigation of the population change patterns between 2010 and 2019 through provincial cities in Thailand, the results of this chapter fulfil the limited understanding of the population changes in those countries.

The results of this chapter reveal that, although Thailand is rapidly urbanising, only 7 out of 76 provincial cities are in the growing city cluster. Most provincial cities are in the stagnant or shrinking city cluster, with urban concentration decline happening as a result. This evidence indicates that several provincial cities may be shrinking. Like many cities in Europe and the United States, suburbanisation is an important variable that causes the population decline in a city. Other significant variables are the decentralisation policy focusing on the development at the local scale and the economic and industrial development projects that the government implemented to respond to globalisation. The economic and industrial development outside the provincial cities or in border towns led the urban population to spill out and decreased the urban concentration in the core areas of the provinces. The result was the emergence of shrinking cities, and the only role left for the provincial cities was the public administration. However, it is noteworthy that there are few Thesaban outside the provincial cities in most of the urban areas with the population growth. And these areas can still accumulate economic activities and public facilities due to the geographic conditions and the economic structure in the cities and the provinces.

In the case of Nong Khai City, although the population in all areas, both provincial city and the surrounding areas, increased in the last decade, the population in the provincial cities changed at a static rate with a negative trend, and the city is likely to become a shrinking city in the future. At the same time, the population in the surrounding areas which were rural areas increased, especially in the sub-districts along with Highway no.2. Due to the trends of the population changes of the provincial cities and the surrounding area, Nong Khai City was in the suburbanisation stage in the last decade.

3.7 Limitation and direction of future study

This study is the foundation that focuses on the existence of the urban decline hidden in the urbanisation. In general, the population data and the economic data at the local scale which are the important insights about shrinking (Hartt, 2017) are the limitations worth considering together with the urban change patterns. The example of these data are non-registered population, population structure, migration information and the data about the employment and economy at the micro scale. For the future step, it is also worthy to criticise the in-depth detail of shrinking cities in the terms of the typology, conditioning factors, mechanism and the effect of population decrease.

The focus of this study is the areas within the provincial cities according to the administration border. The study reveals that the population decline and the urban concentration are associated with other urban areas outside the provincial cities. To gain deep insight, it is necessary to also study the relationship of the population patterns at other scale.

To develop the city management policies which can respond to the population decline in each provincial city when the population across the country is likely to decrease, both urban areas and rural areas should be studied to find out about their population change patterns because it is also possible that the population in the latter areas will spill out to the areas with better resources.

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Chapter 4

The change of the land use in Nong Khai City from 1997 to 2017: patterns and driving factors of the built-up land expansion as a representative of the small provincial cities in the China's Belt and Road Initiative

Contents

4.1 Introduction

China's Belt and Road Initiative (BRI) is a global 21st century economic development megaproject driven by the construction of an extensive transportation infrastructure. BRI not only aims to boost economic status and urbanisation levels, but also significantly affect land-use patterns. It is one of the causes of land-use changes and environmental degradation, particularly in the China-Indochina Peninsula Economic Corridor (CICPEC) (Hughes, 2019).

CICPEC covers the mainland ASEAN nations and is an economic corridor that receives much attention from China (Tritto et al., 2020) due to its geographical proximity and significant trading partnerships. Although development of the infrastructure within CICPEC significantly affects biodiversity (Hughes, 2019), the CICPEC countries still have been investing in infrastructure construction (Tritto et al., 2020). The Pan-Asia Railway Network is an important CICPEC project that will facilitate trade and investment by connecting China, Laos, Thailand, Malaysia and Singapore through high-speed railways. Thailand is the centre of the CICPEC transport connection because it is located between the Maritime Silk Road and Silk Road Economic Belt (Pongsudhirak, 2019).

To enhance the land-transport connection within the Pan-Asia Railway Network project, the Bangkok-Nong Khai railway was constructed to link with the high-speed railway network in Vientiane, Laos. Apart from connecting both countries' infrastructures, the high-speed railway network is expected to be a key mechanism for national and regional development (Pongsudhirak, 2019). As a result, the high-speed railway network very likely will impact cities near the Bangkok-Nong Khai railway stations.

Despite positive economic effects, development of the high-speed railway network comes with some negative effects as well, such as changes in land-use types and expansion of built-up land that supports urbanisation (Shen et al., 2014). Previous studies have indicated that built-up land expansion generates pressure and destroys the natural ecosystem, resulting in unsustainable environments through biodiversity degradation (Hughes, 2019; Marina, 2008), pollution discharge (Dong et al., 2014) and increased flood damage (Oudin et al., 2018) , eliciting social and health problems (Frumkin et al., 2004).

Accordingly, it is necessary to formulate and adopt land-use policies to respond to the expansion of built-up land, particularly in cities along the high-speed railway that the expansion affects directly. Development of sustainable land-use policies requires knowledge of expansion patterns in surrounding cities, and studying this issue is an important process to increase understanding of the patterns and factors concerning built-up land expansion.

Although Thailand has experienced built-up land expansion due to urbanisation for many decades, previous urban studies have focussed on the phenomenon in the Bangkok Metropolitan Region (Cao et al., 2019; Davivongs et al., 2012; Durina et al., 2013; Jongkroy, 2009) and regional cities (Chotchaiwong & Wijitkosum, 2019; McGrath et al., 2017; Thebpanya & Bhuyan, 2015; Yongvanit & Thungsakul, 2013). Furthermore, urban BRI studies also have concentrated on megacities and big cities (Cao et al., 2019; Sun et al., 2021). Consequently, insight is limited on built-up land expansion in small provincial cities that affect future land-use planning. Thus, this chapter aims to fill this literature gap by focussing on Nong Khai City. The studies of the built-up land expansions and their driving factors of Nong Khai City were analysed and explained in five sections as follows. The objective of this chapter is provided in the first section. Then, four driving factors of the built-up land expansion are reviewed in the section of literature review. The third section is the methodologies that were divided into two parts based on the objectives: (1) the method to detect land-use changes that was adopted to clarify the built-up expansion patterns and (2) the method to analyse the driving factors that concentrates on the Logistic regression. After that, the results from both methods were described and discussed along with previous studies. The last section concludes the expansion of the built-up lands in Nong Khai City.

4.2 Objective

1) To clarify built-up expansion patterns in Nong Khai City during the 1997–2017

2) To demonstrate the driving factors of built-up land expansion of Nong Khai City during the 1997–2017

4.3 Literature review

Built-up land expansion is a spatial phenomenon driven by integrated driving factors (Simwanda et al., 2020; Wu et al., 2018; Zhang & Su, 2016) that have been studied worldwide. The adopted driving factors and their influence on built-up land vary based on scholarly context and perspective (Li et al., 2018). These factors can be categorised into four groups: (1) the biophysical factor; (2) socioeconomic factor; (3) spatial policy factor; and (4) neighbourhood and spatial interaction factor (Li et al., 2018, p. 67; Li et al., 2013; Poelmans & Van Rompaey, 2010; Tan et al., 2014; Verburg, van Eck, et al., 2004, pp. 130–135).

4.3.1 Biophysical factor

The biophysical factor is the fundamental driving factor (Kim et al., 2020; Sarkar & Chouhan, 2020) that relates to environmental conditions, such as climate, topography, hydrology and natural disasters. It indicates how land should be used (Verburg, van Eck, et al., 2004, p. 126) and is related to construction costs (Poelmans & Van Rompaey, 2010, p. 18). Elevation and slope are the crucial factors in the group of biophysical factors that influence the expansion of built-up land (Kim et al., 2020; Sarkar & Chouhan, 2020). Low and flat land usually are the spatial characteristics viewed as ideal for new built-up land (Jin & Zhang, 2021, p. 160; Li et al., 2013, p. 7; Wu et al., 2018, p. 34; Zhang & Su, 2016, p. 99). Safety and construction costs are the crucial reason why low and flat areas are associated with built-up land expansion (Li et al., 2013, p. 8). However, in the current climate, development of modern technologies has decreased the influence of these factors on built-up land expansion (Li et al., 2018, p. 74; Tan et al., 2014, p. 275).

Furthermore, other factors have been found that influence biophysical factors in differing geographical contexts, e.g., the influence of distance from rivers on expansion of built-up land was evident in Ghana (Asempah et al., 2021). Similarly, the distance from a lake has influenced expansion of built-up land in a region in China (Li et al., 2018, p. 73). Moreover, natural disasters have been a driving factor in built-up land expansion, e.g., built-up land expansion is avoided in areas with frequent flooding (Poelmans & Van Rompaey, 2009, p. 17)

Previous studies on Thailand have analysed biophysical factors' influence through three variables: elevation; slope; and distance from water bodies (Keeratikasikorn, 2017; Kitrat & Keeratikasikorn, 2018; Ongsomwang et al., 2019; Sakayarote & Shrestha, 2019). Distance from water bodies frequently is indicated as the driving force in this factor group, followed by elevation and slope with the same number of studies. However, elevation and slope exert greater influence on built-up land expansion than the distance to streams and other bodies of water (Ongsomwang et al., 2019; Sakayarote & Shrestha, 2019).

4.3.2 Socioeconomic factor

The socioeconomic factor relates to anthropological activities that transforms land into built-up land. It involves the population and the economy. Sometimes, scholars view demographic and economic factors separately (Zhang & Su, 2016, p. 93). Due to difficulties in transforming socioeconomic information into spatial data, most studies have described the socioeconomic factors' influence in terms of accessibility (Hu & Lo, 2007; Kasraian et al., 2016; Li et al., 2013; Poelmans & Van Rompaey, 2009; Verburg, van Eck, et al., 2004), such as distance to transportation networks, urban centres, commercial and job locations, and schools, among others (Kim et al., 2020, p. 6).

Socioeconomic factors' influence in the form of accessibility has been clarified widely, strongly impacting the expansion of built-up land in various locations, such as the Tabriz metropolitan area in Iran (Dadashpoor et al., 2019), Wuhan city in China (Tan et al., 2014, pp. 275–276), the Greater Cairo Region in Egypt (Salem et al., 2019) and Nakhon Pranom in Thailand (Kitrat & Keeratikasikorn, 2018, p. 266). It usually presents as a negative relationship between driving factors and built-up land expansion (Kitrat & Keeratikasikorn, 2018, p. 266; Li et al., 2018; Li et al., 2013; Shu et al., 2014). Thus, built-up land expands in areas closer to city centres, administrative centres, public amenities and commercial zones (Dadashpoor et al., 2019; Jin & Zhang, 2021, p. 161; Li et al., 2013, p. 7). However, the positive relationship between the accessibility factor and built-up land expansion also can occur due to other factors' intervention, particularly with regard to spatial policy (Li et al., 2018, p.73).

The distance from the road network is a popular factor once used to determine the influence on urban expansion (Jin & Zhang, 2021, p. 162; Kim et al., 2020, p. 9) because this factor decreased construction costs and facilitated daily life to access resources (Li et al., 2013, pp. 4–5). Thus, a negative relationship between built-up land expansion and distance from road networks has been indicated (Dadashpoor et al., 2019, p. 9; Kantakumar et al., 2020, p. 12; Luan & Li, 2021, p. 9; Salem et al., 2019, p. 8; Wu et al., 2018, p. 34). However, the road-network factor's influence and magnitude vary (Li et al., 2018, p. 70; Li et al., 2013, p. 7) based on road conditions (Jin & Zhang, 2021, p. 162; Tan et al., 2014, p. 274).

In the case of Thailand, most extant studies have concentrated on the distance from the road network because it is a fundamental component related to accessibility (Keeratikasikorn, 2017; Keeratikasikorn et al., 2007; Kitrat & Keeratikasikorn, 2018; Ongsomwang et al., 2019; Sakayarote & Shrestha, 2019). Similar to other international cases, road network affects built-up land based on type, road hierarchy and time. However, some studies have observed socioeconomic factors by focussing on accessibility to public amenities within the scope of city centres (Keeratikasikorn, 2017; Kitrat & Keeratikasikorn, 2018; Ongsomwang et al., 2019; Sakayarote & Shrestha, 2019).

4.3.3 Spatial policy factor

Spatial policy is a crucial driving factor associated with the socioeconomic factor. Spatial policy guides new built-up land to avoid hazard-prone areas and unsustainable zones for urban development (Kantakumar et al., 2020, p. 3; Luo et al., 2019, p. 17). Indicating potential areas in which to settle while also protecting the city directly involves patterns of built-up land expansion (Kim et al., 2020, p. 6). The spatial policy factor was implemented in built-up land models worldwide. For example, Luo et al. (2019, p. 17) indicated that the urban spatial strategy plan plays a vital role in leading built-up land expansion in Wuhan City. However, in the case of Thailand, various descriptive studies have suggested a relationship between spatial policy and built-up land expansion (Chotchaiwong & Wijitkosum, 2019, pp. 7–10; Phuttharak & Dhiravisit, 2014; Yongvanit & Thungsakul, 2013), but it does not often function as an independent variable in the Thailand context because of a lack of information, making it difficult to transform the policy into spatial data on a suitable scale.

4.3.4 Neighbourhood and spatial interaction factor

The neighbourhood and spatial interaction factor usually is implemented as an independent variable (Poelmans & Van Rompaey, 2010, p. 18; Verburg, de Nijs, et al., 2004) because the expansion of built-up land is a self-organising system and has a relationship between locations (Verburg, de Nijs, et al., 2004, pp. 668–670). New built-up land usually is expanded from previous built-up land (Poelmans & Van Rompaey, 2009, p. 16; Salem et al., 2019, p. 8; Wu et al., 2018, p. 34). Li et al. (2018) indicated that the proportion of urban areas in a neighbourhood has exerted a positive effect on the urban expansion of China during every time period on national and regional scales, compared with various other factors that influence urban expansion depending on the context. Similar to Wu et al.'s (2018) study, the proportion of urban areas has a positive relationship with built-up land expansion in big cities in China. Previous studies on Thailand that involve new built-up land usually focus on land distributed near existing communities (Kitrat & Keeratikasikorn, 2018) with low built-up land density (Keeratikasikorn, 2017).

4.4 Methodology

Based on the objective, the methodology is divided into two parts: (1) the method to detect land-use changes and (2) the method to analyse the driving factors.

4.4.1 The method to detect land-use changes

4.4.1.1 Data preparation

Land-use maps provide crucial information to detect changes in land use. Although the department of land development in Thailand provides the land-use maps for each province, due to the characteristic of the land change as a dynamic phenomenon, the information on these land-use maps is out of date and not suitable to be used in the study about land-use change. In addition, the dataset of land-use maps is not enough to provide an understanding in the change of land use in terms of spatial-temporal change. Hence, remote sensing and geographical information systems play a vital role in generating land-use maps. The technology of remote sensing provides the information on earth's surface from past to present with acceptable resolution. The continuity of spatial data from satellites and the capacity of the Geographic Information System help most scholars access the land-use data easily in order to study the spatial-temporal land-use change without the onsite survey which required time and cost. Currently, U.S. Geological Survey (USGS) offers the Landsat image free of charge. The acceptable resolution at 30 metres and the long-term historical data from the beginning of the 1980s to the present are useful for producing the land-use map in the specific period and decreasing the limitation of data-scarce environment.

In this study, Landsat satellite images from 1997, 2007 and 2017 during the dry season (Table 7) comprised the subject information. Two chosen satellite images were combined with the stacked imagery method to represent the data for each year.

Table 7

Satellite data in this study

Year	Satellite	Sensor	Resolution (m)	Acquisition
1997	Landsat 5	TM	30	16/03, 29/12
2007	Landsat 7	ETM+	30	08/02, 28/03
2017	Landsat 8	OLI	30	07/03, 20/12

The period in this study is based on the beginning of the new decade years in the Thai Buddhist Era (B.E.); 1997 is 2540 B.E; 2007 B.E is 2550; 2017 is 2560 B.E. In addition, 1997 was chosen to fulfil the understanding of the land-use change in Nong Khai City explained in previous studies (Klinchat, 2003) that used the opening year of the Thai-Lao Friendship Bridge in 1994 as the ending time, reflecting that the Thai-Lao Friendship Bridge is the trigger point for the settlement pattern changes in Nong Khai. For these reasons, 1997 was set up as the beginning year to track the changes of the built-up areas every ten years until 2017.

To generate the land-use maps, the supervised classification with the maximum likelihood classifier (MLC) algorithm was performed on ArcMap 10.6. Altogether, 97,322, 80,551 and 84,426 referenced pixels from 1997, 2007 and 2017, respectively, were selected randomly through visual interpretation. As shown in Figure 27, four land-use types were adopted in the land-use maps: (1) water bodies; (2) built-up land; (3) forest and natural land; and (4) agricultural land.

Visual interpretation was applied to develop the land-use maps' qualities. Their accuracy was assessed using 400 sample points retrieved from Google Earth Pro images. The sample points were selected using a random sampling method. The error matrix, a traditional approach to verifying land-use maps' quality, was chosen to assess accuracy. As shown in Table 8, all land-use map information has an overall accuracy rate of 95.50 %, 91.75 % and 89.00 %, respectively. In the case of the kappa coefficient, the values were 0.89, 0.84 and 0.81, respectively, for the years studied.

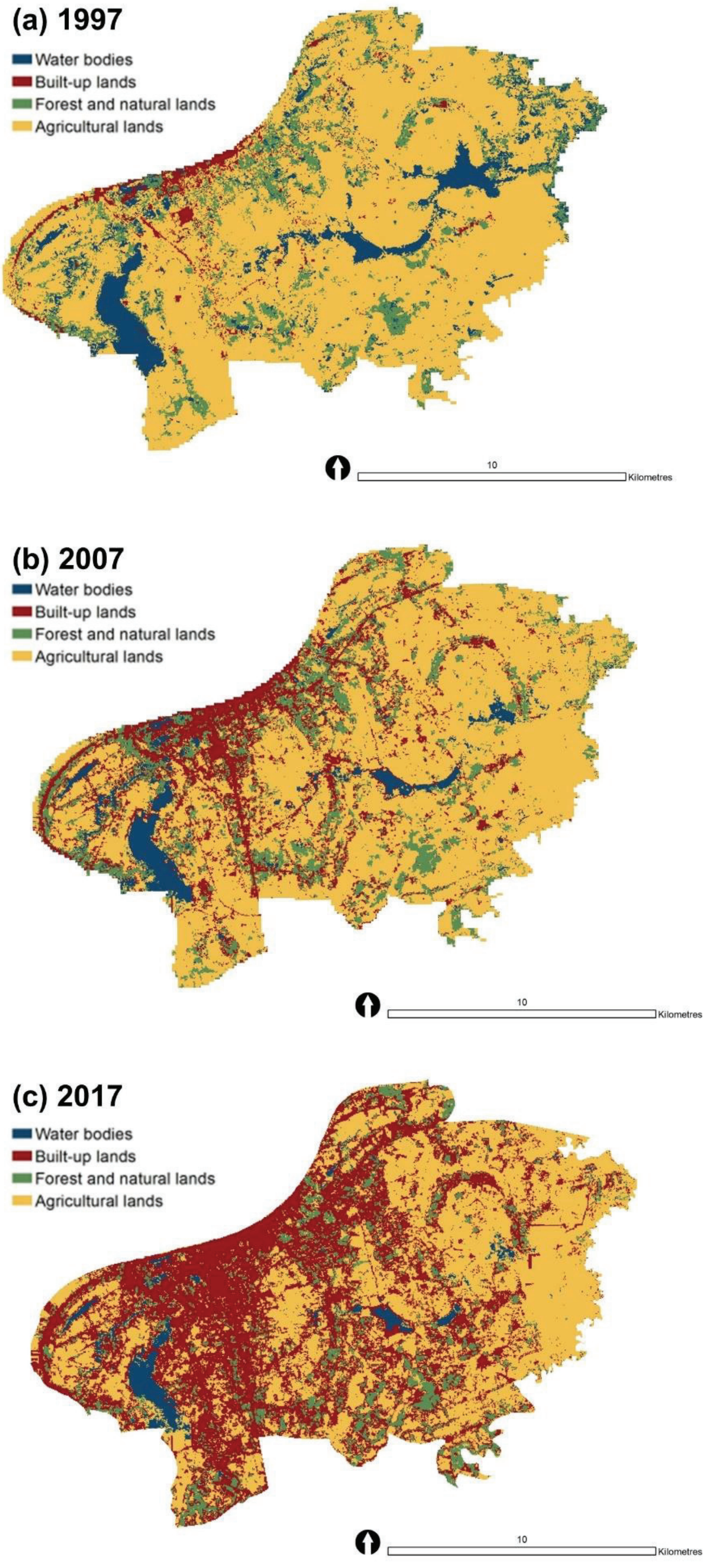

Figure 27 Land-use maps (a)1997; (b)2007; (c)2017

Table 8
Accuracy of land-use maps

	References					
1997	Water bodies	Built-up lands	Forestlands	Agricultural lands	Row total	User's accuracy (%)
Water bodies	37	1	4	4	46	80.43
Built-up lands	1	17	0	0	18	94.44
Forestlands	2	0	37	1	40	92.50
Agricultural lands	1	2	2	291	296	98.31
Column total	41	20	43	296	400	
Producer's accuracy (%)	90.24	85.00	86.05	98.31	Overall accuracy: 95.50%	
2007	Water bodies	Built-up lands	Forestlands	Agricultural lands	Row total	User's accuracy (%)
Water bodies	21	0	0	3	24	87.50
Built-up lands	0	54	2	7	63	85.71
Forestlands	0	1	42	3	46	91.30
Agricultural lands	4	9	4	250	267	93.63
Column total	25	64	48	263	400	
Producer's accuracy (%)	84.00	84.38	87.50	95.06	Overall accuracy: 91.75%	
2017	Water bodies	Built-up lands	Forestlands	Agricultural lands	Row total	User's accuracy (%)
Water bodies	11	0	0	0	11	100.00
Built-up lands	0	122	3	36	161	75.78
Forestlands	2	0	38	1	41	92.68
Agricultural lands	2	0	0	185	187	98.93
Column total	15	122	41	222	400	
producer's accuracy (%)	73.33	100.00	92.68	83.33	Overall accuracy: 89.00%	

4.4.1.2 Land-use change detection

Land-use change detection is a process used to clarify built-up land expansion patterns. Combine function, an overlay technique in ArcMap 10.6, was conducted to compare land-use types. The land-use change matrix was conducted to clarify land-use change patterns during two periods: 1997–2007 (period 1) and 2007–2017 (period 2).

To clarify the land-use change rate, we adopted Equation (4.1) from Xinchang et al.'s study (2004), which represents the complexity of land-use changes by integrating conversion rate and the increasing rate into the model:

$$CCL_i = \{(LA_{i,t2} - ULA_i) + (LA_{i,t1} - ULA_i)\}/LA_{i,t1}/(t2 - t1) \times 100 \quad (4.1)$$

in which CCL_i is the change rate of *i*; *i* is the land-use type; $LA_{i,t1}$ is the area of *i* at the beginning of the period; $LA_{i,t2}$ is the area of *i* at the end of the period; and ULA_i is the area of the unchanged part of *i* during the study period.

4.4.2 The method to analyse the driving factors

The driving factors involved in built-up land expansion are crucial in providing urban planners with the data they need to create suitable land-use policies to cope with urbanisation (Jin & Zhang, 2021; Li et al., 2018; Zhang & Su, 2016). To determine the types of and influence from the relevant driving factors involved, qualitative and quantitative analyses were employed, including focus groups and questionnaires (Rijal et al., 2020), descriptive analysis (Yongvanit & Thungsakul, 2013), logistic regression (Li et al., 2013; Luan & Li, 2021; Salem et al., 2019; Sarkar & Chouhan, 2020), modified logistic regression (Luo et al., 2019), classification and regression tree (Jia et al., 2020), spatial probit modelling (Li et al., 2018) and multi-criteria evaluation (Osman et al., 2016; Simwanda et al., 2020). Among various methodologies, Li et al. (2013, p. 2) indicated that logistic regression is used widely to determine the driving factors in built-up land expansion, offering three advantages: (1) the capacity to handle binary dependent variables; (2) the flexible requirement for the assumption of normality; and (3) the performance of logistic regression to predict where land will be developed in the future. To identify the driving factors of the built-up land expansion, we thus applied logistic regression, which usually is performed to describe the determinants of the built-up land expansion (Hu & Lo, 2007; Kasraian et al., 2016). In this study, we tested physical and socioeconomic variables, which are the fundamental variables for studying the driving factors. We also tested three variables related to land-use characteristics at the time of the initiative, the land-use plan from the provincial comprehensive plan and flooding data, which have not been studied much in Thailand.

4.4.2.1 Data preparation

To clarify the driving factors, all data were divided into regular grid cells at 100-by-100-metre tessellation each. There are 18,957 grid cells, after excluding border cells that lack complete data. The expansion of built-up land in 2007 and 2017 – retrieved from the land-use maps – has been viewed as a dependent variable, as shown in Figure 28. Built-up land expansion was coded as 1, and non-built-up land expansion was coded as 0.

For the driving factors, 17 of the accessible independent variables in four groups were selected for the preliminary study, as shown in Table 9. A biophysical factor comprises four variables: elevation; distance from the Mekong River; distance from big reservoirs; and flooding areas. To assess the biophysical factor's influence, the average elevation value and maximum value of the flooding area were attached to grid cells. The Mekong River and big reservoirs were digitised from the satellite images, then the distance value was determined using the Euclidean nearest distance within the logarithmic form. The elevation data, which have a spatial resolution of 15 metres in the horizontal plane, were retrieved from the Advanced Spaceborne Thermal Emission and Reflection Radiometre (ASTER). The flooding area was retrieved from the data on frequently flooded areas between 2004 and 2018 from Thailand's Geo-Informatics and Space Technology Development Agency. The data indicate that each area within Nong Khai City encountered floods 1–11 times over 15 years, particularly in the southeastern area.

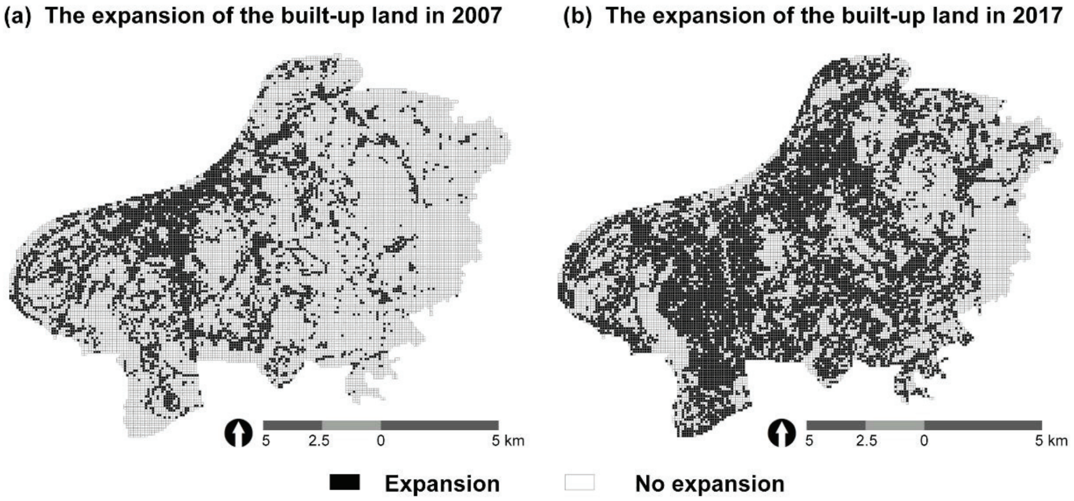

Figure 28 Dependent variable

Table 9

The preliminary study's variables

Variable	Category	Code and Meaning
Dependent variable		No built-up land expansion; 0
		Built-up land expansion; 1
Independent variables	Biophysical	X_1; Elevation
		X_2; Distance from the Mekong River
		X_3; Distance from big reservoirs
		X_4; Flooding area
	Socioeconomic	X_5; Distance from main roads
		X_6; Distance from minor roads
		X_7; Distance from the government centre
		X_8; Distance from temples
		X_9; Distance from malls
		X_{10}; Distance from the original urban area footprint
		X_{11}; Distance from Khon Kaen University (Nong Khai campus)
	Spatial policy	X_{12}; Land-use policy
	Neighbourhood and spatial interaction	X_{13}; Agricultural land
		X_{14}; Forest and natural land
		X_{15}; Water bodies
		X_{16}; Built-up land ratio
		X_{17}; Distance from the previous built-up land

A socioeconomic factor comprised seven variables. The main roads (national highways and rural highways), minor roads (municipal roads and alleys), government centre, temples, malls and Khon Kaen University (Nong Khai Campus), which were digitised from satellite images, were transformed into a proxy value using the Euclidean nearest distance within the logarithmic form. The original urban area footprint – which represented commercial and service areas – was digitised based on Nong Khai Municipality's original boundaries in 1935. The original urban area was coded as 1, and the other areas were coded as 0.

A spatial policy factor considered the land-use plans from the provincial comprehensive plan in 1999 and 2011. The land-use plans were digitised and attached to each grid cell as dichotomous variables. The designated built-up land was coded as 1, while the protected multi-purpose area was coded as 0.

A neighbourhood and spatial interaction factor described land-use characteristics' influence at the initiative time. This group comprised five independent variables. To describe the land-use characteristics in the neighbourhood in the case of forest and natural land, water bodies and agricultural land, we used the design variables. The majority function was performed to analyse the majority of three land-use types in 100-by-100-metre grid cells. If land-use *n* was the majority, it was coded as 1. If land-use *n* was not the majority, it was coded as 0. Furthermore, we analysed the existing built-up land's influence on two independent variables. The first was the proportion of built-up land in the grid cell, which was a simple approach (Poelmans & Van Rompaey, 2010). The second was the distance from the existing built-up land, which was related to the pattern of built-up land expansion (Li et al., 2013). All land-use data were retrieved from the land-use map in 1997 and 2007.

After the data were attached to the grid cells, we used two approaches to develop accurate models. The first was collinearity testing. For the logistic regression model, we needed to check the correlation among 17 independent variables before analysing the relationship. A Pearson correlation coefficient measure was conducted to check collinearity using IBM SPSS Statistic 27. Some independent variables indicated a strong relationship as shown in Figure 29. The distance from the government centre and the distance from the previous built-up land were excluded from both periods. Similarly, the distance from the original urban footprint was excluded from the analysis between 1997 and 2007. Consequently, 14 variables were used for the analysis between 1997 and 2007 and 15 for the analysis between 2007 and 2017, as shown in Figure 30.

The second approach entailed data elimination using Cook's distance value, which is fundamental for detecting influential observations in the regression analysis (O' Hara Hines & Hines, 1995). The highly influential observation is the outlier, which affects model accuracy.

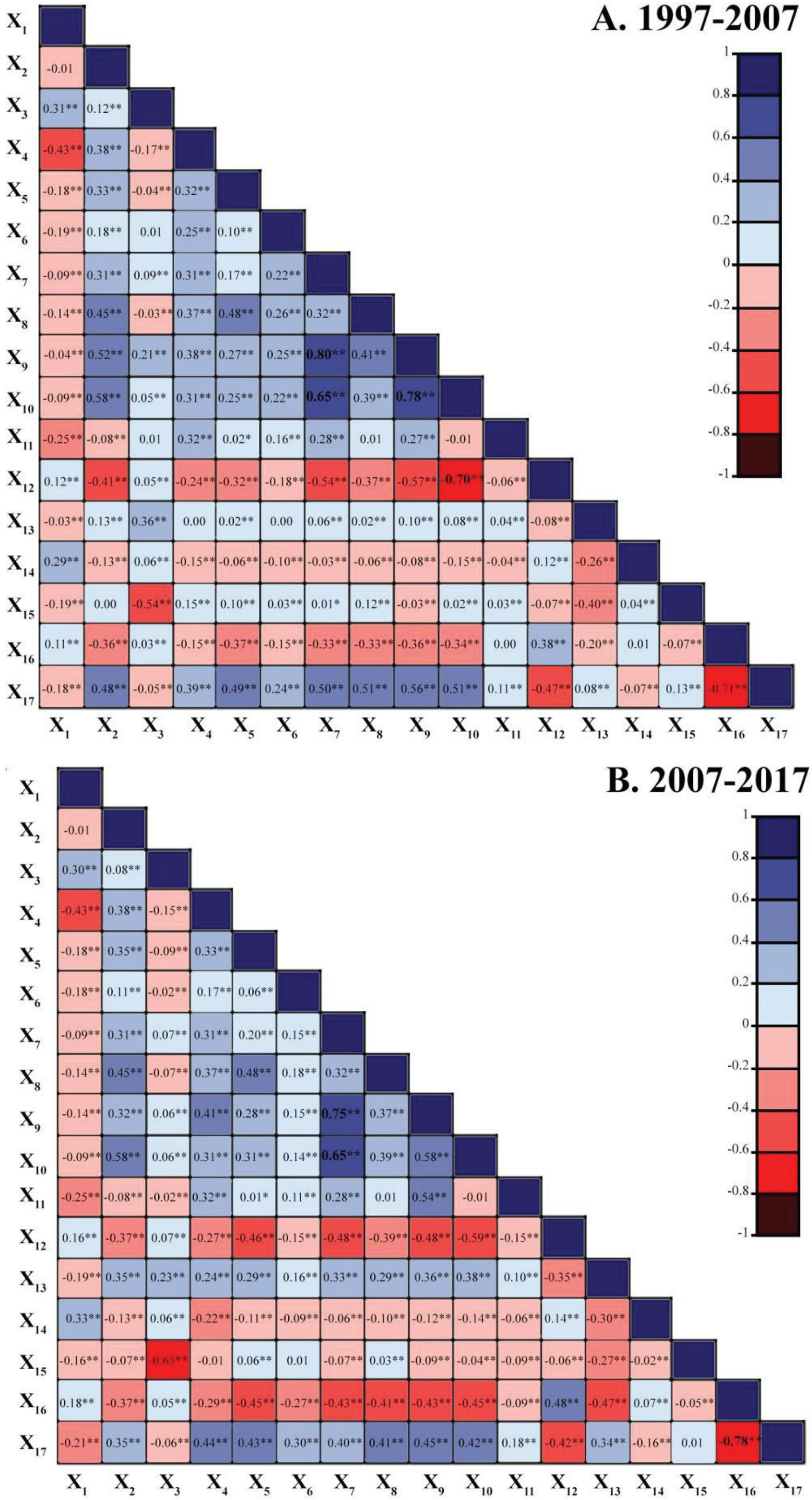

Figure 29 Correlation coefficients of independents in each period

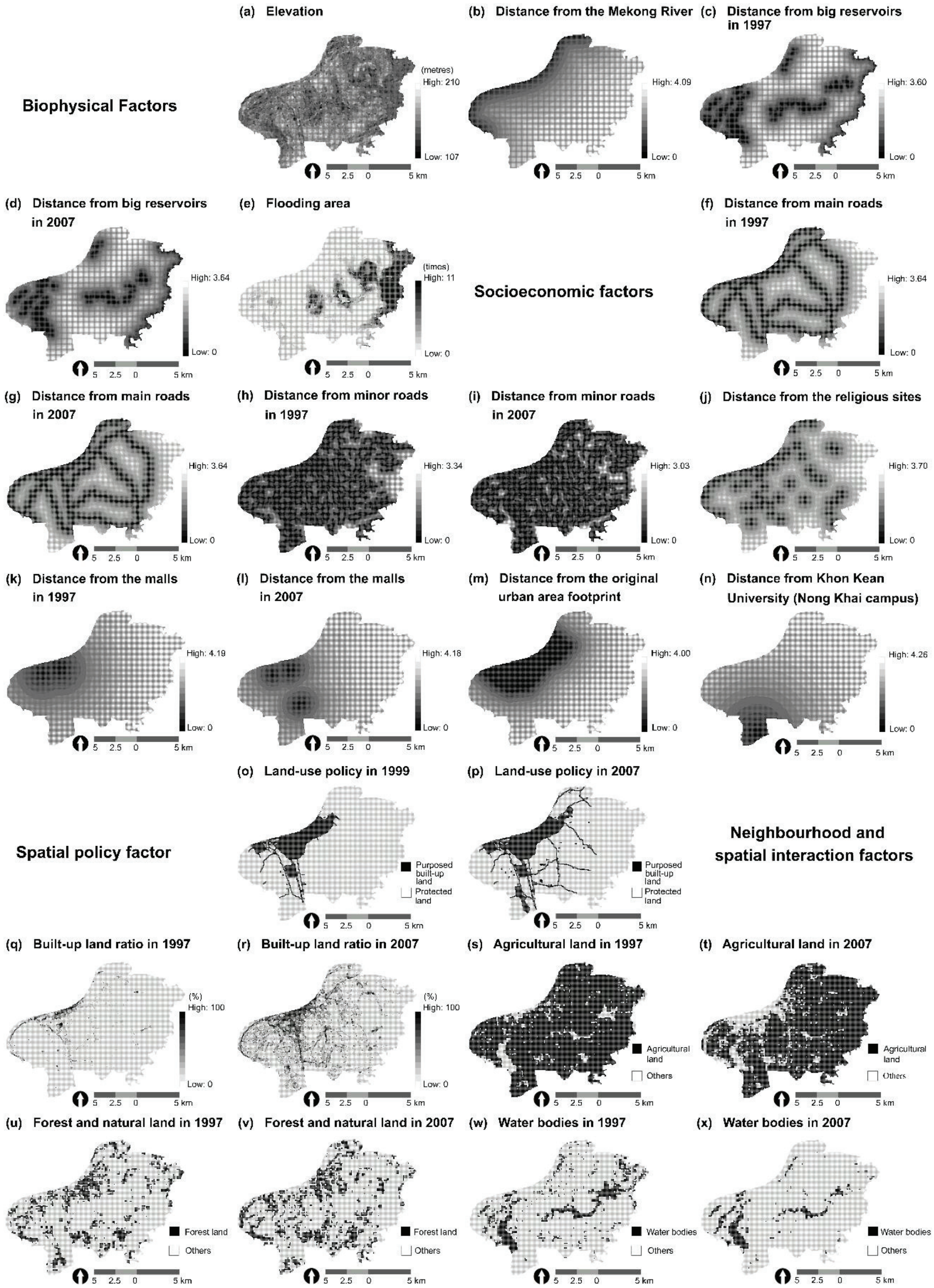

Figure 30 Independent variables

Thus, removal of the highly influential observation is necessary to develop model accuracy. Many criteria can be used to interpret outlier value from Cook's distance value, and in this study, such values were measured using SPSS Statistics 27. We eliminated the grid cell with a Cook's distance value of more than 0.0010. Consequently, 14,609 grid cells were used for the analysis between 1997 and 2007, and 14,379 for the analysis between 2007 and 2017.

4.4.2.2 Logistic regression

The logistic regression model usually is applied to study how independent variables are related to the dependent variable, i.e., the dichotomous form (Harrell, 2015). The relationship between the independent and dependent variables was calculated using the following regression model in SPSS Statistics 27:

$$P = \left(Y = 1 \middle| X_{1,} X_{2,} \dots, X_k\right) = \frac{1}{1+e^{-\left(\alpha+\sum_{i=1}^{K} \beta_i X_i\right)}} \qquad (4.2)$$

in which P $\left(Y = 1 \middle| X_{1,} X_{2,} \dots, X_k\right)$ is the probability of the dependent variable being 1, given $(X_{1,} X_{2,} \dots, X_k)$; X_i is an independent variable that reflects the driving factors of built-up land expansion; and β_i is the coefficient for the variable X_i, which can be used to interpret the influence degree of determinant. A positive value indicates that the independent variable supports the probability value of built-up land expansion, whereas a negative value indicates the opposite.

4.4.2.3 Model validation

The receiver operating characteristic (ROC) curve was adopted to assess the model's goodness of fit in this study. It generally is a methodology used to assess model suitability (Hu & Lo, 2007; Li et al., 2013; Luo et al., 2019; Verburg, de Nijs, et al., 2004). The area under an ROC curve (AUC) can be calculated to reflect the model's performance (Fawcett, 2006). The AUC value is between 0 and 1, with a value closer to 1 indicating greater model perfection. Each model's Nagelkerke R squared also was conducted to assess the model's goodness of fit and can be calculated using Equation (4.3):

$$R^2 = 1 - exp[-2/n\,(l_A - l_0)] \qquad (4.3)$$

in which n is the sample size, l_A is the model's log-likelihood, and l_0 is the null model's log-likelihood, with only the intercept as a predictor.

In this study, both logistic regression models for 1997–2007 and 2007–2017 reached overall satisfaction accuracy levels of 96.7 % and 88.3%, respectively. In the case of AUC, the values were 0.91 and 0.88, respectively. In the case of Nagelkerke R squared, it also reached satisfaction, with values of 0.83 and 0.78 during the 1997–2007 and 2007–2017 periods, respectively. Thus, all models were acceptable.

4.5 Results

4.5.1 Spatial patterns of built-up land expansion

During the 1997–2017 period, Nong Khai City experienced a considerable built-up land expansion (Figure 31), which was the primary land-use change pattern. The built-up area of Nong Khai City has expanded along the roads, especially the southern area of Nong Khai which has the main highway roads no. 2 and no. 232 connecting Nong Khai to the Thai-Lao Friendship bridge and the surrounded provinces.

As shown in Figure 32, compared with other land-use types, built-up land hit the highest land-use change rate, at 37.02 % in 2007 and 14.77 % in 2017. In 1997, built-up land occupied only 6.50 km^2, but in 2017, the total was 75.78 km^2. Agricultural land was the major land-use type transformed into built-up land, which gained 18.19 km^2 and 32.96 km^2 from agricultural land in 2007 and 2017, respectively.

Built-up land's transformation pattern in Nong Khai City corresponded with land-use change patterns on the national scale in many countries in the BRI, including China, Bahrain, Oman, Singapore, Bangladesh (Chen et al., 2018), megacities in the BRI (Sun et al., 2021) and important cities in CICPEC, such as Khon Kaen (Ongsomwang et al., 2019), Yangon, Vientiane, Phnom Penh and Bangkok (Cao et al., 2019). In addition, the transformation of the built-up lands in Nong Khai City was consistent with the study of Manorom et al. (2015, p. 55) which indicates that the built-up lands were increasing in the border cities along the Mekong River including Nong Khai City owing to the economic development cooperation between Thailand and Laos.

Figure 33 indicates that built-up land in Nong Khai City was dense in original urban areas and thin in peri-urban areas, comprising a distance of 9.5 km from the original area. Built-up land in peri-urban areas increased at a high rate. The enormous dispersal of the built-up lands in the peri-urban areas found in this study is in accord with the study of Chaiyapon Keeratikasikorn (2018) which indicates the growing distribution of the built-up lands in Nong Khai City. In addition, it is in accordance with the findings of the previous chapter indicating that the population in the peri-urban area increased, especially in the sub-district along the highway no.2. The increase of the population and the built-up lands in the peri-urban area implies that although Nong Khai City is small, it also encounters the urban sprawl in peri-urban areas just like other megacities in developing BRI countries (Sun et al., 2021).

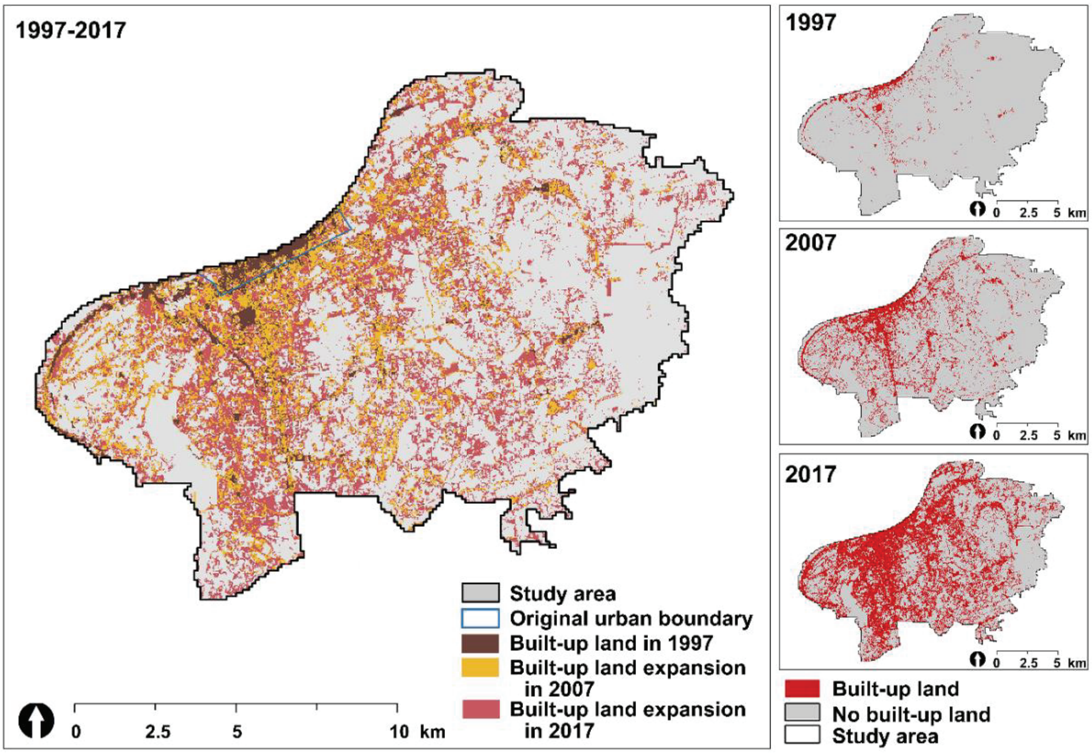

Figure 31 Spatial distribution of built-up land from 1997 to 2017

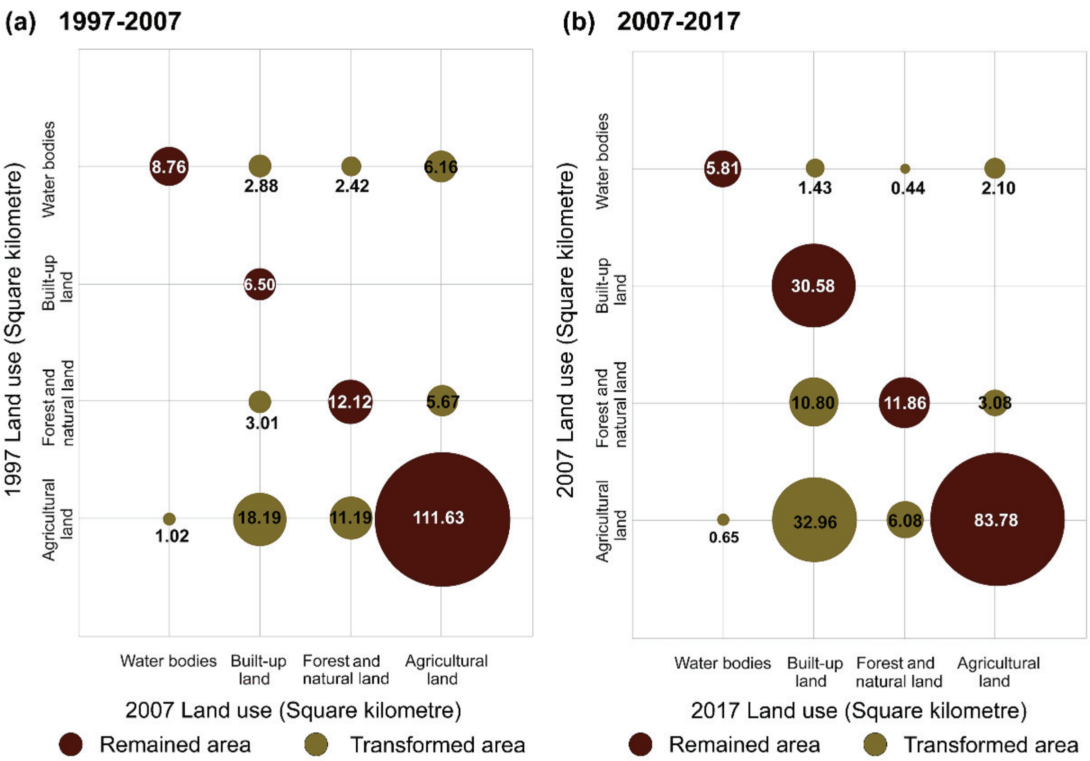

Figure 32 Land-use change pattern: (A) 1997–2007; (B) 2007–2017

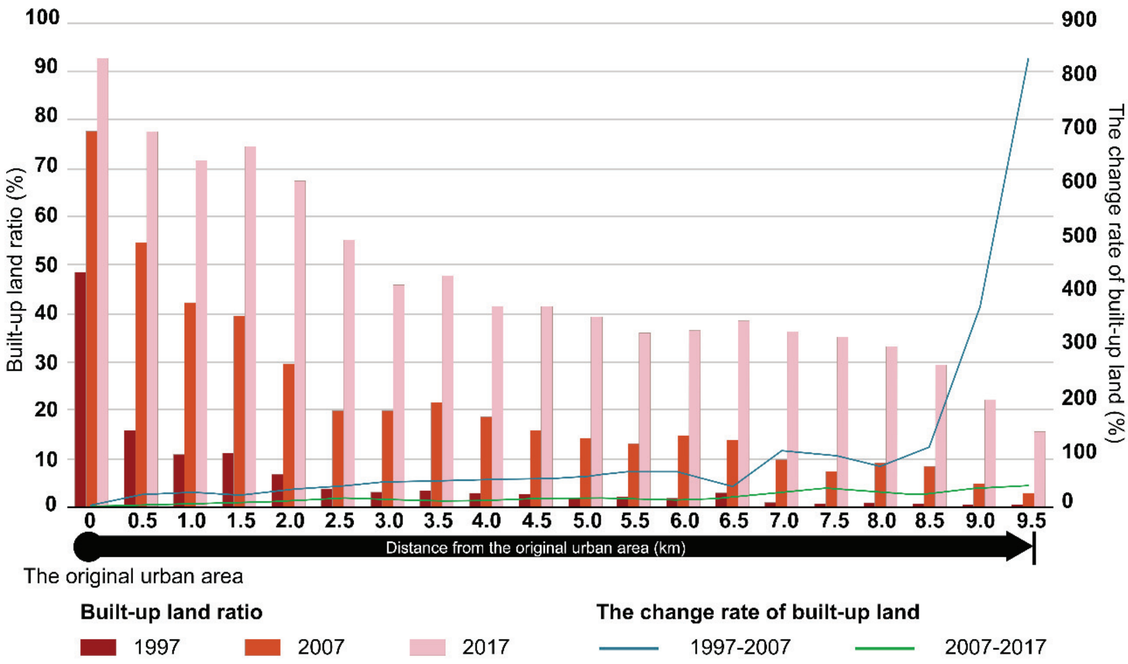

Figure 33 The change rate of built-up land from the original urban area of Nong Khai City for every 500 metres

4.5.2 Driving factors of built-up land expansion

As shown in Table 10, the driving factors of built-up land expansion in Nong Khai City during the 1997–2007 period differed from those during the 2007–2017 period. The socioeconomic factor was the most powerful driving factor during the 1997–2007 period, but this factor weakened during the 2007–2017 period when neighbourhood and spatial interaction factors became more dominant.

Table 10

Logistic regression models

Variable	1997–2007				2007–2017			
	B	S.E.	Wald	Exp (B)	B	S.E.	Wald	Exp (B)
Biophysical factors								
X_1	0.06**	0.01	44.81	1.06	0.07**	0.01	160.50	1.07
X_2	0.66**	0.19	12.80	1.94	1.92**	0.12	251.07	6.79
X_3	0.72**	0.13	30.51	2.06	0.38**	0.07	29.59	1.46
X_4	-0.49**	0.06	58.60	0.61	-0.46**	0.02	699.67	0.63
Socioeconomic factors								
X_5	-1.71**	0.09	393.08	0.18	-1.14**	0.07	245.47	0.32
X_6	-1.88**	0.07	822.54	0.15	-1.37**	0.04	1088.74	0.25
X_8	-1.13**	0.18	37.21	0.32	/	/	/	/
X_9	-6.31**	0.28	504.15	0.00	-0.95**	0.24	15.80	0.39
X_{10}	/	/	/	/	-0.71**	0.07	116.83	0.49
X_{11}	/	/	/	/	-0.61**	0.24	6.67	0.54
Spatial policy factor								
X_{12}	0.99**	0.17	33.47	2.68	1.76**	0.25	50.88	5.84
Neighbourhood and spatial interaction factors								
X_{13}	4.27**	0.54	63.58	71.30	4.50**	0.20	526.09	90.06
X_{14}	0.33*	0.15	4.99	1.39	3.15**	0.15	428.09	23.44
X_{15}	1.57**	0.29	29.76	4.80	/	/	/	/
X_{16}	0.10**	0.01	114.60	1.11	0.06**	0.00	438.71	1.06
Constant	12.24**	1.57	60.45	205993.29	-9.72**	1.09	78.78	0.00
Model summary								
N	14,609				14,379			
−2 Log-likelihood	2762.12				7103.96			
Nagelkerke R Square	0.83				0.78			
AUC	0.91				0.88			

** $p<0.01$, *$p<0.05$

4.5.2.1 Biophysical factor

The biophysical factor was a basic factor that influenced built-up land expansion. In this study, we found that the factor, compared with other factors, was not as influential on built-up land expansion. This finding is consistent with Luo et al.'s (2019) study on built-up land expansion in Wuhan City, which found that the natural environment factor made a marginal impact. Nevertheless, we found that during the 2007–2017 period, the distance from the Mekong River (X_2) positively affected built-up land expansion. The factor reinforcing the influence of the distance from the Mekong River during the second period was the growth of provincial tourism. For Nong Khai Province, which has Nong Khai City as its centre in terms of tourist attractions, the gross provincial product in tourism accommodation and food service activities grew dramatically during the second period (Figure 34). During the 2007–2017 period, average annual growth was 1.09 %, while during the 1997–2007 period, it was 0.86 % (Office of the National Economic and Social Development Council, 2021).

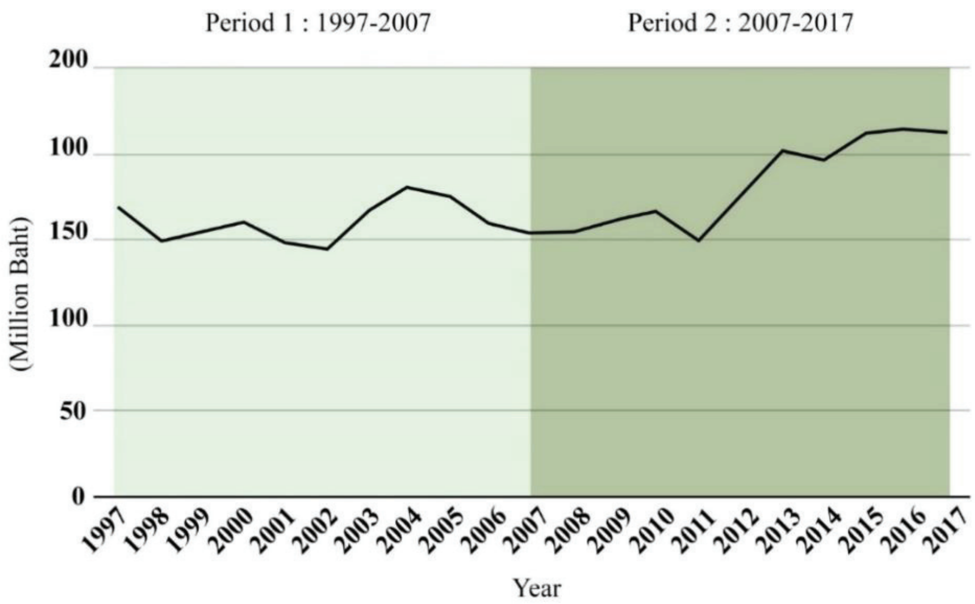

Figure 34 The GPP value of accommodation and food service activities in Nong Khai Province between 1997 -2017

Tourism growth has changed land use near the Mekong River (Saiyarod, 2018), leading to higher land prices. The Office of Nong Khai Provincial Treasury (2015) database indicates that the areas along Panang Chonlaprathan Road, near the river, had a fairly high appraisal price of about US$ 175.98 per m^2 during the 2012–2015 period. Therefore, the high price of land near the Mekong River, which includes picturesque topographical conditions, enabled distance from the river to be the driving factor that pushed locals to settle in areas far from the river.

The factors in this group – elevation (X_1), distance from big reservoirs (X_3) and flooding areas (X_4) – exerted a minimal influence, particularly elevation. This finding differed from Suwit Ongsomwang et al.'s (2019) study on the factors affecting built-up land expansion in Khon Kaen Province, mainly due to characteristics of the land in Nong Khai City, most of which comprises plains, so variations in elevation were small. Thus, there was no need for advanced construction technologies and high construction costs due to the relatively flat terrain, i.e., elevation's influence was small.

For the distance from big reservoirs, there is a positive relationship with the built-up land expansion in Nong Khai City, which was consistent with studies by Sakayarote and Shrestha (2019) and Ongsomwang et al. (2019) implying that the big reservoirs were no longer essential in daily life because people could access water from the waterworks. However, such relationship contradicted with the studies by Keeratikasikorn (2017) and Kitrat and Keeratikasikorn (2018), indicating that the new built-up land often was located near reservoirs so that people could access resources for daily life and recreational activities.

However, the flood frequency has a negative relationship with the built-up land expansion. More specifically, built-up land expansion was likely to occur in areas with low flood frequency, corresponding with Poelmans and Van Rompaey's (2009) study, which found that areas prone to flooding impacted built-up land expansion, i.e., developers avoided building construction in these areas.

4.5.2.2 Socioeconomic factor

The socioeconomic factor's variables exerted a negative influence on built-up land expansion during both periods, corresponding with previous studies (Kitrat & Keeratikasikorn, 2018, p. 266; Li et al., 2018; Li et al., 2013; Shu et al., 2014) and indicating that built-up land expanded near the source of these socioeconomic factors.

During the first period, distance from malls (X_9) was a major variable. This pattern also appears in Suwanlee and Som-ard's (2020) study, which indicates that easy access to malls, which is one of the public amenities that helped increase the city centre's population because they can access amenities easily based on the gravity concept. The concept explains that the population will be distributed densely near areas that are hubs for commerce, and that the population will decrease as distance from service hub centres increases. However, the influence of distance from malls decreased during the second period, mainly because malls increased in peri-urban areas in the expanded communities. Another reason is that transportation was much more accessible; thus, residents in peri-urban areas could access malls easily. Economic centres' diminishing impact on built-up land expansion also was found in Khon Kaen's urban areas (Keeratikasikorn, 2017).

The distance from main roads (X_5) and minor roads (X_6) was another factor that affected built-up land expansion during both periods, corresponding with many studies that have highlighted road networks as an important driving factor (Kasraian et al., 2016; Li et al., 2013) because they increase access and transform land to support urban activities. Furthermore, quality roads are attractive infrastructure features that help lure people to peri-urban areas (Kasraian et al., 2016). Furthermore, the relationship between road networks and built-up land expansion in Nong Khai City was consistent with most studies in Thailand that found the distance from road networks negatively affect built-up land expansion, i.e., built-up land usually expands along roadside areas (Keeratikasikorn, 2017; Ongsomwang et al., 2019; Patarasuk & Binford, 2012). Moreover, this study confirmed and quantified road networks' impact on built-up land expansion in Nong Khai City during the earlier period (Klinchat, 2003; Saiyarod, 2018; Suvathi, 1995).

Table 10 indicates that minor roads made more of an impact than main roads. Connecting minor roads to main roads was an important factor in expansion because it increased access to unused land. Minor roads' impact on Nong Khai City's expansion corresponded with studies on other cities, such as Khon Kaen City and Wuhan City (Cheng & Masser, 2003; Keeratikasikorn, 2017). Nevertheless, in the present study, minor roads' influence in Nong Khai City was not impressive compared with other studies that have found that, despite its importance, the road network was not the most influential factor.

Besides these three variables, other factors also influenced built-up land expansion during each period. During the 1997–2007 period, distance from temples (X_8) was one socioeconomic factor and was considerably influential. Temples traditionally have been centres of Thai communities (Tachakitkachorn & Shigemura, 2005), and this interrelationship between religion and community, together with limited travel capabilities in the past, created a close relationship between communities and temples. The negative relationship implies that during the first period, temples played an important role in determining the new built-up land sites, with new buildings located near temples. However, during later years, access to temples was no longer a significant factor. Community expansion did not happen the same way during the second period, as more transportation options were the main factor that weakened the importance of distance from temples during the 2007–2017 period.

Distances from the original urban area footprint (X_{10}) and from Khon Kaen University (Nong Khai campus) (X_{11}) were the driving factor that affected built-up land expansion only during the second period. Regarding built-up land expansion and the distance from the original urban area footprint – which represented job, commercial and service areas – this study found a negative relationship, corresponding with previous studies that found new built-up land usually was located in areas closer to city centres (Li et al., 2013; Luo et al., 2019). However, this factor was not strongly influential because commercial development and government offices expanded into peri-urban areas, decreasing access to the original urban area footprint.

As for distance from the university, previous studies found that the development of Thai universities affected land use, as the areas around universities were transformed into built-up land to accommodate university needs (Chotchaiwong & Wijitkosum, 2019). In the case of Nong Khai City, Khonkaen University (Nong Khai campus) played a significant role during the second period because the university attracted more students through its new courses added since 2008. This transformed the area around the university as built-up land expanded to accommodate this growth. However, the university was marginally influential in these changes in land use, i.e., this built-up land expansion happened only around the university.

4.5.2.3 Spatial policy factor

The spatial policy factor (X_{12}) was influential during both periods. This study found a positive relationship between built-up land expansion and the areas that the city plan designated as built-up areas, indicating that new built-up land usually expanded into areas designated as built-up land. Thus, built-up areas and protected area designations in the comprehensive land-use plan impacted built-up land expansion. This relationship reflects the comprehensive land-use plan's influence on the expansion.

4.5.2.4 Neighbourhood and spatial interaction factor

The neighbourhood and spatial interaction factors were related to land-use patterns during the earliest years of both periods. This study found that the variables in this group had a positive relationship with built-up land expansion. Agricultural land (X_{13}) initially exerted a strong influence in terms of land use, particularly during the 2007–2017 period. The relationship between agricultural and built-up land expansion indicates that the new built-up land often came from agricultural land because most of the latter land comprised vacant land, which is more suitable for construction than other land with higher costs and legal limitations. The influence from agricultural land increased during the second period, which was consistent with changes in land-use patterns during the period.

As for forest and natural land (X_{14}), the relationship pattern was similar to that of agricultural land: The factor's influence increased during the second period, responding to the transformation of forest and natural land into built-up land.

Water bodies (X_{15}) were related greatly to changes in built-up land expansion. The large water bodies were transformed into built-up land following the exception of Nong Khai's city planning regulations. However, water bodies' influence faded during the second period because the number of water bodies decreased, and fewer changes were made due to city planning regulations, which designated water bodies as land for recreational activities and environmental protection.

As for built-up land's influence, this study used built-up land proportion (X_{16}) and found that its influence was small, particularly during the second period. The positive relationship reflected the increase in built-up land in Nong Khai City, which accommodated initial land development.

4.6 Conclusion

Nong Khai City is a provincial city along the BRI's routes. Although it is a small city, its land-use changes have been dynamic for over two decades. Its built-up land was the land-use type that changed the most, as with other big cities in CICPEC, increasing from 6.50 km^2 in 1997 to 75.78 km^2 in 2017. Most built-up land was transformed from agricultural land in 2017, which was the primary land-use type in 1997.

The logistic regression model indicates that the expansion of built-up land in Nong Khai City was driven by various factors, not just the road network and Thailand's National Economic and Social Development Plan, as other studies had reported using a qualitative methodology. The biophysical, socioeconomic, spatial policy and neighbourhood and spatial interaction factors significantly affected the expansion in different patterns and magnitudes.

However, previous studies have indicated that built-up Nong Khai City land expanded along the road networks, but the most influential determinant was not road network access. Access to malls was the most influential driving factor during the first period, while agricultural land was the most influential driving factor during the second period. Furthermore, the influence from biophysical variables, such as elevation and distance from big reservoirs, was small.

The spatial policy factor moderately influenced the expansion of built-up land throughout this study, which clarified built-up land zones' role in the comprehensive land-use plan. The expansion of built-up land zones during the second period generated more influence on the expansion of built-up land. Furthermore, this study found that the agricultural land surrounding the city during the second period had a high probability of being developed into built-up land because land use of the original agricultural land was more powerful, and the distance from the Mekong River was positively influential.

The findings indicate that Nong Khai's future land-use planning should focus on controlling development and conserving agricultural land around cities because this land is highly likely to become built-up land, particularly when the high-speed railway is constructed in peri-urban areas. The transformation of agricultural and natural conservation zones into built-up areas in the comprehensive land-use plan should be handled carefully because it will trigger built-up land sprawl in agricultural areas and destroy this land's ecological value.

Although the flood frequency has a negative relationship with the built-up land expansion in both periods, we cannot deny that the influence of flood frequency is low compared to other factors. The influence of other factors — such as the agricultural lands, the distance from the Mekong River, and road networks, which have a higher impact on the built-up lands — thus is likely to cause the built-up lands to expand into the frequently flooded areas or flood-prone areas and put Nong Khai at risk of flooding in the future. However, the understanding of the flood-prone areas is still limited and need to be clarified to support the policy to manage the built-up land expansion in the future.

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Chapter 5

Flood- prone areas in Nong Khai City

Contents

5.1 Introduction[1]

As described in Chapter 2, floods are a widespread natural hazard in the north-eastern region of Thailand. Like other provinces in the region, Nong Khai also encounters floods. At the provincial level, the database of repeatedly flooded areas from the Geo-Informatics and Space Technology Development Agency of Thailand (2004 and 2018) indicates that 24.09% of the areas in Nong Khai encounter floods. It is interesting that the flooded areas are clustered in the areas along a meandering river at the southern side compared to the areas along the Mekong River, as shown in Figure 35.

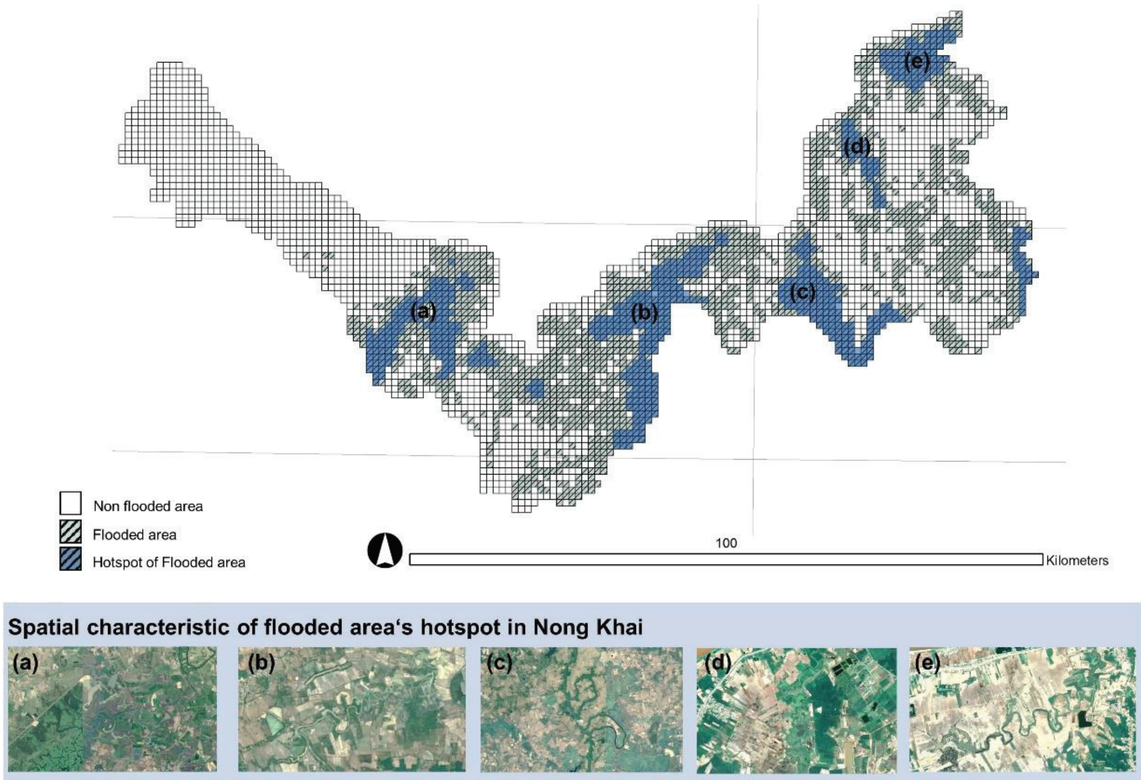


Figure 35 The hotspot of flooded area in Nong Khai Province

Flooding in Nong Khai is caused by river flooding. The high amount of rainwater owing to Southwest Moonsoon and the Intertropical Convergence Zone (ITCZ) is an important factor triggering Nong Khai to encounter the flood, as shown in Figure 36. The Southwest Moonsoon sweeps between mid-May to mid-October from the Indian Ocean and causes heavy rain in Nong Khai (Thailand Meteorological Department, 2020). According to the database of historical weather data from the World Weather Online (Figure 37 and Table 11), between May – September

[1] The information in this section was published in "Bamrungkhul, S. & Takahiro, T. Urbanisation in the Flooded Area of Nong Khai Province: Does the Urbanization Grow on the Sustainable Path? Proceedings of Annual Research Meeting Chugoku Chapter, Architecture Institute of Japan (AIJ) 2022, 6 March 2022, 735–738."

which is the part of monsoon season, it rained in Nong Khai almost every day. During these months, the monthly rainfall was obviously higher, especially in July and August. In addition, the tropical cyclones are also indicated as an important factor in bringing heavy rain to the areas and triggering the mainland of southeast Asia (Chen et al., 2020) including the target areas to encounter the flooding, such as KALMAEGI in 2014 and SONCA in 2017. Thailand Meteorological Department (2020) indicates that 31 tropical cyclones between 1951–2019 had some effects on rainfall over Nong Khai Province. It consisted of 6 Typoons, 8 tropical storms, and 17 tropical depressions.

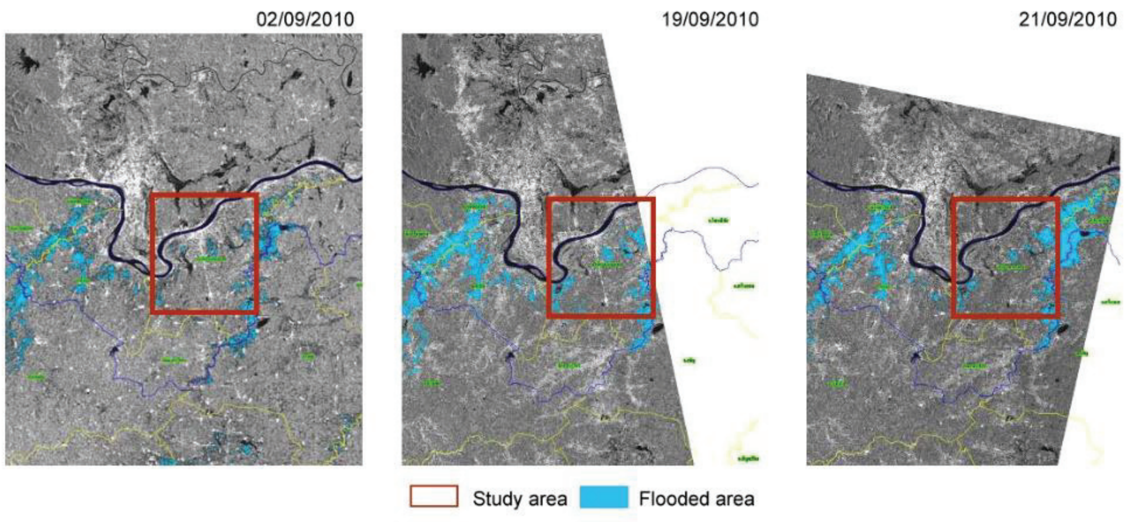


Figure 36 The 2010 flooded area owing to the ITCZ

(Source: Adapted from GISTDA, http://tiwrmdev.hii.or.th/current/flood_sep53.html)

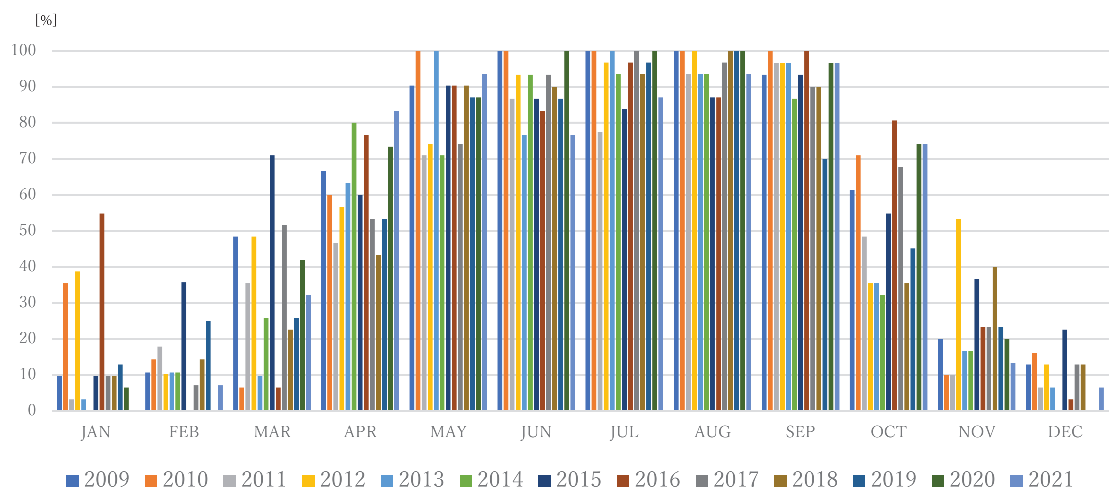


Figure 37 The ratio of average days of rainfall in each month per year from 2009 to 2021

(Source: World Weather Online)

Table 11

The average monthly rainfall (mm) for each month per year from 2009 to 2021

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
January	13.8	151.6	0.9	7.62	2.7	0	10.2	95.6	29.2	4	2.4	4	0
February	3.9	11.45	6.64	7	6	4.2	43.5	0.1	3.3	40	29.9	0	29
March	95.3	1.5	91.83	81.2	8.5	19.23	50.54	7.2	115	15.97	45.2	27.6	34.5
April	270.27	145	98.34	77.8	44.4	93.76	49.37	61.47	70	130.26	48.8	96.5	208.4
May	**753.3**	**876.7**	174.41	309	204.5	104.7	157.53	226.2	347	184.1	354.4	161.1	248.5
June	522.1	769.2	**618.15**	329.23	244.6	321.47	151.86	262.54	437.5	555.73	511.3	319.5	352
July	577.3	743.4	492.7	408.28	**401.9**	283.17	**595.13**	379.27	**597.1**	**828.1**	403.7	595.7	**479.3**
August	602.4	737.7	387.76	**497.41**	343.63	361.81	459.73	**511.22**	555.6	730.3	**782.2**	**875.6**	282.6
September	385.4	428.87	483.1	308.01	349.9	**514.82**	425.97	417.61	346.1	357.09	206.5	518.2	106.5
October	85.4	235.3	65.2	74.4	134.9	21.5	158.22	177.2	248.27	129.83	60.1	278	47.1
November	21.5	0.6	6.5	138.4	10.3	31.46	12.4	42.52	29.1	29.3	36	2.1	3.6
December	10.9	12.9	2.3	9.6	61.3	0.2	20.9	0.4	9	43.6	0.1	0	0.3

Source: World Weather Online

Although the land-use data in 2017 from the land development department indicates that flooded areas in Nong Khai are mainly in the agricultural lands, the built-up lands also sprawl in the flooded areas. 56.44% of new urbanised areas in 2017 are in the repeatedly flooded area. Therefore, it's undeniable that the settlements in Nong Khai are increasingly at risk of flooding.

However, the flood is a natural hazard that the local in Nong Khai have encountered for a long time, and there's even an increase in the settlements in the flooded areas. The information on flood-prone areas is lacking leading to improper flood management. From the literature review, the flood susceptibility map (FSM) in Nong Khai consists of two parts: (1) The FSMs in the rained agricultural area zone. It was produced by the Water Crisis Prevention Centre, Department of Water Resources of Thailand. Although the FSMs were produced monthly and these FSMs are up to date, their scopes of the areas only cover the rained agricultural areas. (2) The FSM by M. Oya (Mekong Committee, 1967) after the big flood in Nong Khai in 1966. This FSM was produced based on the geomorphological type. Its scope of the areas is limited, and the flood-prone areas were implied from only geomorphological types. To sum up, currently, the information about flood susceptibility in Nong Khai is not enough to support the promulgation of the land-use policy and mitigate the problems from the flood.

The FSM is a crucial tool to manage a city to achieve sustainability. It presents information about the probability of flood occurrence in a specific area by synthesising the hydrological, geomorphological and climatological data (Mudashiru, Sabtu, & Abustan, 2021). The understanding about the flood-risk location identifies the zones subject to the flood that need a policy to prohibit the new settlement and a policy to mitigate the loss in the settlement with highly susceptibility of floods (Vojtek & Vojteková, 2019). In addition, this understanding also informs a safe zone from flooding suitable to be a new urbanised area in order to decrease the exposure of flood in the future. Hence, before planning the land-use policies in Nong Khai City, the flood-prone areas should be identified through the FSM supporting the land-use decision.

Generally, the FSMs were developed from the physically based model method (Marchesini, 2020; Mudashiru, Sabtu, Abustan, et al., 2021) which can produce the FSMs with the information about the extent, flood height, velocity, and flow times which are crucial information related to the urban flood risk hazard (Ezzine et al, 2020, p. 309). To create the FSMs, this model requires intense input about the hydraulic and meteorological data and the geometry characteristics of the areas at micro scale to calibrate such as the riverbeds, infiltration data, and roughness (Cotugno et al., 2021; de Moel, Alphen & Aerts, 2009, p.292; Marchesini, 2020). Hence, the model is suitable for data-rich areas, especially the areas along the rivers with gauging stations that provide the peak flow data as well as other hydraulic and meteorological data in the long term because missing data input causes the model to be uncertain and inappropriate (Getahun & Gebre, 2015; Hurtado-Pidal et al., 2020, p.2). However, scholars attempt to develop a method to enhance the capacity of the physically based model to support the FSM creation in the data-scarce environment. The analysis still requires intense detailed data such as the river section and the data from the gauging station (Hurtado-Pidal et al., 2020, p.4). As a result, the physically based model method is still difficult to apply in the data-scarce environment. To develop the FSMs under the data-scarce environment, numeral statistical techniques were integrated into the GIS framework in the ungauged territories where the hydro-meteorological data is not available (Marchesini, 2020). The integration uses the input data from accessible sources and creates the FSMs from DEM (Tehrany et al., 2017; R. K. Samanta et al., 2018; S. Samanta et al., 2018; Sarkar & Mondal, 2020). Although the FSMs from the statistical techniques cannot provide information about flood height and velocity, they can indicate the extent of flood-susceptibility which is adequate for guiding urban planning (de Moel, Alphen & Aerts, 2009). However, just as other models, the uncertainty of the model is varied based on the quality of data input and spatial characteristics. To apply the statistical techniques in the GIS framework, it is necessary to compare the performances of the potential models.

Although there is a hydrological station located in Nong Khai City, the hydrological data from this station is not suitable for creating the FSMs of Nong Khai City because it is the data of Mekong River. Based on the earlier discussion that the hotspots of flooded areas in Nong Khai City are the areas along meandering rivers like the Mesuai River, which don't have hydrological data and river section in detail. Due to this situation, to create the FSMs of Nong Khai City, the statistical modelling method was integrated in the GIS framework with the accessible data to support the land-use policy in the data scarce environment.

This chapter is divided into six sections. The first is the objective of this study. The second is the literature review where the methods to generate the FSMs are reviewed in three parts: (1) the physically based model method, (2) the physical modelling method, and (3) the empirical modelling method. Then, the data and seven models — four standalone models of the statistical modelling method and three ensemble models — to generate the FSMs in this study are presented in the section of methodology. The results of this chapter are divided into two parts. The first part focuses on the spatial relationship between the conditioning factors and flood occurrence, and the conditioning factors of flooding in Nong Khai City based on the types of the models. The second part is about the FSMs of Nong Khai City based on flood-susceptibility levels. Afterwards, the performances of the models and the influence of the conditioning factors on flood occurrence are discussed along with the previous study. The last section is the conclusion.

5.2 Objective

1) To clarify the effects of the conditioning factors of flooding in Nong Khai City
2) To implement the statistical modelling methods to create the FSMs of Nong Khai City
3) To compare the performance of each model from AUC and create the FSMs

5.3 Literature review

FSM is an essential tool to support planners detect the areas that have the high possibility to be flooded and need a suitable land-use policy to prepare for to mitigate the effects of flooding on the settlement (Saleh et al., 2020; Tehrany et al., 2013; Vojtek & Vojteková, 2019; Wubalem et al., 2021). To improve the performance of FSMs, many models were performed to generate the FSMs (Tehrany et al., 2013). Mudashiru, Sabtu, Abustan, et al. (2021) categorised the methods to generate FSMs into three groups: the physically-based model method, the physical modelling method and the empirical modelling method. Between 2000-2020, the empirical model played a crucial role in generating the FSMs, followed by the physically-based model and the physical modelling, respectively (Mudashiru, Sabtu, Abustan, et al., 2021).

5.3.1 Physically-based model method

The physically-based model method creates the FSMs based on the simulation of the hydrological processes and the principle of fluid mechanics (Mudashiru, Sabtu, Abustan, et al., 2021). Currently, there are many physically-based models such as Hydrologic Center- Hydrologic Modelling System (HEC-HMS), Soil and Water assessment Tool (SWAT), and Kinematic Runoff and Erosion Model (KINEROS), and others. The physically-based model can generate the FSMs with acceptable accuracy (Puno et al., 2020; Talisay et al., 2019). However, due to the fluid motion simulation, the model requires time and intense data input such as the hydrological data and meteorological data to create the FSMs (Mudashiru, Sabtu, Abustan, et al., 2021).

5.3.2 Physical modelling method

The physical modelling method is a method to simulate flood events by using a physical model. Although, the result from the physical models is accurate (Bellos, 2012), there are many disadvantages, such as the cost of the model development, the required highly-accurate data, and the time-consuming process (Bellos, 2012; Mudashiru, Sabtu, Abustan, et al., 2021). Because of the limitations, this method is unpopular compared with the others (Mudashiru, Sabtu, Abustan, et al., 2021). The physical model was often used to detect the flooded area through the scenario of infrastructure construction and special events such as the sewer network construction, the simulation of the flooded area due to Tsunami, and dam failures (Bellos, 2012).

5.3.3 The empirical modelling method

The empirical modelling method is a model to simulate the FSMs based on the spatial data relating to the flooding occurrence and the statistical method. Comparing with other methods, the empirical modelling method is easy to implement because it requires less data input. Furthermore, it produces the FSMs with acceptable accuracy. However, the method has a limit on the prediction of the future situation and the generation of the hydrological characteristic such as flow depth and velocity (Mudashiru, Sabtu, Abustan, et al., 2021). As the physical and physically-based models require the hydrological data that are scarce or insufficient in some target areas, the empirical modelling method, which has less requirement about the input data, becomes the popular methodology of FSM generation in the last two decades (Mudashiru, Sabtu, & Abustan, 2021)

Many empirical modelling methods were performed to create the FSMs, such as frequency ratio (FR), artificial neural network, analytical hierarchy process, logistic regression (LR), Decision tree, and so on (Khosravi et al., 2016). Mudashiru, Sabtu, & Abustan (2021) divide the empirical modelling methods into three approaches: the multi-criteria decision-making modelling method, the statistical modelling method, and the artificial intelligence and machine learning model method.

The multi-criteria decision-making modelling method is the most popular approach in the group between 2000–2020 (Mudashiru, Sabtu, Abustan, et al., 2021). It is a semi-quantitative model (Mudashiru, Sabtu, & Abustan, 2021) to analyse complex decision problems related to the incommensurable data (Fernández & Lutz, 2010) by weighing and ranking the influence level of condition factors and then integrating them within a GIS framework to create the FSMs (Vojtek et al., 2021). An analytic hierarchy process (AHP) is a fashionable model of the multi-criteria decision-making modelling method to create the FSMs (Fernández & Lutz, 2010; Msabi & Makonyo, 2021; Vojtek et al., 2021). Several studies regard AHP as a suitable model to create the FSMs. For example, the study of Vojtek & Vojteková (2019) created the FSM of Slovakia at the national scale by using AHP. They found that 70.9% of historical flood events occurred in the high and very high susceptibility classes of the FSMs. Likewise, in the study of Msabi & Makonyo (2021), which created the FSMs in the Dodoma region of Tanzania using AHP, the FSM has a very high AUC of 87.24%. However, AHP also has a disadvantage in the terms of uncertain or bias judgement of the experts (Tehrany et al., 2013).

The statistical modelling method is a quantitative method that generates the FSMs by using the weight indices from the relationship between spatial conditioning factors and flood occurrence distribution. The method is simpler than other methods because it doesn't require specific data, a computing software, and system capacity. At the same time, it can produce FSMs with reliable accuracy. The statistical modelling methods can be divided into two approaches: the bivariate and the multivariate (Meliho et al., 2021). *(1)The bivariate statistical models*, such as FR and Weight of Evidence (WoE), generate the FSMs by evaluating the relationship between a pair of variables (Mudashiru, Sabtu, & Abustan, 2021). It assigns the weight value from the relationship between the conditioning factor class and flood occurrence. Scholars indicate that the bivariate statistical models are suitable for creating the FSMs because they can produce the FSMs with high accuracy. For example, the study of Lee et al. (2012) that creates the FSMs in Busan by using FR found that the FSMs from the FR model can achieve very high accuracy of 91.5%. Similarly, in the study of R. K. Samanta et al. (2018) that produces the FSM in Subarnarekha River Basin from FR, the AUC values of the success rate and prediction rate achieve 0.84 and 0.81 respectively. The high efficiency of the FR model to create the FSM was also presented by other studies in the different contexts (S. Samanta et al., 2018; Sarkar & Mondal, 2020). In addition to FR model, other models in this group, such as WoE (Khosravi et al., 2016; Paul et al., 2019; Tehrany et al., 2017), Shannon's entropy (Arora et al., 2021; Islam et al., 2021), and Evidential Belief Function (EBF) model (Bui et al., 2019), were reported as reliable models. *(2) The multivariate statistical models* generate the FSMs by evaluating the interrelationship of independence and dependence variables. However, it cannot determine the relationship between the class of conditioning factor and flood occurrence (Mudashiru, Sabtu, & Abustan, 2021). LR is a conventional model of the multivariate statical models frequently performed to create the FSMs because LR is straightforward and comprehensible (R. K. Samanta et al., 2018). Many scholars indicate that the LR model can produce the FSMs with reliable accuracy (Al-Juaidi et al., 2018; Lim & Lee, 2018; Malik et al., 2021).

The artificial intelligence and machine learning model method is a recently popular trend for generating the FSMs (Vojtek & Vojteková, 2019). The FSMs were created based on the relationship between flood conditioning factors and their distribution (Meliho et al., 2021). Owing to the computing power development, many machine learning models were performed to create FSMs, such as random forest, ANN, K-nearest neighbours, and others. The capacity of the model that can handle complex nonlinear problems without statical assumptions (Msabi & Makonyo, 2021) leads the FSMs to have a high accuracy compared to other methods (Meliho et al., 2021; Saleh et al., 2020). The study of Khosravi et al. (2019) indicates that machine learning has better performance than the multi-criteria decision model. The AUC values from the machine learning such as Naïve Bayes Trees (NBT) and Naïve Bayes (NB) are greater than 0.97. The performance of machine learning to create the FSMs was presented in the study of Meliho et al. (2021). The machine learning produced the FSMs with very high accuracy as the AUC values are more than 80% in every model. However, Mudashiru, Sabtu, Abustan, et al.(2021) reflect that although machine learning can provide FSMs with high accuracy due to the computational efficiency, the model's accuracy is also sensitive to input and length of data. In addition, machine learning also requires a high-performance computing system and software. A complex procedure that affects machine learning is difficult to perform in a wide range of circles (Tehrany et al., 2013; Wubalem et al., 2021).

Recently, scholars have attempted to determine the most suitable method to generate FSMs by comparing the performance of each model. However, the performance of each method is various based on the target area. For example, the study of Wubalem et al.(2021) compared the performance of four methods which are AHP, Information Value (IV), FR, and LR. FR was indicated as the best performance for FSM making, followed by AHP, LR, and IV, respectively. FR is also better than MCDA in the study of S. Samanta et al. (2018) that created the FSM in the Markham River basin. However, the FR model was also identified as the lowest efficiency to create the FSMs in other studies (Malik et al., 2021; Paul et al., 2019; Tehrany & Kumar, 2018; Tehrany et al., 2019; Tehrany et al., 2017)

In addition, Although the standalone method of the empirical modelling can create good accuracy of FSMs, each model has its limitations. For example, the LR can clarify only the interrelationship between the conditioning factors and flood occurrence but cannot analyse the influence of conditioning factor classes and flood occurrence. The FR can clarify the influence of conditioning factor classes and flood occurrence but cannot determine the influence between the factor levels (Tehrany, Pradhan, et al., 2014; Wubalem et al., 2021). To dissolve the problem, the integrated or ensemble methods were developed to create the high accuracy of FSMs (Costache & Zaharia, 2017; Saleh et al., 2020). For example, the study of Tehrany, Pradhan, et al.(2014) shows that the accuracy of Ensemble WoE and the support vector machine is higher than the standalone model in almost all scenarios. The performance of Ensemble WoE was also presented by Tehrany et al. (2017). They found that the WoE was integrated with LR to create the FSM to achieve the highest prediction rate. Tehrany et al. (2013) also performed the other ensemble models to create the FSMs by integrating FR and LR and found that the ensemble model of FR and LR can produce the FSMs with the high accuracy and is better than a rule-based decision tree (DT) which is a model of machine learning.

Although most scholars claim that the ensemble model will develop the performance of standalone models, some scholars indicate that standalone has a higher performance than the ensemble model. For example, Tehrany et al.(2017) show that the WoE can produce the FSMs with a higher success rate than the ensemble model. The ensemble of FR and AHP also has the lowest success rate and prediction rates in the study of Khosravi et al. (2016). Similarly, the study of Youssef et al. (2016) indicates the FR model produces a better model than the ensemble FR and LR model. In addition, Bui et al. (2019), who compare the efficiency of the EBF model and its ensemble models, found that the standalone model of EBF achieve the highest success rate and prediction rate.

To sum up, although there are some developments of the models to create the FSMs, the accuracy of each model are various and uncertain based on each study. Accordingly, it is difficult to select a suitable model to create FSMs from the previous result of the study. The comparation of each model to discover the most suitable model to create FSMs is necessary to achieve the model that fits the local context (Wubalem et al., 2021).

5.4 Methodology

Due to the limitation of hydrological and climatological data at the local scale of Nong Khai City, especially the hydrological data of Mesuai River, which is a significant waterway at the south-eastern part of Nong Khai City, this study thus creates the FSM by using the statistical modelling method that doesn't require intense hydrological data.

As mentioned in the literature review section, to generate the FSM, it is necessary to compare the performance of various models to select the most suitable model for the study because each model has its advantages and disadvantages. Hence, in this chapter, seven models—four standalone models of the statistical modelling method and three ensemble models — were performed to create the FSMs. Those models are FR, Modified Frequency ratio (MoFR), WoE, LR, Ensemble LR-FR, Ensemble LR-MoFR, Ensemble LR-WoE. Then, the FSMs derived from all models were validated with ROC. The model achieving the highest value of AUC was selected as the most suitable model to create the FSM and to classify flood susceptibility at the final step. The framework of this chapter was presented in the Figure 38.

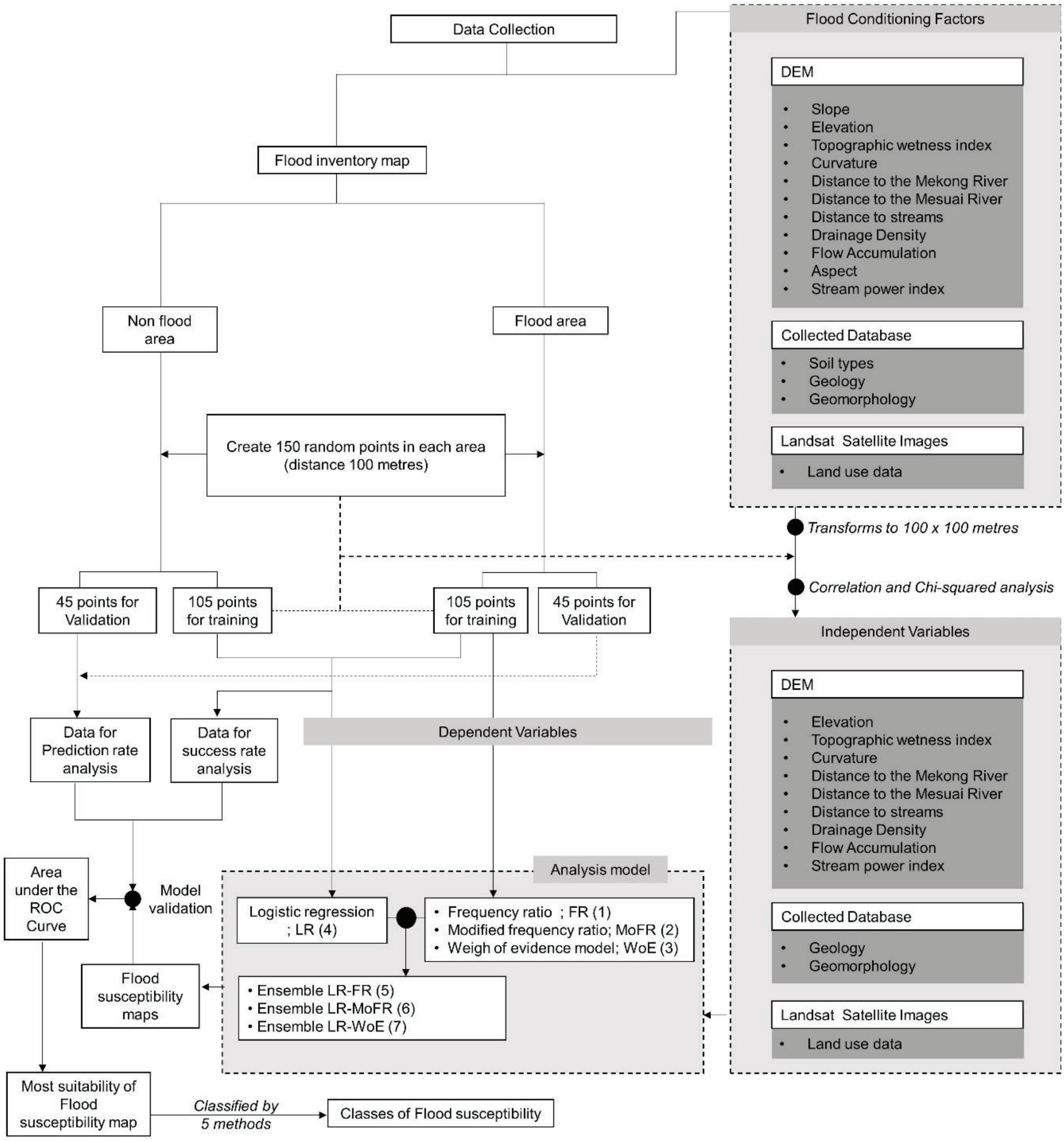


Figure 38 Framework to analyse the areas susceptible to flood in Nong Khai City

5.4.1 Data

The statistical modelling method creates the FSM from the weight value deriving from the analysis of the relationship between flood occurrence distribution and the flood conditioning factors (Mudashiru, Sabtu, Abustan, et al., 2021). The data in this study have been categorised into two parts: (1) flood inventory map related to the distribution of flood occurrence and (2) the flooding conditioning factors.

5.4.1.1 Flood inventory map

Historical flood data plays an important role in analysing the areas susceptible to flood (Mudashiru, Sabtu, Abustan, et al., 2021; Tehrany et al., 2013) because the data present the location of the flooded areas and explain the relationship between the flood occurrence and spatial conditioning factors (R. K. Samanta et al., 2018). In this study, historical flood locations are the repeatedly flooded areas between 2004 and 2018 retrieved from the Geo-Informatics and Space Technology Development Agency of Thailand.

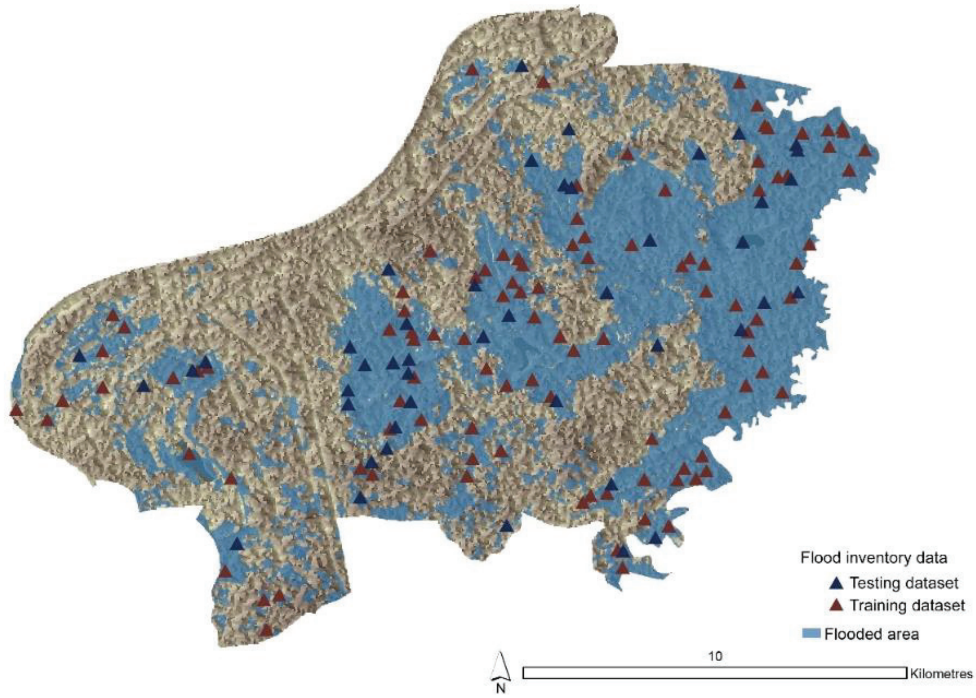


Figure 39 Flood location of Nong Khai City

As shown in Figure 39, 150 random points were created in the flooded areas with the distance of at least 100 metres between each point, as the flood inventory dataset. Then, all flood inventory dataset is divided randomly with a ratio of 70 to 30, which is the common ratio for creating FSM (Wubalem et al., 2021). 70% (105 points) were used as the training dataset for the bivariate statistical models. At the same time, 30% (45 points) were used as the testing dataset for validation. Additionally, the same number of points (150 points) were selected randomly from no-flood area and divided randomly with the ratio of 70 to 30. Precisely 70% were combined with 70% of flood inventory dataset to be used as the dependent variable in the LR model. At the same time, 30% were used as the testing dataset for validation.

5.4.1.2 Flood conditioning factors

The flood conditioning factors have an important role in guiding the model performance and accuracy (Msabi & Makonyo, 2021; Mudashiru, Sabtu, Abustan, et al., 2021). However, there are no universal flood conditioning factors to create the FSM (Msabi & Makonyo, 2021). To select flood conditioning factors, the physical characteristics that directly and indirectly affect the characteristics of surface runoff were considered (Towfiqul Islam et al., 2021), including the condition of data available (Kabenge et al., 2017; Wubalem et al., 2021) In this study, there are three steps to identify flood conditioning factors in this study, as shown in Table 12.

Table 12

Steps to identify flood conditioning factors

Step	Detail
Step 1 Literature review	Like previous studies, this study identifies the flood conditioning factors primarily by using the literature review process and selecting frequently used flood conditioning factors (Msabi & Makonyo, 2021). In the study, 49 flooding conditioning factors were collected from 38 articles that are related to flood susceptibility and flood risk analyse and were published between 2017–2021. (List of articles is presented in Appendix 1). Then the 15 most common flood conditioning factors were selected, as shown in Figure 40.
Step 2 multicollinearity analysis	The multicollinearity analysis is an important process to prepare the input data for LR analysis to achieve unbiased model results (Arora et al., 2021). Variance inflation factor (VIF) and tolerance (TOL) are common indices for detecting the multicollinearity problem. VIF> 10 and TOL < 0.1 indicate the explanatory variables have the multicollinearity problem (Arora et al., 2021; Lee et al., 2018). In this step, all data of each flood conditioning factors in step 1 were prepared in the raster format with the cell size of 100 x 100 m. The distance to the river was divided into two factors based on the topography: distance to the Mekong River and distance to the Mesuai River. In addition, the rainfall intensity was removed from the limitation of data with the suitable scale. Then, all data of flood conditioning factors were input into the training dataset for LR (210 points) and analysed the multicollinearity status. Table 13 (a) indicates that OL of the soil type and geomorphology are lower than 0.1, reflecting the multicollinearity problem between these variables. One variable needed to be removed to solve the problem. Finally, soil types were removed, and all TOL of each conditioning factor are higher than 0.100, as shown in Table 13 (B).
Step 3 Chi-square analysis	Because the conditioning factors were gathered from the worldwide case in the different contexts. Before performing the condition factors as the independent variables, the relationship between the factors and flood occurrence at the local context needs to be analysed. Pearson's Chi-square is a statistical test performed to clarify the relationship between the factor and flood occurrence in this study. Lee et al. (2018) indicate that the performance of the phenomena identification is shown through the higher Pearson's Chi-square value. As shown in Table 13 (C), slope and aspect are insignificant at 0.1 level. In contrast, other conditioning factors are significant. Therefore, the slope and aspect were removed from the independent variables in this step. The distance to the Mesuai River hits the highest value of Pearson's Chi squared, and the distance to streams shows the lowest value of Pearson's Chi Squared.

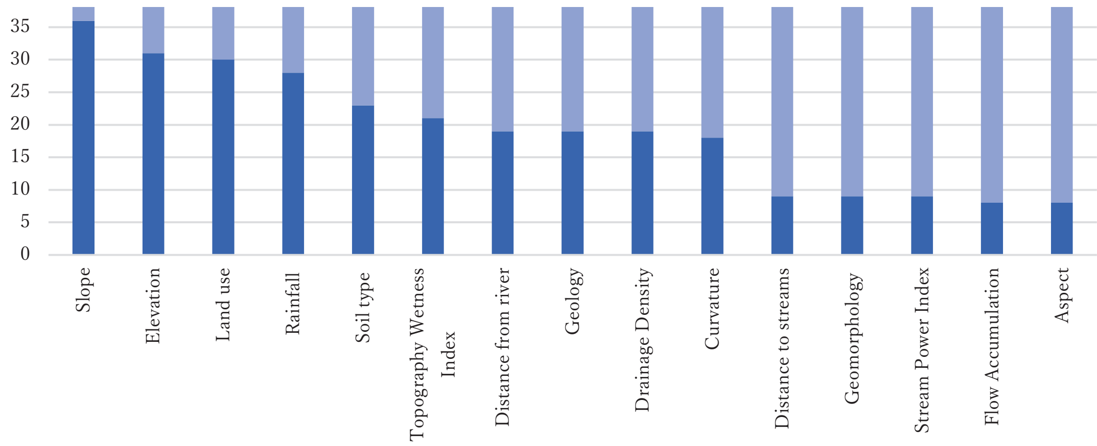


Figure 40 The 15 most common flood conditioning factors in the last five years.

Table 13

Multicollinearity analysis of the conditioning factors

Conditioning factors	Before revision (A)		After revision (B)		Pearson's Chi-squared value (C)
	TOL	VIF	TOL	VIF	
Elevation	0.54	1.86	0.56	1.79	40.52***
Slope	0.65	1.55	0.65	1.55	**7.51**
Topography Wetness Index	0.24	4.22	0.24	4.17	25.28***
Curvature	0.47	2.12	0.47	2.11	14.11***
Distance to the Mekong River	0.33	3.06	0.34	2.98	32.90***
Distance to the Mesuai River	0.30	3.28	0.32	3.16	48.80***
Distance to streams	0.83	1.21	0.83	1.21	7.37*
Drainage density	0.72	1.39	0.72	1.39	40.24***
Flow accumulation	0.46	2.17	0.46	2.17	11.70*
Aspect	0.95	1.06	0.95	1.05	**9.30**
Stream Power Index	0.326	3.066	0.328	3.045	16.17**
Land use	0.774	1.293	0.784	1.276	27.40***
Geology	0.510	1.959	0.516	1.940	26.66***
Geomorphology	**0.019**	**53.872**	0.784	1.276	38.64***
Soil types	**0.018**	**56.794**	-	-	45.01***

*P ≤ 0.05; **P ≤ 0.01; ***P ≤ 0.001

Finally, a total of twelve conditioning factors were used as the independent variables to create the FSMs: (1) elevation, (2) Topography Wetness Index, (3) curvature, (4) distance to the Mekong River, (5) distance to the Mesuai River, (6) distance to streams, (7) drainage density, (8) flow accumulation, (9) Stream Power Index, (10) land use, (11) geology, and (12) geomorphology. The detail of each conditioning factor was presented in Table 14.

Table 14

Detail of flood conditioning factors

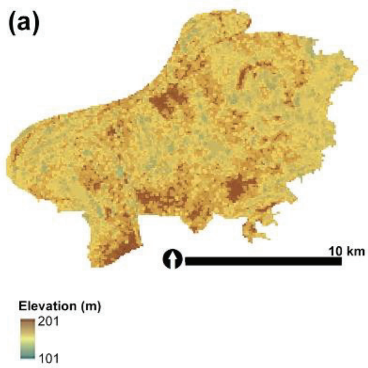
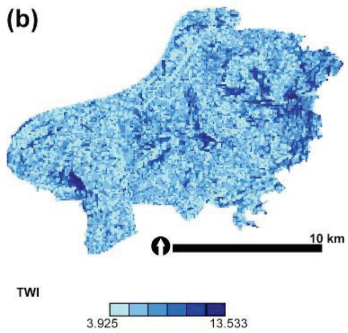
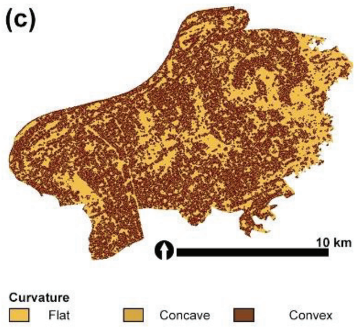
Conditioning factors	Detail
Elevation 	The elevation is a fundamental conditioning factor. It is related to the movement and direction of surface runoff. The elevation has an inverse relationship with the flood occurrence (Towfiqul Islam et al., 2021) because the surface runoff usually flows from the high-elevated areas to the low elevated areas (Msabi & Makonyo, 2021). Scholars indicate that low-lying areas have higher flood susceptibility than high-elevated ones (Sarkar & Mondal, 2020; Tehrany et al., 2013). The elevation was derived from ASTER-DEM and then was classified into six classes: 100-120, 120-140, 140-160, 160-180, 180-200, and more than 200 metres.
Topography Wetness Index: TWI 	TWI is an index to indicate the effect of the topography on the runoff generation and the flow of accumulation (Ullah & Zhang, 2020, p. 7). The TWI helps planners identify waterlogged areas in the catchment (Tehrany & Kumar, 2018, p. 5). The areas with high TWI value are more saturated with water and are usually detected in the flooded areas (Tehrany & Kumar, 2018, p. 24; Tehrany et al., 2019, p. 87). TWI is calculated with the following equation: $$TWI = \ln \left({}^{\alpha}/_{tan\beta} \right)$$ Here α is the cumulative upslope area draining through a point (per unit contour length), and $tan\beta$ is the slope angle (Rahmati et al., 2015). TWI was constructed from ASTER-DEM, and then it was categorised into six classes based on a natural breaks (jerks) scheme.
Curvature 	Curvature, which reflects topography characteristics, is the rate of change in slope gradient (Ullah & Zhang, 2020, p. 7). Curvature is a popular conditioning factor performing to create the FSM. It affects surface runoff and water accumulation (Meliho et al., 2021). It was constructed from ASTER-DEM and categorised into three types depending on the value: (1) concave; the negative value, (2) flat; the zero value, and (3) convex; the positive value. Many studies indicate that the areas with zero value usually have a higher probability of flood compared the positive and negative values (Paul et al., 2019; Rahmati et al., 2015; Tehrany & Kumar, 2018)

Table 14 (continued)

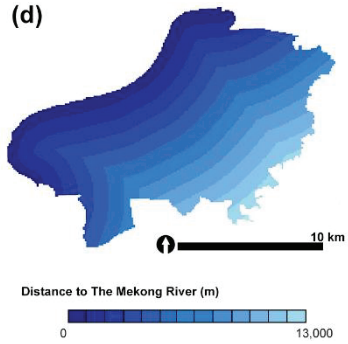
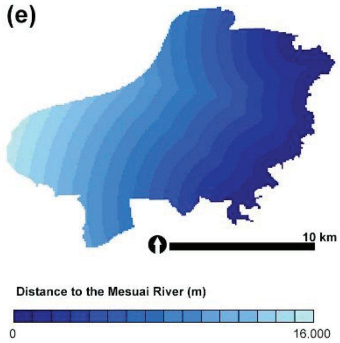
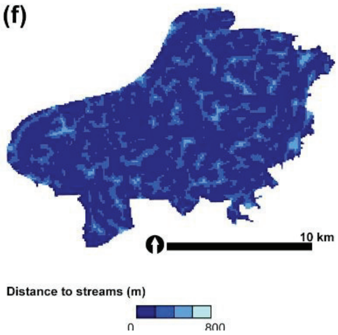
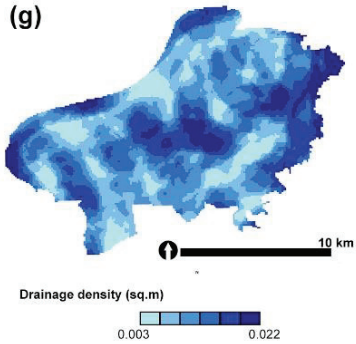
Conditioning factors	Detail
Distance to the waterways and streams • Distance to the Mekong River • Distance to the Mesuai River • Distance to streams (d)  (e)  (f)  	Generally, the flooded areas are usually adjacent to the waterways and risk being engulfed when the water overflow (Kabenge et al., 2017). These areas have a high possibility of encountering floods. Hence, the distance to waterways is a crucial conditioning factor that is usually performed to analyse flood-prone area (Kabenge et al., 2017; S. Samanta et al., 2018; Wubalem et al., 2021). The distance to waterways was generated from the Euclidean distance tool in ArcMap and categorised into classes every 1 kilometre. The distance the Mekong River and the Mesuai River was used as the distance to waterway by dividing it into two variables. The distance to streams was constructed from ASTER-DEM and categorised into four classes every 200 metres: 0-200, 200-400, 400-600, and 600-800 metres.
The drainage density (g)  	The drainage density is an index indicating the intensity and the concentration of the streams per unit (Paul et al., 2019). It is a key conditioning factor in flood occurrence (Msabi & Makonyo, 2021). The flooded areas are directly related to the drainage density and surface runoff (Ullah & Zhang, 2020, p. 7). The higher runoff in the areas with the higher density of drainage system causes these areas to have a high opportunity to face flood (Costache & Zaharia, 2017; Rahmati et al., 2015; Ullah & Zhang, 2020). The drainage density was created from the drainage network which was developed from ASTER-DEM and then categorised into six classes based on a natural breaks (jerks) scheme.

Table 14 (continued)

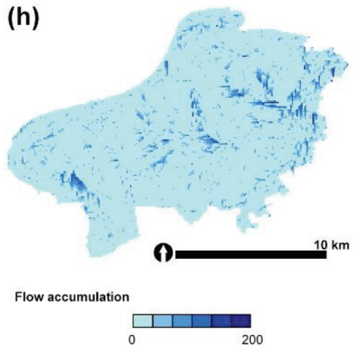
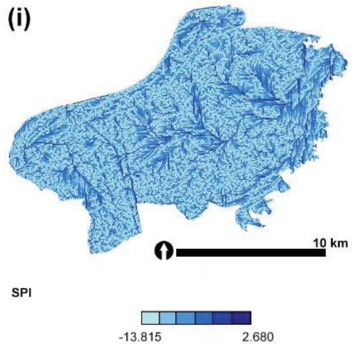
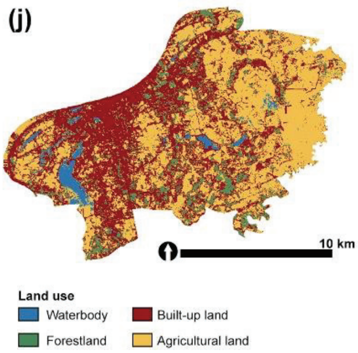
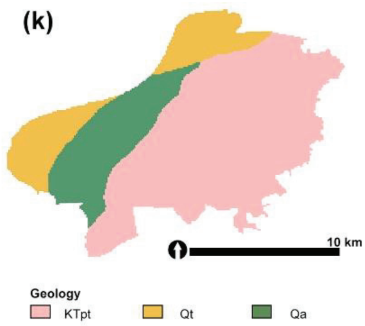
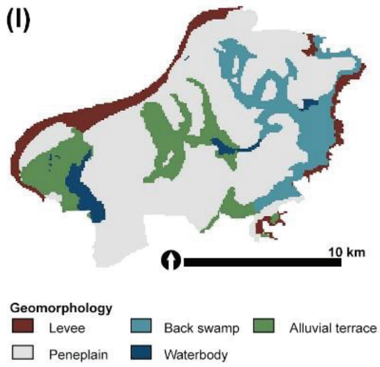
Conditioning factors	Detail
Flow accumulation  	Flow accumulation is the total amount of water flowing along the slope (Meliho et al., 2021). Flow accumulation is directly related to flood occurrence (Kabenge et al., 2017). The areas with a high flow accumulation value are highly susceptible to flood. The flow accumulation was constructed from ASTER-DEM and categorised into six classes based on a natural breaks (jerks) scheme.
Stream Power Index: SPI  	SPI presents the potential erosive power of the streams in the catchment (Tehrany et al., 2019, p. 87), based on assumed discharge, which directly triggers the erosion and the river incision (Paul et al., 2019). SPI was constructed from ASTER-DEM and categorised into six classes based on a natural breaks (jerks) scheme by using the following equation: $SPI = A_s \tan(slope)$ Here, A_s is the specific catchment area and slope in degrees (Paul et al., 2019)
Land use  	Land use is an important physical component that influences flood because it controls the infiltration and evapotranspiration and generates the surface runoff (Arora et al., 2021; Rahmati et al., 2015; S. Samanta et al., 2018; Towfiqul Islam et al., 2021). The land use data in this study is the land use in 2017. It was generated from the Landsat satellite images using the supervised classification with the maximum likelihood classifier (MLC) algorithm (See details of land-use map in chapter 4). Land use in Nong Khai is comprised of four types: (1) the water bodies, (2) the built-up lands, (3) the forest and natural lands, and (4) the agricultural lands.
Geology  	Geology is a fundamental conditioning factor. The character of geology is related to the permeability of the rock and the hydrological process. The highly permeable material, such as clay, has high flood susceptibility level (Rahmati et al., 2015). The geology data was digitised from the 2009 Geological Map of Changwat Nong Khai of Department of Mineral Resource, Thailand, with the scale of 1:250,000. According to the geology map, four types of geology are found in Nong Khai City: (1) KTpt: PhuThok Formation in Khorat Group, (2) Qt: Terrace deposits, and (3) Qa: Alluvial deposit

Table 14 (continued)

Conditioning factors	Detail
Geomorphology 	Geomorphology is a crucial physical component influencing the local flooding patterns (Nagumo & Sawano, 2016; Oya, 1966). There is a strong relationship between flood occurrence and geomorphology characteristics (Arora et al., 2021). Hence, flood-prone areas were detected from the characteristic of geomorphology (Kumaki & Kubo, 2019; Oya, 1966). However, it was ranked as the least important factor in the study of Das (2019). In this study, the geomorphology was produced from the soil data that have a relationship to the geomorphology (Hydro and Agro Informatics Institute, 2018; Land Development Department, 2015). The soil data is the shapefile data with 1:25,000 deriving from database of Land development department (http://dinonline.ldd.go.th). Based on the relationship between soil type and geomorphology, The geomorphology consists of five types: (1) levee, (2) back swamp, (3) alluvial levee, (4) peneplain, and (5) waterbodies

5.4.2 Model

To create the FSMs, the data were adopted to calculate weight values through seven models. Then, the conditioning factors were overlaid in the GIS framework based on the weight value of each model to create the final FSM. Models in this study are popular statistical modelling methods used to make the hazard susceptibility map (Tehrany et al., 2017). It comprises seven models: three bivariate statistical models, one multivariate statistical model, and three ensembled models that combines three bivariate models and a multivariate statistical model.

5.4.2.1 Frequency ratio and Modified frequency ratio

Frequency ratio (FR) and modified frequency ratio (MoFR) is a bivariate statistical model (Mudashiru, Sabtu, Abustan, et al., 2021). FR is a common method to detect areas susceptible to disasters such as floods and landslides (Rahmati et al., 2015). In addition, it was used as the based model to be compared with the ensembled or developed model (Arora et al., 2021).

FR presents the level of flood-prone areas from the ratio of the presence and the absence of an interesting phenomenon by using the following equation:

$$FR = {}^{f/tf}\!\big/_{x/tx} \quad (5.1)$$

Here f is the amount of flood sample in the sub-class of flood conditioning factor; tf is the total of flood dataset; x is the number of areas in the sub-class of the flood conditioning factor; tx is the total areas.

The higher value of FR presents the stronger relationship between the class of conditioning factor and flood occurrence, especially a value greater than 1 shows a strong relationship between flood occurrence and the class of conditioning factor (Tehrany et al., 2013).

Modified Frequency Ratio (MoFR) is used to create the susceptibility map for landslides in previous study (Sifa et al., 2020). However, the studies about FSM are lacking. MoFR is similar to the conventional FR. But the value of FR was normalised to a range of 0-1 and added to create the FSI. MoFR can be calculated by using the following equation:

$$MoFR = {FR_i}/{\sum FR} \quad (5.2)$$

Here Fr_i is the frequency ratio of a $factor_i$, and $\sum FR$ is the total value of the frequency ratio of the class (Sifa et al., 2020).

The Flood Susceptibility Index (FSI) of FR and MoFR can be calculated by finding the total frequency value of all conditioning factors using the following equation:

$$FSI_{FR} = \sum_{i=1}^{n} FR_i \quad (5.3)$$

$$FSI_{MoFR} = \sum_{i=1}^{n} MoFR_i \quad (5.4)$$

Here FSI is the Flood Susceptibility Index, Fr_i is the frequency ratio of a $factor_i$, $MoFr_i$ is the modified frequency ratio of a $factor_i$, and n is the total number of conditioning factors.

5.4.2.2 Weight of Evidence

Weight of Evidence (WoE) is a bivariate statistical model similar to the FR (Mudashiru, Sabtu, Abustan, et al., 2021). It is usually performed to indicate the areas susceptible to disasters such as landslide and flood (Costache & Zaharia, 2017). It is a probabilistic approach based on a log-linear form of Bayes' rules (Rahmati et al., 2015). The weight value of each class is calculated from the presence or absence of a flooding pixel in the class (Costache & Zaharia, 2017).

The final weight value of WoE is originally constructed from two components: The positive (W^+) and negative (W^-) weight (Rahmati et al., 2015). It can be calculated with the following equation:

$$W^+ = \ln\left(\frac{P\{B|A\}}{P\{B|\bar{A}\}}\right) \quad (5.5)$$

$$W^- = \ln\left(\frac{P\{\bar{B}|A\}}{P\{\bar{B}|\bar{A}\}}\right) \quad (5.6)$$

Here P is the probability, B is the presence and $\bar{B}$ is the absence of the class of conditioning factor. Similarly, A is the presence and $\bar{A}$ is the absence of flood occurrence. The class has an impact on flood occurrence when Wi^+ is positive and has no impact when Wi^+ is negative. While Wi^- indicates the level of negative correlation between the class and the flood occurrence (Rahmati et al., 2015).

To indicate the overall spatial correlation between the class and flood occurrence, Contrast value (C) between Wi^+ and Wi^- was calculated with the following equation:

$$C = (W^+) - (W^-) \quad (5.7)$$

If C is a positive value, it reflects that there is a positive spatial association between the class and flood occurrence, while the negative will reflect the contrast relationship (Pradhan et al., 2010, p. 207).

In addition, the standardised value of C (S(C)) was calculated as the ratio of C to its standard deviation with the following equation(Vakhshoori & Zare, 2016).

$$S(C) = \sqrt{S^2(W^+) + S^2(W^-)} \quad (5.8)$$

Where $S^2(W^+)$ and $S^2(W^-)$ are the variances of with W^+ and W^- as

$$S^2(W^+) = \frac{1}{P\{B|A\}} + \frac{1}{P\{B|\bar{A}\}} \quad (5.9)$$

$$S^2(W^-) = \frac{1}{P\{\bar{B}|A\}} + \frac{1}{P\{\bar{B}|\bar{A}\}} \quad (5.10)$$

The relative certainty of the posterior probability of each class was calculated from the value of standardised contrast by using the following equation

$$W_{final} = \left(\frac{C}{S(C)}\right) \quad (5.11)$$

Here the value from C/S(C) guides the significance level of the spatial correlation between class and flood occurrence.

After the W_{final} of each class was calculated in every pixel. the FSI of WoE was calculated by combining the value of W_{final} from the following equation:

$$FSI_{woe} = \sum_{i=1}^{n} W_{final} \quad (5.12)$$

Here FSI is the Flood Susceptibility Index and W_{final} is the final weight from WoE (Rahmati et al., 2015).

5.4.2.3 Logistic Regression

Logistic Regression (LR) is a multivariate statistical model that is a fundamental method usually adopted to create the disaster susceptibility map with the reliable result (Wubalem et al., 2021, p. 1675). LR is applied to study how the conditioning factors (independent variables) are related to the occurrence of the flood (dependent variables) in the form of dichotomous. The relationship between the independent and dependent variables was calculated using the following regression model in IBM SPSS Statistics 27.

$$P = \left(Y = 1 \middle| X_1, X_2, \ldots, X_k\right) = \frac{1}{1+e^{-\left(\alpha+\sum_{i=1}^{K}\beta_i X_i\right)}} \quad (5.13)$$

where P $\left(Y = 1 \middle| X_1, X_2, \ldots, X_k\right)$ is the probability of the dependent variable being 1 given $(X_1, X_2, \ldots, X_k)$; X_i is an independent variable reflecting the conditioning factors of flood occurrence; and β_i is the coefficient for the variable X_i, which can be used to interpret the influence degree of a determinant. A positive value indicates that the independent variable supports the probability value of flood susceptibility whereas a negative value indicates the contrast effect.

In this study, 210 random points of historical flood areas have been considered as a dependent variable. Precisely, 105 points with flood occurrence were coded as one, and 105 points with non-flood occurrence were coded as zero. At the same time, the data of the condition factors were attached to each point to perform as the independent variables.

5.4.2.4 Ensemble model

The bivariate statistical model, such as FR and WoE, cannot determine the relationship between variables (Arora et al., 2021). Therefore, scholars recommend integrating the bivariate statistical model with the multivariate statistical model like LR that can determine the relationship of each variable with the flood occurrence (Arora et al., 2021). In this study, the ensemble model consists of three models: Ensemble LR-FR, Ensemble LR-MoFR, and Ensemble LR-WoE. The weight value from all bivariate statistical models was used as each independent variable's input data to integrate the bivariate statistical model and LR. Then LR was performed to calculate the weight value of each conditioning factor.

5.4.3 Validation

The model evaluation is an important process of FSM development. In this process, the FSMs were validated and their predictive capabilities were checked (Mudashiru, Sabtu, Abustan, et al., 2021). The receiver operating characteristics (ROC) method is commonly used to evaluate the performance of the model by comparing it with the existing flood data (Wubalem et al., 2021). ROC evaluates the model based on assessing true- and false-positive rates (Tehrany et al., 2013). The area under the curve (AUC) of the relationship between true- and false- positive rates ranges from 0.5 to 1.0. The value of 1 presents the highest accuracy. The model that can achieve the AUC value closer to 1 has a high, trustable performance with greater precise (Tehrany et al., 2013).

In this study, the FSM from every model has been validated using three criteria: overall rate, success rate, and prediction rate. The overall rate was obtained using the overall dataset. The success rate was obtained using the training dataset while the prediction rate was obtained using the testing dataset. Finally, only one FSM from the model that can produce the highest accuracy rate in the study was chosen.

5.4.4 Classification of flood susceptibility level

After the FSM with the highest accuracy rate was derived from step 5.4.3. The techniques to classify the level of flood susceptibility were performed to create the final FSM. There are many used classification methods such as natural breaks(Kabenge et al., 2017; Paul et al., 2019; Wubalem et al., 2021), quantile method(R. K. Samanta et al., 2018; Tehrany, Lee, et al., 2014;

Tehrany et al., 2013), geometrical interval(Costache & Zaharia, 2017), and others. The technique that can produce the highest ratio of flooding in the very high susceptibility class was selected as the suitability technique (Costache & Zaharia, 2017). In many cases, the suitability technique was chosen from the highest Chi-squared value (Basofi et al., 2015; Sarkar & Kanungo, 2004).

In this study, the FSM was classified according to the levels of flood susceptibility through five techniques: (1) positive and negative value, (2) hotspot area, (3) natural breaks, (4) quantile classification, and (5) equal interval. Then Chi-squared value of each technique was calculated. The model that achieves the highest Chi-squared value was used to classify the flood susceptibility and create the final FSM.

5.5 Results

This part describes two main results: 1) the spatial relationship between conditioning factors and floods in Nong Khai City and 2) the FSMs of Nong Khai City.

5.5.1 Spatial relationship between conditioning factors and flood occurrence

The spatial relationship between conditioning factors and flood occurrence was analysed from the weight value patterns. This section is divided into two sub-headings based on the statistical models: (1) bivariate statistical model and (2) multivariate statistical and ensemble model. Based on the character of each statistical model, the information about the spatial relationship between conditioning factors and flood occurrence is different. The bivariate statistical models determine the weight value of flood susceptibility in every class of each conditioning factor. The multivariate statistical and ensemble models determine only the weight values of the significant conditioning factors. In addition, the weight values deriving from the bivariate statistical models are presented at class level. The weight values from the multivariate statistical and ensemble models are presented at the conditioning factor level. Every conditioning class has an impact on the flood occurrence with the same weight value.

5.5.1.1 Spatial relationship between conditioning factors and floods in terms of bivariate statistical models

In terms of the bivariate statistical models, 105 sample points of flood inventory were analysed to determine how much the classes of 12 conditioning factors affect the flood occurrence, as shown in Table 15.

Table 15

Weight of conditioning factors derived from the bivariate statistical models

	Conditioning factor	Classes	FR	MoFR	WoE		Conditioning factor	Classes	FR	MoFR	WoE
a	Elevation (metres)	100-120	0.00	0.00	-	e	(continued)	12,000-13,000	0.00	0.00	-
		120-140	2.84	0.52	1.82			13,000-14,000	1.27	0.09	0.49
		140-160	1.38	0.25	4.08			14,000-15,000	0.76	0.05	-0.38
		160-180	0.45	0.08	-4.26			15,000-16,000	0.81	0.06	-0.21
		180-200	0.84	0.15	-0.45	f	Distance to streams (metres)	0-200	1.09	0.38	1.62
		>200	0.00	0.00	-			200-400	0.67	0.24	-1.73
b	TWI	3.925 - 5.357	0.69	0.07	-1.85			400-600	1.07	0.38	0.12
		5.357 - 5.960	0.86	0.08	-1.18			600-800	0.00	0.00	-
		5.960 - 6.864	0.88	0.09	-0.60	g	Drainage density (sq.m)	0.003 - 0.006	0.45	0.07	-2.06
		6.864 - 8.032	1.89	0.19	2.73			0.006 - 0.009	0.48	0.07	-2.73
		8.032 - 10.105	2.31	0.23	3.09			0.009 - 0.010	0.91	0.14	-0.55
		10.105 - 13.533	3.51	0.35	1.78			0.010 - 0.013	1.28	0.20	1.35
c	Curvature	Concave	0.92	0.37	-2.15			0.013 - 0.015	1.63	0.25	2.75
		Flat	1.60	0.63	2.23			0.015 - 0.022	1.78	0.27	2.14
		Convex	0.00	0.00	-	h	Flow accumulation	0 - 2.352	0.91	0.06	-2.63
d	Distance to the Mekong River (metres)	0-1,000	0.31	0.02	-2.14			2.352 - 9.41	1.42	0.10	1.27
		1,000-2,000	0.43	0.03	-1.98			9.411 - 20.392	2.09	0.14	1.83
		2,000-3,000	0.51	0.03	-1.74			20.392 - 42.352	2.62	0.18	1.37
		3,000-4,000	0.92	0.06	-0.28			42.352 - 78.431	7.87	0.53	2.06
		4,000-5,000	0.98	0.06	-0.07			78.431 - 200	0.00	0.00	-
		5,000-6,000	1.40	0.09	1.41	i	SPI	-13.815 - -9.740	0.85	0.09	-2.91
		6,000-7,000	1.57	0.10	1.90			-9.740 - -6.958	2.50	0.25	1.59
		7,000-8,000	1.34	0.08	1.00			-6.958 - -2.947	1.53	0.16	1.24
		8,000-9,000	0.46	0.03	-1.37			-2.947 - -1.718	1.57	0.16	1.61
		9,000-10,000	1.20	0.07	0.49			-1.718 - -0.619	1.11	0.11	0.26
		10,000-11,000	1.57	0.10	1.13			-0.619 - 2.680	2.23	0.23	1.81
		11,000-12,000	5.37	0.33	5.03	j	Land use	Waterbody	1.95	0.33	2.47
		12,000-13,000	0.00	0.00	-			Built-up land	0.66	0.11	-4.81
e	Distance to the Mesuai River (metres)	0-1,000	2.55	0.18	5.14			Forest and natural lands	1.67	0.28	1.28
		1,000-2,000	1.46	0.10	1.35						
		2,000-3,000	0.38	0.03	-1.72			Agricultural land	1.62	0.28	3.47
		3,000-4,000	0.85	0.06	-0.45	k	Geology	KTpt	1.36	0.65	4.55
		4,000-5,000	0.84	0.06	-0.46			Qt	0.49	0.23	-2.35
		5,000-6,000	1.33	0.09	0.97			Qa	0.26	0.12	-3.32
		6,000-7,000	1.60	0.11	1.76	l	Geomorphology	Levee	0.66	0.11	-1.06
		7,000-8,000	0.57	0.04	-1.33			Back swamp	2.20	0.37	4.57
		8,000-9,000	0.50	0.03	-1.45			Alluvial terrace	1.46	0.25	1.91
		9,000-10,000	0.54	0.04	-1.29			Peneplain	0.69	0.12	-3.89
		10,000-11,000	0.00	0.00	-			Waterbody	0.91	0.15	-0.16
		11,000-12,000	0.91	0.06	-0.18						

5.5.1.1.1 Patterns of the spatial relationship

Although each model produces the weight value from the same input data, the spatial relationship patterns between the conditioning factors and the flood occurrence are varied based on the algorithm of each model, as shown in Table 15.

Regarding the influence patterns of FR and WoE, we found that in the overview the number of classes with the value greater than 1 in FR and the positive value in WoE is the same. 37 classes of the conditioning factors have a positive and strong relationships with flood occurrence. 33 classes have a negative relationship and little relationship with flood occurrence, and 8 classes do not affect flood occurrence. However, considering the ranking of each weight value, only 13 classes out of 78 classes are in the same ranks in the FR and WoE models.

Regarding the patterns of the weight values in each condition factor, curvature, geology, geomorphology are only three conditioning factors out of twelve conditioning factors that share the same pattern of weight value. In comparison, other conditioning factors show different patterns.

Regarding the spatial relationship between conditioning factors and flood occurrence, there is no specific correlation between flood occurrence and the conditioning factors in the groups of distance to Mekong River, distance to Mesuai River, and distance to streams. Their weight values are varied and random. It's noteworthy that although all of these conditioning factors are the distance to waterways, they show different relationship patterns with the flood occurrence. The classes with the nearest distance to Mesuai River and streams has the highest values while the weight values of the classes with further distance fluctuated. For the distance to the Mekong River, the classes within 5 kilometres to the river have a negative relationship with or less impact on the flood occurrence while the weight value of the class with the distance between 11-12 kilometres is the highest.

The strong relationship between the conditioning factors and flood occurrence was found in TWI, drainage density, and flow accumulation deriving from FR and MoFR. Their weight increased as the values increased. For other conditioning factors, we found a moderate correlation with flood occurrence. Although the patterns of the weight values do not parallel with the values of the conditioning factors in every class, their patterns can be inferred from the turning point that changes the influence patterns of flood occurrence.

For example, the weight values of TWI from WoE indicates that the values lower than 6.864 have a negative pattern while the values greater than 6.864 have a positive effect on flood occurrence with the various magnitude of weight values. Like the drainage of density from WoE, the values lower than 0.010 have a negative pattern while the values greater than 0.010 have a positive effect on flood occurrence. Flow accumulation from WoE is also a conditioning factor that has a moderate positive correlation. The weight values indicate that the flow accumulation between 0-2.352 has a negative relationship while the values greater than 2.352 have a positive relationship. However, the patterns of the positive weight values are varied and do not depend on the increase of flow accumulation values. The weight values of the SPI from all models that are lower than -9.740 also have a negative relationship while the weight values of the SPI which are greater than -9.740 have a positive relationship.

Not only the moderate positive relationship, the moderate negative relationship between the conditioning factors and flood occurrence was also found in the elevation. The weight values of the elevation from every bivariate model indicate that the areas with the elevation lower than 160 metres have a positive or strong relationship with flood occurrence while the elevation greater than 160 metres has a negative or little relationship with flood occurrence.

Regarding the conditioning factors with categorical variables, the first conditioning factor is the curvature. All bivariate statistical models indicate that flat surface has a strong or positive relationship with the flood occurrence while concave surface has a negative relationship or less impact on the flood occurrence. The second conditioning factor is the land-use types. Waterbodies, forest and natural lands, and agricultural lands have a positive relationship. In comparison, the built-up lands have a negative relationship or less influence on the flood occurrence. The third is the geology, KTpt which is the main geology in Nong Khai City has a strong and positive relationship with flood occurrence. Meanwhile, Qt and Qa have a little, and negative relationship with flood occurrence. The last conditioning factor is geomorphology. The back swamp and alluvial terrace have a strong and positive relationship with the flood occurrence, while other geomorphologies have little and negative relationships.

5.5.1.1.2 Magnitude of conditioning factors on flood occurrence

Table 15 shows that the magnitude of the classes of the conditioning factors on flood occurrence is different among the three models. The top ten classes of the highest weight values deriving from three models are different, as shown in Table 16. The back swamp and the distance to the Mekong River (11-12 kilometres) are the only two classes found in every model.

For FR, the flow accumulation between 42.352 - 78.431 has the highest weight value. However, it ranks third in the MoFR model and ranks thirteenth in the WoE model. The KTpt of geology ranks first in the MoFR model while it ranks fourth the WoE model and ranks 29th in the FR model. For WoE, we found that the distance to the Mesuai River ranks first while it ranks 6th rank in FR and 25th in MoFR.

Table 16

Classes of the top weight values from bivariate statistical models

Ranking	FR		MoFR		WoE	
	Conditioning factors	Class	Conditioning factors	Class	Conditioning factors	Class
1	Flow accumulation	42.352 - 78.431	Geology	KTpt	Distance to Mesuai River	0-1,000
2	**Distance to Mekong River**	**11,000-12,000**	Curvature	Flat	**Distance to Mekong River**	**11,000-12,000**
3	TWI	10.105 - 13.533	Flow accumulation	42.352 - 78.431	**Geomorphology**	**Back swamp**
4	Elevation	120-140	Elevation	120-140	Geology	KTpt
5	Flow accumulation	20.392 - 42.352	Distance to streams	0-200	Elevation	140-160
6	Distance to Mesuai River	0-1,000	Distance to streams	400-600	Land use	Agricultural lands
7	SPI	-9.740 - -6.958	**Geomorphology**	**Back swamp**	TWI	8.032 - 10.105
8	TWI	8.032 - 10.105	Curvature	Concave	Drainage density	0.013 - 0.015
9	SPI	-0.619 - 2.680	TWI	10.105 - 13.533	TWI	6.864 - 8.032
10	**Geomorphology**	**Back swamp**	**Distance to Mekong River**	**11,000-12,000**	Land use	Waterbodies

The weight values of FR point out that TWI, SPI, and flow accumulation are crucial in analysing flood-prone areas. Two classes from each conditioning factor are detected in the top ten weight values. The great influence of TWI also occurs in the WoE; two classes of TWI and land-use types were found in the top ten weight values. At the same time, the patterns of the highest weight values in the classes of MoFR are different. Two classes of curvature and the distance to streams are crucial in analysing the flood-prone areas.

5.5.1.2 Spatial relationship between conditioning factors and floods in terms of multivariate and ensemble statistical models

Table 17 shows that seven conditioning factors are regarded as the significant conditioning factors. The elevation and geology are the basic conditioning factors that are significant in every model. The distance to Mesuai River is a conditioning factor in three models except LR. Like the drainage density which is significant in three models except the ensemble LR-WoE. While Land use is a conditioning factor in the ensemble LR-FR and the ensemble LR-MoFR. Other conditioning factors such as the distance to the Mekong River and geomorphology are a significant conditioning factor in LR and the ensemble LR-WoE, respectively.

Table 17

Result of logistic model and ensemble statistical model

		LR	Ensemble LR-FR	Ensemble LR-MoFR	Ensemble LR-WoE
Number of Factors		4	5	5	6
Significant conditioning factors	**Elevation**	**-0.091*** **	**2.041*** **	**11.245*** **	**0.237*** **
	Distance to Mekong River	0.000183*	-	-	-
	Distance to Mesuai River	-	1.226***	17.613***	0.379***
	Drainage density	263.648***	1.393**	9.082**	-
	Land use	-	0.791*	4.662*	-
	Geology	**-0.689***	**1.829*** **	**3.845*** **	**0.249*** **
	Geomorphology	-	-	-	0.191**
Constant		11.823**	-7.673***	-7.674***	-0.623*
Accuracy		75.2	78.1	78.1	77.1
Nagelkerke R Square		0.454	0.557	0.557	0.509

*P ≤ 0.05; **P ≤ 0.01; ***P ≤ 0.001

For LR, elevation and geology negatively correlate with flood occurrence. After calculating the influence of each conditioning factor by using their weight values with the values of each conditioning factor, we found that the elevation is an impactful influence on flood occurrence, followed by the drainage density, the distance to the Mekong River, and geology, respectively. The highest impact of elevation on the flood occurrence also appears in the ensemble LR-FR. The second impactful influence of the ensemble LR-FR is the geology, followed by drainage density, the distance to the Mesuai River, and land use types, respectively. For the ensemble LR-MoFR and ensemble LR-WoE models, the distance to the Mesuai River is the most impactful conditioning factor. The influence of other conditioning factors is different.

Comparing the patterns of conditioning factors in the bivariate statistical models, multivariate statistical models, and ensemble models, we found that although the ensemble models were developed from the weight values of the bivariate statistical models, many important conditioning factors omitted in the multivariate and ensemble models. For example, the flow accumulation, SPI, and TWI — which have the highest weight values in some classes in the bivariate statistical models— are not significant in the LR and ensemble models.

5.5.2 FSMs of Nong Khai City

The FSMs were created with seven models, as shown in Figure 41. The flood susceptibility index of each model is presented in Table 18. In the overview, the patterns of flood susceptibility levels are similar. The areas highly susceptible to flood are in the southeastern region. In contrast, the areas lowly susceptible to flood are in the original and surrounded areas, especially in the western region.

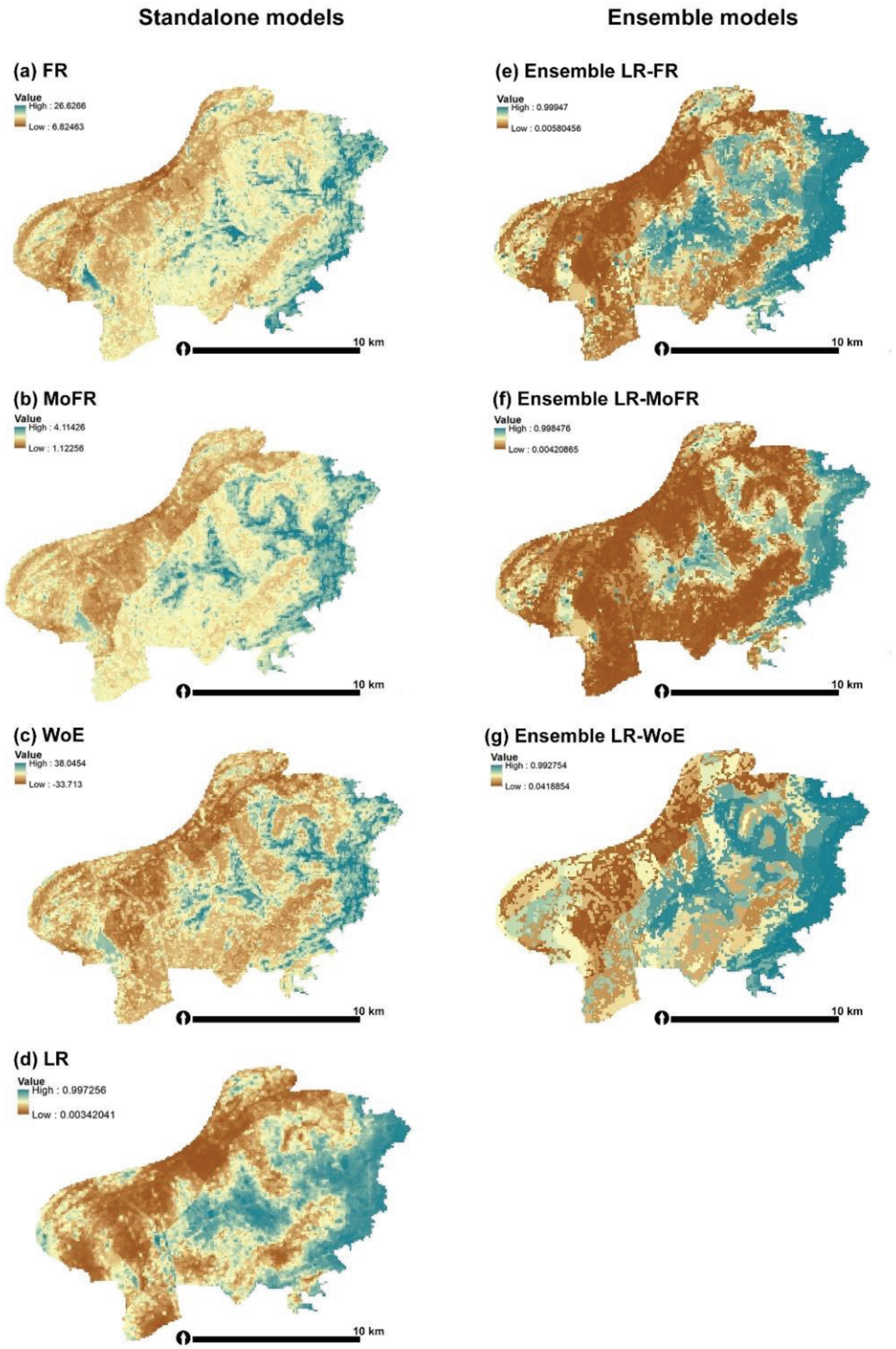


Figure 41 FSMs from all models

Table 18

The flood susceptibility index of each model

Bivariate statistical model	Flood susceptibility index	Multivariate statistical model and ensemble model	Flood susceptibility index
FR	6.825 — 26.627	LR	0.003 — 0.997
MoFR	-33.713 — 38.045	Ensemble LR-FR	0.005 — 0.999
WoE	1.123 —4.114	Ensemble LR-MoFR	0.004 — 0.998
		Ensemble LR-WoE	0.041 — 0.993

Every model can create the FSMs with an acceptable accuracy rate in terms of success rate and prediction rate. All of the accuracy rates are over 0.800. Table 19 and Figure 42 present the models that achieve the best and worst accuracy for success rate and prediction rate are different. For the success rates, which are analysed from the training dataset, the ensemble LR-FR is the best model because it creates the FSM with the highest value of AUC at 0.8823, followed by the WoE and MoFR with the accuracy rates of 0.8713 and 0.8689, respectively. LR creates the FSM with the lowest value of 0.8384. At the same time, the prediction rates, which are analysed from the testing dataset, demonstrates that the WoE is the best model. It creates the FSM with the highest value of AUC at 0.8538, followed by MoFR and the ensemble LR-WoE. In contrast, FR is the worst model in terms of the prediction rate creating the FSM with the lowest value of 0.8005. So, to select the most suitable model to create the FSM in this study, the training data and testing data were combined to analyse the overall accuracy rate. For the overall rate, the WoE can create the FSM with the highest accuracy of 0.8675, followed by the ensemble LR-FR and MoFR with close accuracies of 0.8674 and 0.8659, respectively. In contrast, the FR is the worst model with the lowest accuracy of 0.8288. Hence, this study adopted the FSM from the WoE model to classify flood susceptibility at the last step.

Table 19

AUC value of each model

Model	Accuracy type		
	Success rate	Prediction rate	Overall
FR	0.8395	0.8005	0.8288
MoFR	0.8689	0.8519	0.8659
WoE	0.8713	0.8538	0.8675
LR	0.8384	0.8119	0.8309
Ensemble LR-FR	0.8823	0.8207	0.8674
Ensemble LR-MoFR	0.8634	0.8185	0.8504
Ensemble LR-WoE	0.8620	0.8398	0.8540

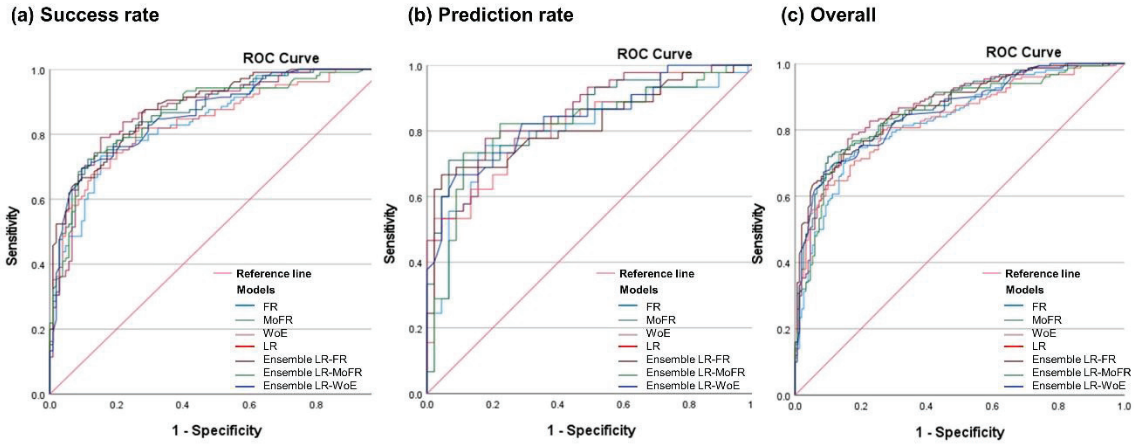


Figure 42 The ROC curve of overall rate, success rate, and prediction rate

Five techniques were performed to classify the flood susceptibility of the FSM from WoE, as shown in Figure 43. The natural breaks, the quantile classification method, and the equal interval are the auto-functions in ArcMap adopted to classify the data into five classes. At the same time, this study also classifies flood susceptibility by using the values of flood susceptibility index: the positive and negative values. The positive values were coded as the high flood susceptibility, and the negative values were coded as the low flood susceptibility. The classification with the hotspot area is also adopted to classify the flood susceptibility based on the spatial clusters that have high flood susceptibility index. The clusters were analysed by using the Hot Spot Analysis function in ArcMap. The hotspot areas were coded as the high flood susceptibility, and others were coded as the low flood susceptibility. As shown in Table 20, the natural breaks achieve the highest chi-squared value, followed by the quantile method and equal interval, respectively. To confirm the capacity of the natural breaks in terms of flood susceptibility classification, the ratios of the flood occurrence in the flood susceptibility classes from the natural breaks technique were calculated as shown in Table 21 and Figure 44. It indicates that the areas with very high flood susceptibility have the highest flood frequency ratio, followed by high, moderate, low, and very low. Hence, the natural breaks technique was used to classify the level of flood susceptibility to create the final FSM.

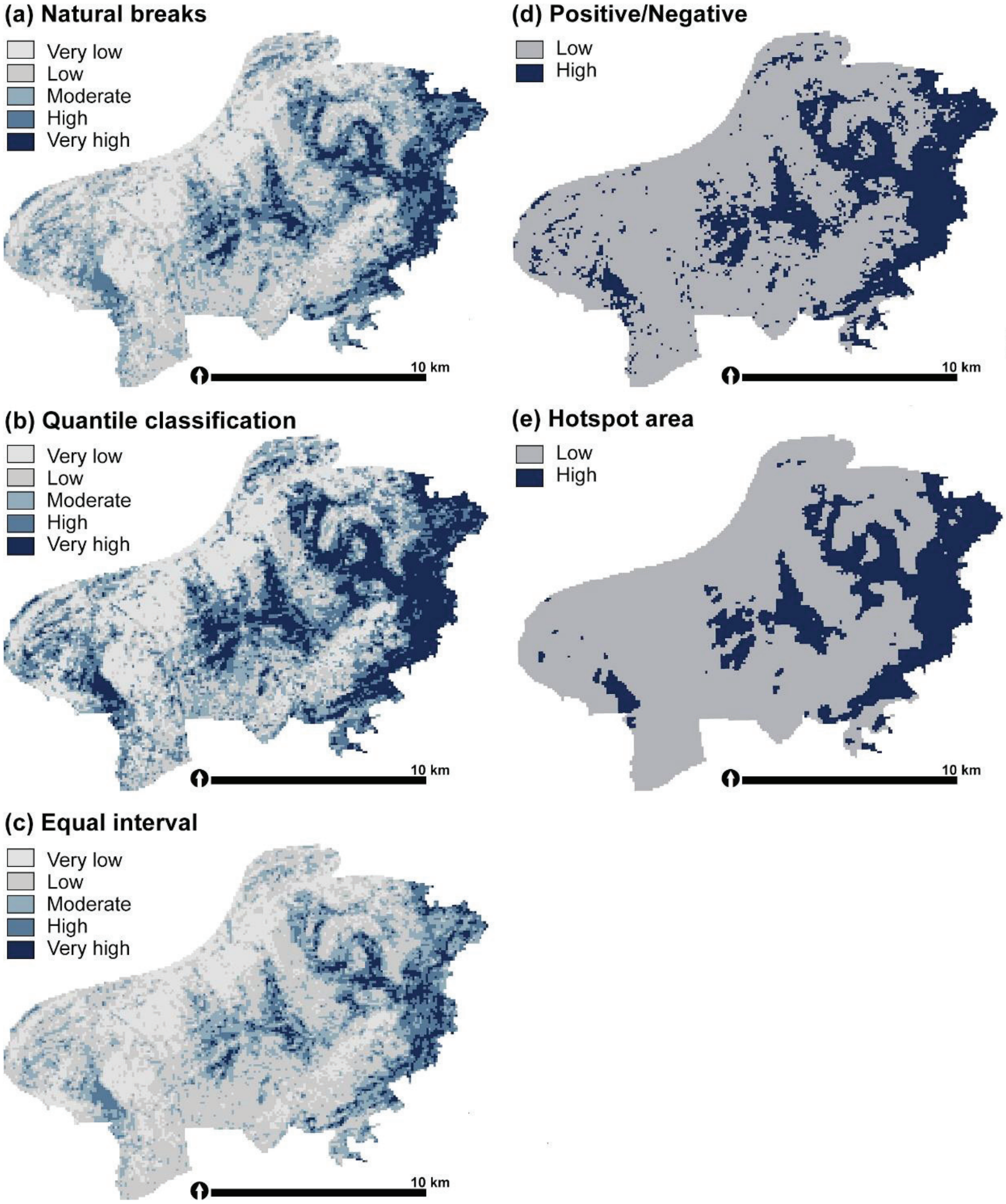


Figure 43 Classes of flood susceptibility based on five classification techniques

Table 20

Chi-squared values of the classification techniques

Number of classes	2		5		
Technique	Positive/ Negative	Hotspot area	Natural breaks	Quantile classification	Equal interval
Chi-squared value	3112.771	3251.445	4348.18	4295.394	4169.21

Table 21

Distribution of flood susceptibility class and flood inventory

Flood susceptibility class	Area		Flood occurrence (pixel)	Ratio of flood frequency
	Pixel	%		
Very low	3428	18.08	847	0.25
Low	6185	32.63	2856	0.46
Moderate	4369	23.05	2880	0.66
High	3205	16.91	2800	0.87
Very high	1770	9.34	1737	0.98

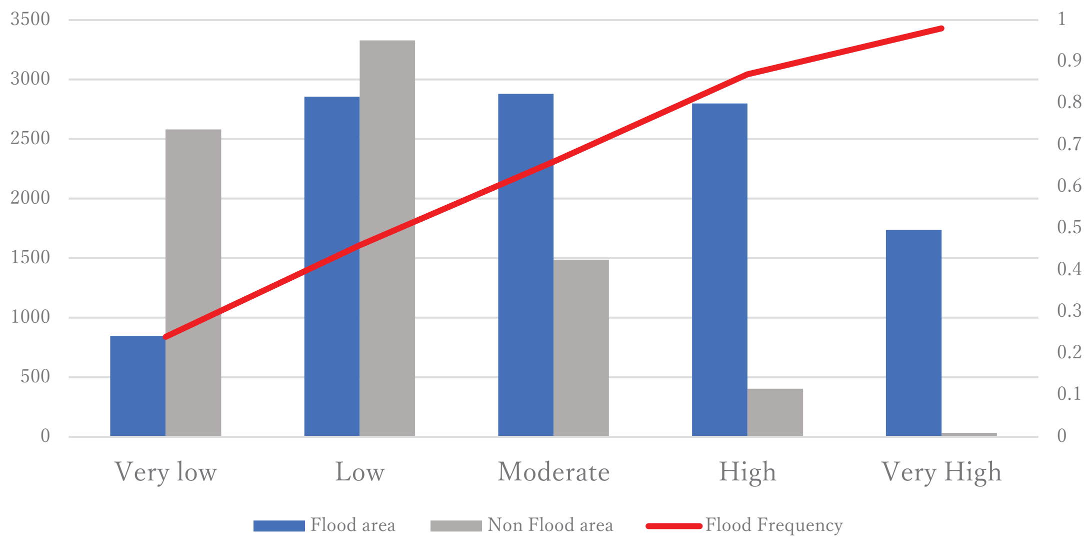


Figure 44 Distribution of flood susceptibility classes and flood inventory

Finally, the range values of the flood susceptibility index, which was classified with the natural breaks method, consists of five classes: very low (-33.713 – -19.924), low (-19.923 – -9.794), moderate (-9.793 – 1.744), high (1.745 – 15.814), and very high (15.815 – 38.045). Although the FSM of Nong Khai City created with WoE cannot inform the information about the flood height and velocity as same as the FSM developed with the physically based modelling that requires intense data at the micro level, at least the FSM from the WoE can assign the flood susceptibility boundary which is important data to support the planning in the floodplain and manage the flood risk, especially in the step of pre-flood risk management. Figure 45 shows that the very high and high flood susceptibility areas are in the southeastern areas near the Mesuai River. The river is a meandering river flowing through the flat area with a very gentle slope into the Mekong River. The low slope and the meandering river cause the water to slowly flow and overflow to the adjacent areas. Oya (1966) indicates that the valley plain along the Mesuai river was inundated for two weeks. In addition, these areas are back swamps and flat with the high values of drainage density, TWI, SPI, and flow accumulation that support the probability of flood occurrence.

In comparison, the areas with low and very low flood susceptibility are in the central and southwestern areas. These areas are far from the Mesuai River and characterised by the peneplain and the natural levees with a high elevation. In addition, the drainage density, flow accumulation, TWI, and SPI are low.

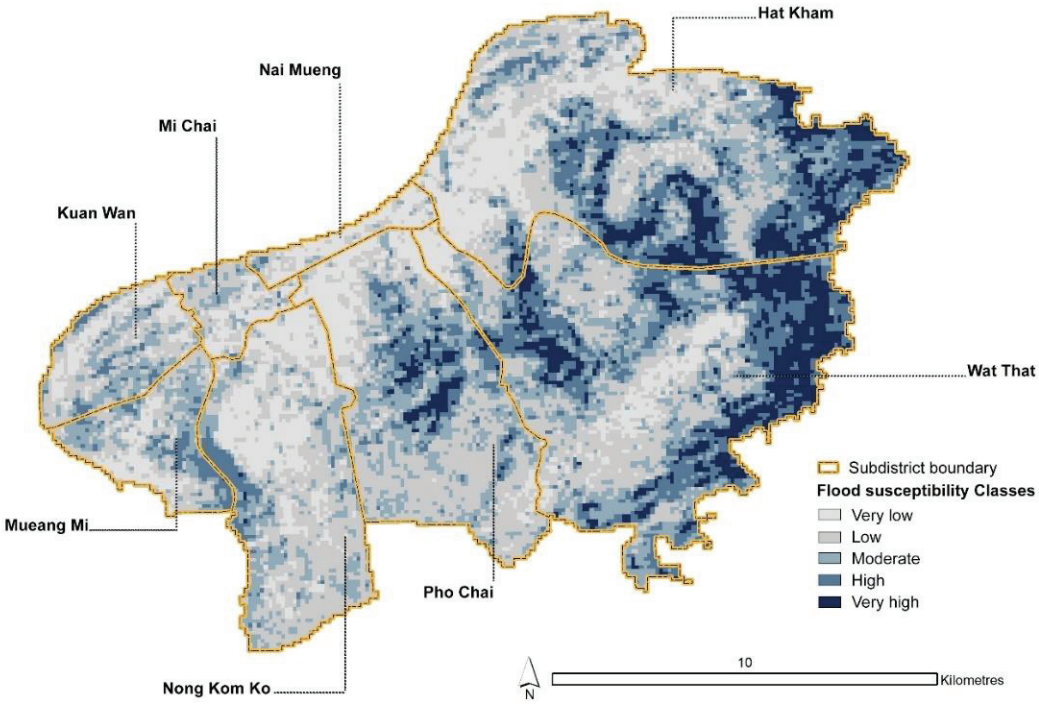


Figure 45 The final FSM divided by the subdistrict boundary

In terms of subdistrict boundaries (Figure 45), the areas with very high and high flood susceptibility are mainly in Wat That and Hat Kham Subdistrict, respectively. Precisely, 41.38 % and 34.62 % of the areas in Wat That and Hat Kham Subdistrict are in the zones of high and very high flood susceptibility. In other subdistricts, however, less than 10 % of the areas are in the zone of high and very high flood susceptibility, except Pho Chai Subdistrict. Interestingly, three subdistricts — Kuan Wan, Mi Chai, and Nai Mueang — are not in the very high susceptibility zone. In addition, 91.93 % of Nai Mueang Subdistrict, which is the original settlement area, are mainly in the zone of low and very low flood susceptibility. The peri-urban area responds to the expansion of built-up areas like Mi Chai and Nong Kom Ko Subdistricts. 79.25 and 73.42 % of the areas in the two subdistricts are in the low and very low susceptibility zones, respectively.

5.6 Discussion

5.6.1 The conditioning factors of flood occurrence

The conditioning factors of flood occurrence in each model vary in terms of magnitude and pattern. Generally, the influence of the condition factors in flood occurrence is shown through a linear relationship. The level of weight value will increase or decrease based on the value of the conditioning factors. For example, the elevation and the distance to the river have an inverse relationship with flood occurrence while the drainage density and rainfall usually have a direct relationship with flood occurrence (Chakraborty & Mukhopadhyay, 2019; Kabenge et al., 2017). However, in this study, the weight value from FR, MoFR, and WoE demonstrate that there is not a strong relationship between the value of each conditioning factor and flood occurrence. Only three conditioning factors — TWI, drainage density, and flow accumulation — from FR and MoFR show a strong relationship between the flood occurrence and their values.

In comparison, the other conditioning factors show a moderate correlation or no relationship between the flood occurrence and their values, especially for the distance to the waterways. The weight values of the three conditioning factors related to the distance to the waterways are varied and random. The crucial reason is the limited and short-distance influence of the waterways, including the intervention from other conditioning factors. The random weight value of the conditioning factors about the distance to the water network is also found in other studies (S. Samanta et al., 2018, p. 66; Tehrany et al., 2013, p. 72; Tehrany et al., 2017, p. 1543).

Based on the patterns of the conditioning factors from WoE, the top two weight values are the conditioning factors of the distance to the waterways. It is in line with the study of Kabenge et al. (2017) that shows the flood hazard risk in Uganda with AHP. Despite this strong influence on the flood occurrence, different waterways have a different correlation with the flood occurrence. The distance to the Mekong River and the Mesuai River show a reverse relationship. The distance to the Mesuai River has a negative relationship with flood occurrence while the distance to the Mekong River has a positive relationship with the flood occurrence. Hence, to analyse the influence of the waterways on the flood occurrence, it is necessary to divide the waterway networks into small units based on the topography.

Regarding the strong and moderate correlations between the conditioning factors and flood occurrence, we found that the TWI, SPI, drainage density, and flow accumulation have a positive relationship with flood occurrence. It is similar to the finding of R. K. Samanta et al.(2018, p. 401), Sarkar & Mondal (2020, p. 8), and Arora et al.(2021, p. 21), which found that the weight values of TWI increased according to its values. The study of Tehrany et al. (2017, p. 1544) also indicates that the TWI and SPI from the FR model have a positive relationship with the flood occurrence. In contrast, other studies indicate that the influence of TWI and SPI are in random patterns (Paul et al., 2019; Sarkar & Mondal, 2020; Tehrany, Pradhan, et al., 2014).

In terms of flow accumulation and drainage density, the positive relationship reflects that the increase of flow accumulation and drainage density increase the probability of flood occurrence. Other studies also confirmed these findings (Rahmati et al., 2015; Wubalem et al., 2021, p. 1678). It can imply that the areas densely with the drainage system and the flow accumulation will have a high level of flood susceptibility.

While the elevation has a negative relationship with flood occurrence, it is in line with the previous study (R. K. Samanta et al., 2018, p. 401). The negative relationship with flood occurrence confirmed that floods usually occur in low land compared to high land (Paul et al., 2019; Sarkar & Mondal, 2020; Tehrany, Pradhan, et al., 2014; Wubalem et al., 2021).

For other conditioning factors, which is the categorical variables, we found that the flat surface has the highest weight value in terms of curvature. The concave surface has a negative relationship with flood occurrence. It is similar to the finding of Paul et al. (2019, p. 132) and Wubalem et al. (2021, p. 1678). The result confirms the natural characteristic of floods which usually occur in a flat area that has a high capacity to be deluged. The result about the flat area also supports the result about the elevation that floods usually occur in the low land with flat topography.

Regarding land use, the previous studies indicate that the built-up lands or residential lands have a high probability of flood occurrence (Tehrany et al., 2013, p. 72; Tehrany et al., 2017, p. 1543). However, in any case, the built-up lands also have less influence on the flood occurrence (Rahmati et al., 2015; S. Samanta et al., 2018, p. 66; Tehrany, Pradhan, et al., 2014, p. 338). This study found that the flood occurrence has a positive relationship with every land-use type except built-up lands. It is similar to the study of Paul et al. (2019, p. 133) and R. K. Samanta et al. (2018), which indicate that the agricultural land has the highest value in WoE and FR, respectively. The crucial reason is the agricultural land with a fallow area do not have vegetation coverage to control and prevent the flood. Most of the agricultural lands in Nong Khai are also unused rice fields in some seasons. The positive relationship between the fallow land and the flood occurrence also occurred in the another study (Sarkar & Mondal, 2020, p. 9).

Regarding geology, KTpt is indicated as the high weight value on the flood occurrence with the positive relationship. KTpt is a geology type that consists of mudstone, siltstone, and fieldstone. The units of rock, such as mudstone and siltstone, have a low permeability leading this area to high drainage density and high probability of floods.

In terms of geomorphology, the result from all bivariate statistical model indicates that the back swamp achieves the highest weight value. R. K. Samanta et al. (2018) and S. Samanta et al. (2018) also indicate that the swampy area has a high probability of flood. Oya (1966), who analysed the relationship between geomorphology and flood patterns in Nong Khai City, described the back swamps sunk under the flood for several months in the rainy season. Their soils are silt or clay with poor drainage. The soils have the highest weight value in previous studies (R. K. Samanta et al., 2018, p. 401; S. Samanta et al., 2018, p. 66). At the same time, the natural levee has a negative relationship with the flood occurrence. It is in line with the study of Oya (1966) which shows that the natural levee is a hilly area constructed from the sand and silt. The water quickly flows through the natural levee into the back swamps area. This is why the natural levee has a negative relationship with flood occurrence. In the case of the alluvial terrace, considering the soil types, we found that the drainage capacity of the soil types of alluvial terrace is quite poor, and the surface had been waterlogged for about 3–5 months (Hydro and Agro Informatics Institute, 2018). Therefore, the alluvial terrace has a high probability of flood occurrence in this study. In contrast, the peneplain has a negative relationship with flood occurrence. Based on the elevation, we found that the elevation of the peneplain area is higher than the back swamp and the alluvial terrace which have a positive relationship with flood occurrence.

5.6.2 The performance of the models to create FSM

In this study, seven models can produce the FSMs with acceptable accuracy. The output maps of bivariate and multivariate statistical models are similar, and they are close to the output maps of the ensemble models. The result is in accord with the study of Costache & Zaharia (2017) and Rahmati et al. (2015), which compared the accuracy of FR and WoE and found that the accuracy rates of both models are similar.

In this study, the performance of WoE in the prediction rate is better than other models. It is similar to the study of Paul et al. (2019, p. 141) which found that the prediction rate of WoE is better than FR. Tehrany et al. (2017) also indicate that the prediction rate of WoE is better than FR and LR. However, the study of Tehrany et al. (2017) shows a different result for the ensemble model; the ensemble model LR-WoE has a higher prediction rate than the WoE. But our study found that the prediction rate of the ensemble LR-WoE is lower than that of the WoE. Moreover, the accuracy rates of the success rates in this study and the study of Tehrany et al. (2017) are also dissimilar. Tehrany et al. (2017) indicate that the WoE has the highest success rate, followed by the ensemble LR-WoE, the ensemble LR-FR, LR, and FR, respectively whereas our finding demonstrates that WoE does not achieve the highest success rate. The ensemble LR-FR performed the highest success rate, followed by WoE, and ensemble LR-FR, respectively. In addition, LR was detected as having the lowest success rate. The different patterns of accuracy between this study and the study of Tehrany et al. (2017), which performed a similar model, help confirm that the models to create the FSMs are sensitive and uncertain. The accuracy of the models depends on the conditioning factors and context. Arora et al. (2021, p. 3) indicate that to responding to the different local contexts in the areas such as the topography, the hydrology, the vegetation, the socio-economic, and so on, many models to create FSMs should be tested to improve the performance of the FSMs and select the most suitable model in each context.

MoFR is an uncommon model performed in this study. Although the accuracy of MoFR in terms of success rate and prediction rates is not the highest, their accuracy is acceptable; it ranks forth, second, and third in the success, prediction, and overall rate rankings. The accuracy of MoFR which is better than that of FR was also found in the study of Sifa et al. (2020) that compares the performance of FR and MoFR to create the landslide susceptibility map and found that the MoFR can develop the accuracy of FR.

Many previous studies indicate that the ensemble model that integrated the bivariate and multivariate statistical models will enhance the performance of the model (Tehrany, Lee, et al., 2014; Tehrany et al., 2013). The result of our study is slightly dissimilar because the ensemble models in this study are not the best scenario in some scenarios. Our study indicated that the WoE has the highest accuracy for the prediction rate and the second-highest accuracy for the success rate. Although in terms of the success rate, WoE does not achieve the highest accuracy, the success rate of WoE is still higher than that of the ensemble LR-WoE. Therefore, in this case, the ensemble model cannot enhance the performance of the bivariate statistical model.

For the bivariate statistical model, we found that the integration of multivariate statistical model cannot enhance the performance of the bivariate statistical model because the accuracy of most ensemble model is lower than that of the bivariate model, except the prediction rate of the ensemble LR-FR which is higher than that of FR. This finding is similar to the result of Tehrany et al. (2017) that the accuracy of the ensemble model is higher than that of LR. Still, the accuracy of the ensemble model is both higher and lower than that of the bivariate statistical model. However, in terms of the multivariate statistical model, we found that all ensemble models have higher accuracy than LR. It implies that all bivariate statistical models can develop the accuracy of the multivariate statistical model.

5.7 Conclusion

The areas susceptible to flood are the crucial information to develop the land-use policy because it will assist planners in identifying the areas that need to avoid making the settlement in the future. However, to create the FSMs to determine the level of flood susceptibility, the comparative model is an important process because each analysis model has its advantage and disadvantage. Hence, to create the FSM in Nong Khai City which lacks this information to support the flood management, this study performed seven statistical models to develop the FSMs and compare their accuracy to select the most suitable model in the context of Nong Khai City.

To create the FSMs, 12 conditioning factors were adopted as the independent variables: (1) elevation, (2) TWI, (3) curvature, (4) the distance to the Mekong River, (5) the distance to the Mesuai River, (6) the distance to streams, (7) drainage density, (8) flow accumulation, (9) SPI, (10) land use, (11) geology, and (12) geomorphology. As the dependent variables, 105 random points in the flood areas and 105 random points in the non-flood areas were used. Then, seven models — FR, MoFR, WoE, LR, Ensemble LR-FR, Ensemble LR-MoFR, and Ensemble LR-WoE — were adopted to calculate the weight value of each conditioning factor. The weight value from each model was integrated into the GIS framework to create the FSMs, and the ROC of the FSMs from every model was calculated and compared to select the most suitable FSM.

Regarding conditioning factors, TWI, SPI, drainage density, and flow accumulation have a positive relationship with flood occurrence. Like the flat areas, agricultural lands; the back swamps and alluvial terrace; and the geology of KTpt, which consists of mudstone, siltstone, and fieldstone were also indicated as the positive impactful conditioning classes of flood occurrence in Nong Khai City. In contrast, the elevation has a negative correlation with flood occurrence. Interestingly, the relationship between the flood occurrence and the conditioning factors in terms of the waterways is varied and random.

From the result, seven models of the bivariate statistical, multivariate statistical, and ensemble models can produce the FSMs with acceptable accuracy. The final FSM from WoE achieves the highest overall accuracy and prediction accuracy while the model of ensemble LR-FR achieves the highest success rate. The FSM of WoE was selected as the most suitable FSM. It presents the distribution of the areas susceptible to flood based on five classes. The areas with very low flood susceptibility cover 18.08% of the total areas. These areas surround the original settlement area and are also distributed in the areas in Nong Kom Ko Subdistrict near the government centre of Nong Khai Province. In contrast, the areas with very high and high flood susceptibility are in the southeastern part of Nong Khai City. These areas cover 26.25% and are mainly the back swamp, low elevation, high drainage density, and agricultural lands. They are located near the Mesuai River which has the highest influence for flood susceptibility analysis.

Although the FSM of Nong Khai City created with the statistical method cannot inform the information about the flood height and velocity. However, the final FSM of Nong Khai City reveals that most of the areas with very high and high flood susceptibility are the agricultural areas and water bodies. To manage the land use in this zone to respond to the flood, the information about the flood height and velocity is not too necessary. It implies that the FSM from WoE is adequate to generate the information to guide land-use planning, especially in the areas with very high and high flood susceptibility or flood-prone areas. However, to fulfil the flood-risk management in practical terms due to the limitation of the FSM from WoE, the FSM from WoE can be used as a starting tool to collect the high-water mark in the zone of very high and high flood susceptibility to support the architectural renovation and design coping with the flood in the future.

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Chapter 6

The suitable areas for urban development in Nong Khai City

Contents

List of abbreviations in this chapter:

A, Physical components; A01, Topography; A101, Slope; A102, Soil type; A02, Hazard; A201, Flood; A03, Land use; A301, Land-use types.

B, Accessibility; B01, Accessibility to transportation; B101, Distance to major roads; B102, Distance to train stations; B02, Accessibility to communities and neighbourhoods; B201, Distance to city centres; B202, Distance to neighbourhood centres; B03, Accessibility to natural infrastructure; B301, Distance to public natural waterbodies; B302, Distance to parks and public open spaces; B04, Accessibility to public amenities; B401, Distance to medical facilities; B402, Distance to commercial areas; B403, Distance to police stations; B404, Distance to education institutes; B405, Distance to gas stations.

C, Population; C01, Population; C101, Population density.

D, Policy; D01, Policy to conserve the natural assets; D101, Policy to conserve and protect the waterbody and areas with significant biodiversity; D02, Policy to conserve the cultural assets; D201, Policy to conserve and protect ancient sites and surrounding areas

6.1 Introduction

Land suitability analysis is a mapping process that city planners use to find the most suitable areas for each activity, subject to certain restrictions (Hopkins, 1977). Owing to the complexity of the urban environment (Barredo et al., 2003; White et al., 2015), which is the result of the interaction between the socioeconomic component and the natural environment (White et al., 2015), suitability analysis for shaping land-use policies to respond to urban development is a complicated process related to several factors. The capacity to manage complicated factors to support the urban environment with different influences is thus an important function for analysing suitable areas for urban development.

Due to its ability to determine the impact of complicated factors on interesting phenomena, multi-criteria decision analysis (MCDA) is widely used in land-use suitability analysis to develop prescriptive guidelines (Cerreta & De Toro, 2012; Dai et al., 2001; Huang et al., 2021; Mosadeghi et al., 2015) or identify the most suitable areas for specific activities by being integrated within geographical information system (GIS) frameworks. Currently, the MCDA within the GIS framework (GIS-MDCA) is a fundamental technique for developing several models related to spatial planning to manage complicated factors. For example, it is necessary to consider the multifunction of green infrastructure in an analysis of suitable areas for green infrastructure (Meerow & Newell, 2017), including factors that are suitable for ecosystem services and the conditions of the urban environment. These factors are presented as suitable in terms of needs and opportunities to develop green infrastructure (Kuller et al., 2019). The GIS-MDCA was also applied to manage the universal benefits and was performed in forest management, which needs to link the benefits to goods and services of the ecosystem (Ananda & Herath, 2009; Gebre et al., 2021).

Analytical Hierarchy Process (AHP) is a popular technique used for MCDA (Gebre et al., 2021; Malczewski & Rinner, 2015), developed by Saaty (1987). It is a hierarchical structural analysis process used to identify the suitability of certain activities which involve several factors. A relative measurement by paired comparison was used to clarify the different influences of these factors. Hence, scholars generally use AHP to analyse suitable areas supporting decision-making in the process of city planning because of its capability to identify and manage the importance of complicated factors (AlFanatseh, 2021; Kumar & Shaikh, 2013; Mosadeghi et al., 2015; Parry et al., 2018; Sedigheh et al., 2009; Ullah & Mansourian, 2016). However, AHP is reportedly uncertain (Quinn et al., 2015). Another methodology was developed and applied to identify suitable areas to address uncertainty (Mosadeghi et al., 2015). Despite the concern about the uncertainty of the AHP, most studies indicate that the suitability maps generated from the AHP and other developed methodologies at the final step are not vastly dissimilar (Foroozesh et al., 2022; Mosadeghi et al., 2015). As a result, AHP is still an effective methodology for urban planning, especially in terms of small cities like Nong Khai City, because, in addition to its simplicity and flexibility, it requires relatively less skill (Gebre et al., 2021) compared to other advanced technologies.

In addition, Although the AHP has been applied to urban planning globally, it has not been used quite often in Thailand. Most techniques that have been used are the ranking method (Srivanit and Selanon 2018), modified sieve analysis (Loakaewnoo 2018), and potential surface analysis (Ativitavas and Thongsukplang 2006; Phokhachonphisut, Summaniti, and Hongvityakorn 2019). Regarding most analyses to identify suitable areas for settlement, the areas usually inherit unique characteristics such as residential development around the Suvarnabhumi Airport (Srisungvorn 2019) and the eco-industrial town (Modwatthana et al. 2017). Consequently, the application of the AHP for urban development in the small cities of Thailand is rare and needs the cases to support their application.

Consequently, this chapter aims to assess land suitability for urban development in Nong Khai City using AHP. Despite the AHP being a fundamental technique, this chapter applied the land suitability indices from a unique set of criteria. In addition, this chapter not only assesses suitable areas for urban development, but it also reflects the capability of the AHP and GIS framework to generate a suitability map of urban development that assists planners in making reasonable decisions in urban planning. Grouping analysis was performed to increase the performance of the traditional style of the suitability map for urban development, which is difficult to apply practically. This chapter consists of five sections. The objective is presented in the first section. Then, the methodology is described with the discussion of criteria to assess the land suitability. The results are presented in two parts. The first result is '*the Importance of the criteria for the urban development in Nong Khai City.*' In this part, the weight values from AHP are used to indicate the influence of the criteria on the assessment of land suitability analysis in Nong Khai City. The second result is '*Spatial characteristics of suitable areas for urban development in Nong Khai City.*' In this part, the characteristics of the zones of suitable areas for urban development are described based on the suitability level. Following that, the section of discussion is presented to discuss about the criteria for urban development along with previous studies and the application of AHP to support the urban planning in terms of urban suitability mapping. The last section is to conclude the findings in this chapter.

6.2 Objective

To assess the land suitability for urban development in Nong Khai City using AHP in order to determine the suitable and non-suitable areas for urban development in the future.

6.3 Methodology

In this study, the AHP was integrated with the GIS framework to evaluate suitable areas for urban development. The study is divided into five sections. The methodology described in sections 6.3.1–6.3.4 was constructed based on the AHP components: decomposition, comparative judgment, and synthesis of priorities (Malczewski & Rinner, 2015). Section 6.3.1 is related to decomposition and aims to design and construct a criteria decision hierarchy for urban development, as shown in Figure 46. Sections 6.3.2 –6.3.4 are related to comparative judgment and priority synthesis. They comprise an expert survey, weight determination, and test accuracy. Then, the final weights from the AHP were integrated with the GIS framework in section 6.3.5 to link with spatial data, and suitable areas for urban development were assessed by calculating the land suitability index using the weighting linear combination method. Subsequently, the land suitability index was converted into raster data using a 100 × 100 m raster grid cell with an average value. The average value was then applied to classify the levels of suitable areas for urban development using the Jenks natural breaks classification. Finally, the areas in each group were categorised into subgroups using the method of grouping based on the spatial characteristics to make recommendations for urban development policy. The framework of the methodology is illustrated in Figure 47.

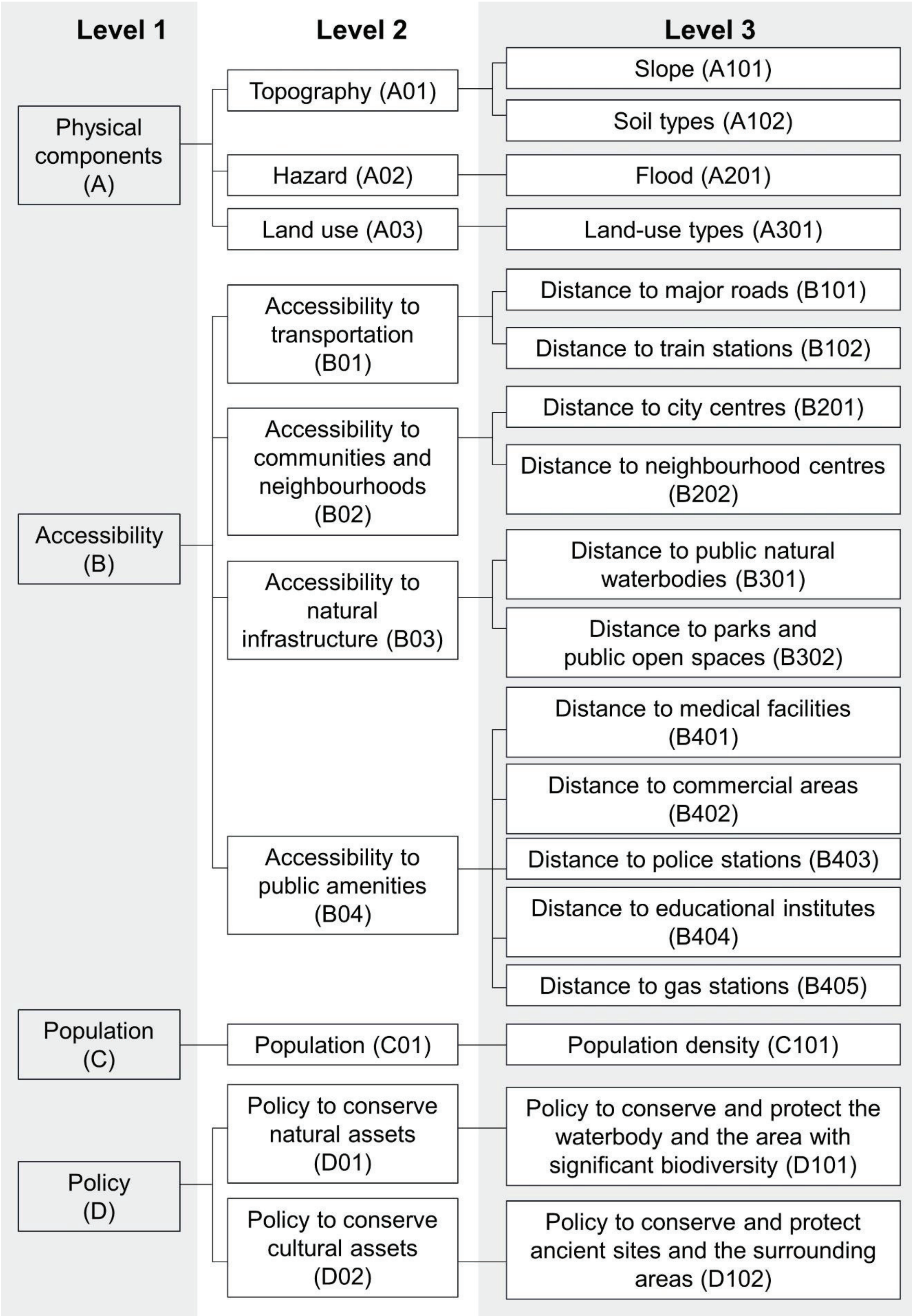

Figure 46 The criteria decision hierarchy

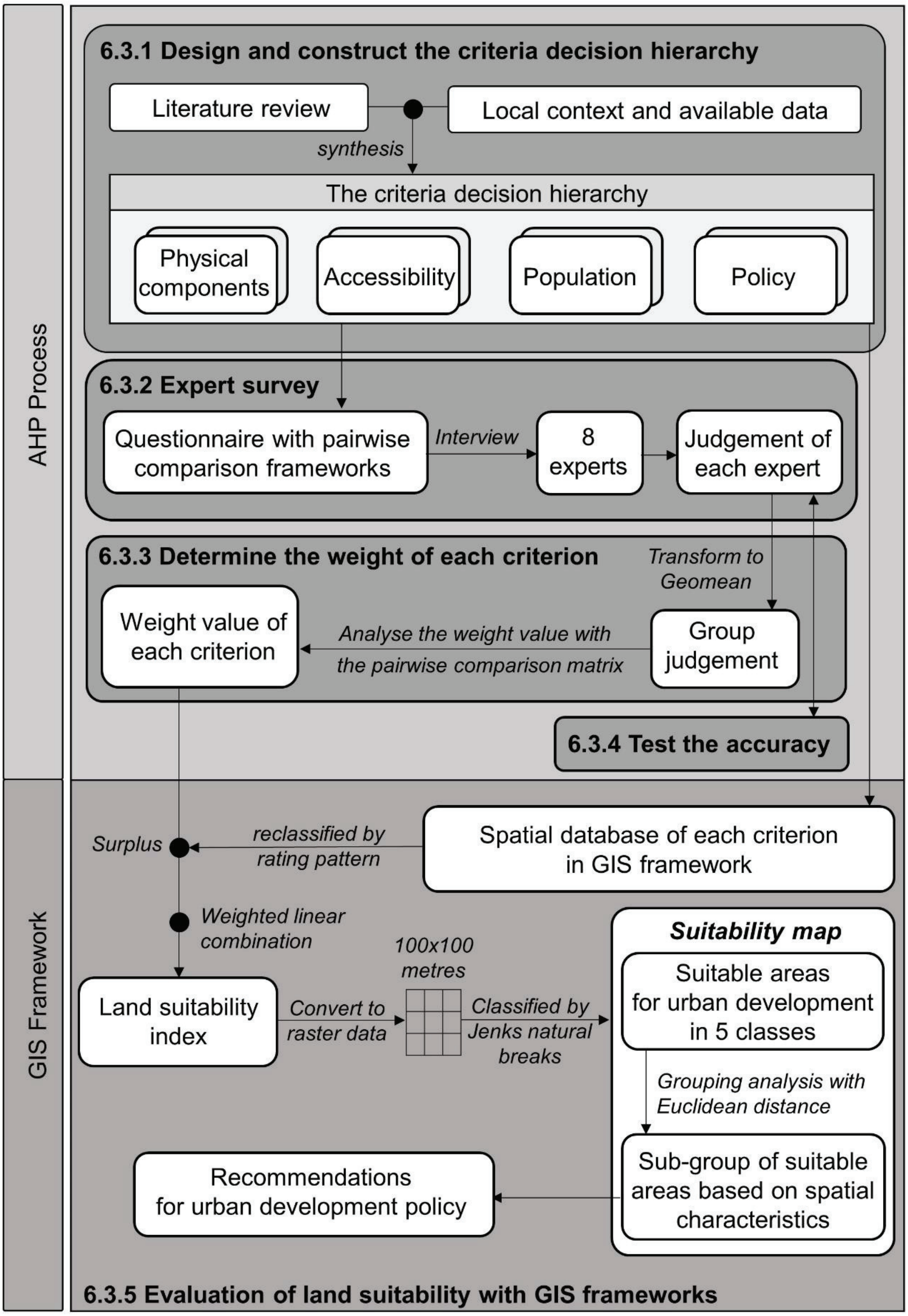

Figure 47 Methodological framework

6.3.1 Design and construct the criteria decision hierarchy

Crucial input for suitability analysis, a set of criteria should be considered for a reliable result (AlFanatseh, 2021; Huang et al., 2021; Youssef et al., 2011). However, there is no universally agreed-upon system to select the criteria (Ullah & Mansourian, 2016). The selected criteria are based on the target area condition and the perspective of the researcher (Morales & de Vries, 2021; Youssef et al., 2011). The criteria in this study were identified from the literature review. They were then filtered using the target area condition and available data. Finally, 18 criteria were grouped into a three-level hierarchical structure. The physical components, accessibility, population, and policy were set as the criteria at the first level.

Physical components are fundamental factors in analysing suitable urban development areas (Sedigheh et al., 2009; Yang et al., 2008). They reflect the perfect condition and safety in a natural aspect. The study areas are not large, and the site is a moderate plain, so the physical components in the study area, such as geology formation, are similar. As shown in Table 22, the physical components are divided into three criteria at level 2: topography, hazard, and land-use types.

Table 22

Descriptions of sub-criteria in the physical components group

Criteria level-2	Descriptive
Topography	Topography is information about the spatial suitability and safety of the settlement. It is a local natural condition required to analyse the land-use suitability because each topography has a different kind of suitability and land-use limitation (MacHarg, 1969). The study considers the topography in the aspects of slope and soil types. • The slope is a fundamental factor that most scholars usually study as a representative of topography. The settlement in a steep slope will affect the safety and result in a high cost of construction (Bathrellos et al., 2012; Kumar & Shaikh, 2013; MacHarg, 1969). The settlement in a less slope area will encounter floods (Bathrellos et al., 2017). This study classifies suitability data into six groups. • Soil type is a physical component reflecting the suitable activities. It can reflect suitability in engineering construction and land fertility. Lands with fertile soil should not be used for built-up land and should be conserved as good agricultural land (Ativitavas & Thongsukplang, 2006; Doygun et al., 2008; MacHarg, 1969).
Hazard	Hazard is the most crucial variable (Malmir et al., 2016; Mosadeghi et al., 2015) to find suitable areas and plan land uses for sustainable urban development (Bathrellos et al., 2012) because it provides information on safety. The urban development in the areas prone to hazard will lead to them becoming vulnerable locations (Bathrellos et al., 2012). This study only considers flood, the only hazard occurring every year.
Land-use types	The land-use types reflect the current use of land and indicates a possibility of transforming them into built-up lands. In this study, land-use suitability is classified into three levels based on the four types of land uses: waterbodies, built-up lands, forest and natural lands, and agricultural lands.

Accessibility is a criterion commonly used to analyse suitable areas for urban development (Ayik et al., 2017; Kapoor et al., 2020; Luan et al., 2021; Yang et al., 2021). It represents the ability of people to reach activities and amenities (Gil Solá et al., 2018). Owing to gravity, accessibility should be considered a part of urban planning when developing sustainable urban areas (Moroke et al., 2019). Suitable areas for urban development should be located close to public amenities, and the residents in the existing neighbourhoods should be able to access those facilities equally (Pozoukidou & Chatziyiannaki, 2021). Equal and convenient accessibility will lead to a better quality of life for citizens, both socially and economically. Hence, distance or proximity to facilities representing accessibility is a crucial index for developing sustainable settlements (Moreno et al., 2021; Moroke et al., 2019). Besides providing equal accessibility, proximity to the existing infrastructure and services leads to a compact city (Bibri et al., 2020), decreasing the redundant expansion of built-up lands and the ratio of land consumption to population growth—which is an indicator of Target 11.3 of the Sustainable Development Goals (SDGs) (United Nations, 2021).

Accessibility can be measured using various methods (Curl et al., 2011; Salonen et al., 2012). The Euclidean method is fundamental for clarifying accessibility (Mushkani & Ono, 2021; Salonen et al., 2012; Tian et al., 2017; White et al., 2015). Currently, integration between the Euclidean method and walkable distance is a popular method for clarifying accessibility (Mavoa et al., 2012; Mushkani & Ono, 2021; Tian et al., 2017). A sustainable settlement should provide public amenities and infrastructure within walkable distances (Coplák & Rakšányi, 2003; Medved et al., 2020) to decrease the use of cars, which consume energy and lead to environmental problems (Gil Solá et al., 2018). In this study, accessibility was classified by adapting the 15-minute city concept of Carlos Moreno and the standards and recommendations of the Department of Public Works and Town & Country Planning. The 15-minute city is proximity-based planning, which helps citizens access the infrastructure in their daily lives within 15 minutes by walking or biking (Moreno et al., 2021). In this study, the accessibility to infrastructures within 15 minutes was defined as three cycles of a five-minute walk, a walkable distance of 400 metres which is a standard for the pedestrian catchment analysis (Matan, 2017). In addition, to make the result consistent with the local context, the rating method for some criteria was adjusted based on the standards and recommendations of Department of Public Works and Town & Country Planning and local contexts. As shown in Table 23, accessibility consists of four and eleven criteria at levels 2 and 3, respectively.

Table 23

Descriptions of sub-criteria in the accessibility group

Criteria level-2	Description
Accessibility to transportations	It is commonly found in the analysis of suitable areas because transportation is a basic medium to access the infrastructure equally. Owing to the shortage of public transportation, the distance to major roads and train stations are considered as the accessibility to transportation. • The distance to major roads is the basic accessibility. The urban development that makes it easy to access the major roads will decrease the expense of transportation and services (Kumar & Shaikh, 2013; Ustaoglu & Aydınoglu, 2020). Moreover, it can reduce the cost and the environmental impacts of road construction. • The distance to train stations indicates the type of public transportation connecting Nong Khai City to other locations. The areas suitable for urban development should be easily accessible to train stations. This study uses the distance to two train stations: Nong Khai and Na Tha.
Accessibility to communities and neighbourhoods	The neighbourhood is a settlement unit that should be considered for urban planning (Patricios, 2002). It leads to sustainable urban development (Moroke et al., 2019), especially in response to the fast-growing cities (Pozoukidou & Chatziyiannaki, 2021). In this study, the accessibility to communities and neighbourhoods comprises two sub-criteria: • The distance to city centres represents the space of economic activities, employment, society, and government services. Consequently, it can indicate economic opportunities. In this study, the city centres of Nong Khai City are in two places: the original city hall and the government complex. • The distance to neighbourhood centres is the most crucial factor in analysing suitable urban development areas (Malmir et al., 2016). The suitable areas should be within neighbourhood units, measured by the distance to schools or communities' centres (Patricios, 2002). Therefore, the urban areas will be compact. The neighbourhood centres of Nong Khai City in this study are temples — the settlement centres of the communities (Boonkrajangsopee, 2009)
Accessibility to natural infrastructure	Natural infrastructure is the natural and designed landscape components such as waterbodies, green areas, open spaces, and more (Ghofrani et al., 2017). It provides multifunctional solutions for the urban environment, such as storing water, controlling floods, and mitigating climate change while having social functions (Ghofrani et al., 2017). In this study, we analyse the natural infrastructure based on the Blue-Green infrastructure as a part of (1) distance to public natural waterbodies and (2) distance to parks and public open spaces.
Accessibility to public amenities	Accessibility to public amenities usually indicates the city sustainability (Moroke et al., 2019) because all citizens in the city should access their basic needs (Pozoukidou & Chatziyiannaki, 2021). The suitable areas for urban development should be in a service area of the public amenities. In this study, the public amenities consist of five sub-criteria: medical facilities, commercial areas, police stations, education institutes, and gas stations.

The population is the third criterion at level 1. The population density was the only criterion performed in this group because of information accessibility. It was calculated at the sub-district level using the population data in 2017 from the Department of Provincial Administration (2021). Then, it was classified using the Jenks natural breaks classification method. The highest density was identified as the lowest suitability whereas the lowest density was identified as the highest suitability.

The policy factor is the last criterion at level 1 and is related to the possibility of urban development regarding regulations. Regulations were promulgated to conserve vulnerable areas and prevent them from urban development because the activities for urban development will degrade the value of the areas. In this study, the policy to conserve and protect the waterbody and areas with significant biodiversity and the policy to conserve and protect ancient sites and the surrounding areas were indicated as the criteria at level 3. The former was derived from land-use and conservation policies while ancient site data in the latter were obtained from the database of the Fine Arts Department (2021). The boundary of the buffer zone is within one kilometre from ancient sites. Ancient sites had the lowest suitability while the surrounding areas had marginal suitability. The buffer zone data were based on the recommendation of the Department of Public Works and Town & Country Planning (2008).

6.3.2 Expert survey

AHP is a technique used to determine the weight of each criterion by using judgment from experts. A questionnaire to conduct the expert survey was developed within the pairwise comparison framework which evaluates the importance of each criterion by rating the relative importance of the pair criteria on a numerical scale of 1–9, as shown in Table 24 (Saaty, 1987).

Table 24
The definition of scale in the questionnaire based on the pairwise comparison

Intensity	Definition and explanation
1	Equal importance: two criteria equally contribute to the urban development
3	Moderate importance: experience and judgement slightly favour one criterion over another
5	Strong importance: experience and judgement strongly favour one criterion over another
7	Very strong importance: one criterion is favoured very strongly over another, and its dominance is demonstrated in practice
9	Extreme importance: the evidence favouring one criterion over another is of the highest possible order affirmation
2,4,6,8	Intermediate values between the two adjacent judgements

Source: Saaty (1987)

The experts are lecturers in Thai universities with experience in specific fields for at least ten years. We used the judgment of eight people from four areas of expertise: geography, urban and regional planning, landscape, and residence, and construction. To collect data from the experts, questionnaires were distributed to them for preparation, and then an in-depth interview was conducted with each expert individually. The interview began with an explanation of the study. Then, an evaluation method and examples are described to confirm their understanding. Finally, the experts were interviewed using questionnaires to evaluate the importance of the criteria at each level.

6.3.3 Determine the weight of each criterion by AHP techniques

The weight of each criterion was determined from the values of the group judgement. The judgement values of eight experts were aggregated into a group judgement by using the geometric mean because it is consistent with the judgments and priorities (Malczewski & Rinner, 2015; Mosadeghi et al., 2015; Saaty, 1987). The geometric mean values were then added to the pairwise comparison matrix (Table 25 –Table 27) to analyse their relative weights. The weight of each criterion was calculated by taking the eigenvector corresponding to the largest eigenvalue of the final matrix and then normalising the result as the sum of the criterion to unity (Feizizadeh et al., 2014; Saaty, 1987). The final weight of each criterion at level 3 was analysed by multiplying its weight at that level by the weight value of the corresponding criteria at the level above (Saaty, 1987).

Table 25

Pairwise comparison matrix of the criteria at level 1

Criteria	A	B	C	D
A	1.00	1.15	3.70	0.81
B	0.87	1.00	2.31	0.49
C	0.27	0.43	1.00	0.32
D	1.23	2.02	3.17	1.00
CI	0.01			
CR	0.01			

Table 26

Pairwise comparison matrix of the level 2- criteria

Criteria in the group of physical components				Criteria in the group of policy		
Criteria	A01	A02	A03	Criteria	D01	D02
A01	1.00	0.61	2.47	D01	1.00	0.68
A02	1.63	1.00	3.70	D02	1.47	1.00
A03	0.40	0.27	1.00	CI	0.00	
CI	0.00			CR	0.00	
CR	0.00					

Criteria in the group of accessibility				
Criteria	B01	B02	B03	B04
B01	1.00	1.90	3.55	1.54
B02	0.53	1.00	2.90	0.60
B03	0.28	0.34	1.00	0.34
B04	0.65	1.67	2.91	1.00
CI	0.01			
CR	0.01			

Table 27

Pairwise comparison matrix of the level 3- criteria

Criteria in the group of topography			Criteria in the group of accessibility to transportation		
	A101	A102		B101	B102
A101	1.00	4.04	B101	1.00	2.46
A102	0.25	1.00	B102	0.41	1.00
CI	0.00		CI	0.00	
CR	-		CR	-	
Criteria in the group of accessibility to communities and neighbourhood			**Criteria in the group of accessibility to natural infrastructure**		
	B201	B202		B301	B302
B201	1.00	1.59	B301	1.00	0.90
B202	0.63	1.00	B302	1.11	1.00
CI	0.00		CI	0.00	
CR	-		CR	-	
Criteria in the group of accessibility to amenities					
	B401	B402	B403	B404	B405
B401	1.00	0.77	4.56	1.16	2.64
B402	1.30	1.00	5.69	2.05	3.05
B403	0.22	0.18	1.00	0.27	0.45
B404	0.86	0.49	3.68	1.00	2.50
B405	0.38	0.33	2.23	0.40	1.00
CI	0.01				
CR	0.00				

6.3.4 Test the accuracy

The weight values issued by the experts' judgment can cause inconsistencies. The consistency ratio (CR) was analysed to assess the consistency of the experts' logic behind the judgment at each level. The CR was analysed using the following equation:

$$CR = \lambda_{max} - n/(n-1) \times RI \quad (6.1)$$

Here, λ_{max} is the largest eigenvalue of the pairwise comparison matrix, n is the order of the matrix, and RI (Table 28) is the average of the resulting consistency index depending on the order n, as recommend by Saaty (1987).

Table 28

Random Index (RI)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty (1987)

The judgment is reasonable when the CR value is lower than 0.1 (Saaty, 1987). If it is higher than 0.1, the opinion of the expert is inconsistent. The expert will be asked to revise the opinion. In this study, all CR values were < 0.01. Hence, the weight of each criterion was reasonable and acceptable.

6.3.5 Evaluation of land suitability with GIS frameworks

The evaluation of land suitability using the GIS frameworks consisted of four steps. First, the spatial database of each criterion at level 3 was created in GIS environments using ArcMap 10.8.1, from different sources and methods, as shown in Table 29. Subsequently, all spatial information was reclassified based on the rating pattern, as indicated in Table 30.

Table 29

Description of data sources in this study

Data layer	Raw data type	Processing Method	Source
Slope	DEM in a raster format	The slope function in ArcMap 10.1.8	Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
Soil type	Soil map in a shapefile format	Clipped boundary	Land Development Department
Flood	Map of the repeatedly flooded areas between 2004 and 2018 in a shapefile format	Clipped boundary	Geo-Informatics and Space Technology Development Agency of Thailand
Land-use types	Landsat satellite images of 07 March 2017 and 20 December 2017	The supervised classification with the maximum likelihood classifier (MLC) algorithm.	USGS
Data layer in the group of accessibility	Landsat satellite images of 07 March 2017 and 20 December 2017	Digitised feature from the satellite image and assigned the buffer distance	USGS
Population density	2017 population data in a statistical format	Calculating the density at the sub-district level and classified by using the Jenks natural breaks classification method	Department of Provincial Administration
Policy to conserve and protect the waterbody and areas with significant biodiversity	Boundary of local and national waterbody and wetland	Digitised the feature and assigned the buffer distance	Nong Khai Province comprehensive plan 2017 and database of National wetland from the Office of Natural Resources and Environmental Policy and Planning
Policy to conserve and protect ancient sites and the surrounding areas	Location of the ancient sites	Digitised the feature and assigned the buffer distance	Database of the Fine Arts Department

Table 30

Rating pattern of criteria for urban development

Class	Least suitable →				Most suitable
Rating	0	1	2	3	4	5
Physical components						
A101	> 35.0%	25.0 -35.0 % or less than 0.5 %	10.0 – 25.0 %	5.0 -10.0 %	2.5-5.0 %	0.5-2.5 %
A102*	No data	1,2,3,4	-	5,6,7,8	-	9
A201	-	More than 7 times	5-6 times	3-4 times	1-2 times	0 time
A301	-	Waterbodies and Forest and natural lands	-	Agricultural lands	-	Built-up lands
Accessibility						
B101	Roads	-	-	800-1,200 m	400-800 m	≤ 400 m
B102	-	-	-	800-1,200 m	400-800 m	≤ 400 m
B201	-	1,500-3,000 m	1,200-1,500 m	800-1,200 m	400-800 m	≤ 400 m
B202	-	-	-	800-1,200 m	400-800 m	≤ 400 m
B301	-	3,000 -6,000 m	1,200-3,000 m	800-1,200 m	400-800 m	≤ 400 m
B302	-	-	-	800-1,200 m	400-800 m	≤ 400 m
B401	-	-	-	800-1,200 m	400-800 m	≤ 400 m
B402	-	-	-	800-1,200 m	400-800 m	≤ 400 m
B403	-	-	-	800-1,200 m	400-800 m	≤ 400 m
B404	-	-	1,200-1,500 m	800-1,200 m	400-800 m	≤ 400 m
B405	-	0-500 m	-	500-1,000 m	-	≥ 1,000 m
Population						
C101	-	Highest density	High density	Medium density	Low density	Lowest density
Policy						
D101	National wetland	Local significant waterbodies and the area in the agricultural and rural zone in the Nong Khai Province comprehensive plan 2017	-	-	-	Area located outside the indicator 1 and 0
D102	Ancient sites	-	-	Distance from ancient sites ≤ 1 km	-	Distance from ancient sites > 1 km

* Soil series are based on the soil taxonomy of United States Department of Agriculture (USDA): 1 is Fine, mixed, active, nonacid, isohyperthermic Vertic (Aeric Vertic) Endoaquepts; 2 is Clayey-skeletal, mixed, semiactive, isohyperthermic Ultic Haplustalfs; 3 is Loamy-skeletal over clayey, kaolinitic, isohyperthermic Typic (Oxyaquic Plinthic) Paleustults; 4 is Loamy-skeletal, mixed, subactive, isohyperthermic Plinthic (Aeric Plinthic) Paleaquults; 5 is Fine-loamy, mixed, semiactive, isohyperthermic Aeric Endoaqualfs; 6 is Fine, mixed, semiactive, isohyperthermic Aeric Endoaqalfs; 7 is Fine, mixed, semiactive, isohyperthermic Aeric (Aeric Plinthic) Endoaqualfs; 8 is Fine-silty, mixed, semiactive, isohyperthermic Oxyaquic (Oxyaquic Ultic) Haplustalfs; and 9 is Coarse-loamy, mixed, active, isohyperthermic Fluventic Dystrustepts.

Second, the land suitability for urban development was evaluated. The land suitability index was calculated using the overlay technique with the weighting linear combination method that multiplied the weight of each criterion from the AHP with the rating pattern to evaluate the land suitability index, and then find the sum of the multiplied values from every criterion to create the land suitability index. The land suitability index was calculated using the following equation:

$$LSI = \sum_{j=1}^{n} W_j w_{ij}, \tag{6.2}$$

where LSI is the land suitability index, W_j is the overall weight value of the criteria, w_{ij} is the weight value of class i of criterion j from the rating pattern, and n is the number of criteria at level three.

Third, to classify the levels of land suitability, the calculated land suitability indices were converted into raster data by calculating the average value within a 100 × 100 metre raster grid cell. This is a suitable size to develop spatial planning because it can capture the character of an urban landscape and the scatter of built-up area (Grădinaru et al., 2017) under the constraints of computation capacity (Gharbia et al., 2016). The Jenks natural breaks classification method was then adopted to classify the suitability index into five levels: very high suitability, high suitability, marginal suitability, low suitability, and very low suitability. Jenks natural breaks classification method is widely used to classify suitability levels (Mallick et al., 2022; Yang et al., 2021). The characteristics of the members at each level are similar because this method attempts to classify the members at each level by minimising the variance within the level and maximising the variance between levels (Chen et al., 2013). In addition, Jenks natural breaks classification method is suitable for classifying data which are not evenly distributed (Całka, 2018). The method fits with the distribution of the land suitability index in this study because the p-value from the Kolmogorov-Smirnov test is 0.00, reflecting that the data are not normally distributed.

Finally, because the areas of each suitability level were determined from the land suitability index, which is a scale that does not consider spatial characteristics, the areas in each suitability level contain different spatial characteristics; to make the recommendation for urban development policy from the suitability map, the function of grouping analysis (spatial statistics) with Euclidean distance in ArcMap 10.1.8 was adopted to categorise the areas in each level based on the similarity in characteristics. Subsequently, a recommendation for urban development policy was developed.

6.4 Results

6.4.1 Importance of the criteria for the urban development in Nong Khai City

From the expert survey, the importance of each criterion in Figure 48 varies in terms of weight values and ranking patterns based on experts' perspectives. The statistical data in Table 31 show that almost all the coefficients of variation (CV), except for accessibility to amenities and slope, are greater than 30 %, indicating that the set of data from each expert is heterogeneous (Favero & Belfiore, 2019). In addition to the differences in judgement, the individual weight values generated from the pairwise comparison analysis differed in ranking. However, the first and last places in the ranking are generally the same for most experts and the group judgement, as shown in Table 31.

Table 31

Statistical information and ranking of weight values from every expert

Level	Criteria	Min.	Max.	Mean	Std. Dev.	CV (%)	Ranking of criterion								
							Experts								Group judgement
							1	2	3	4	5	6	7	8	
1	A	14.35	73.26	34.01	18.84	55.38	1	2	2	3	2	2	1	4	2
	B	3.58	58.71	25.18	19.46	77.29	4	1	4	2	3	3	1	1	3
	C	4.00	25.00	10.86	7.70	70.90	3	4	3	4	4	4	1	3	4
	D	7.58	58.00	29.96	18.44	61.56	2	3	1	1	1	1	1	2	1
2	A01	9.55	73.34	33.53	20.16	60.12	2	1	1	2	2	1	1	3	2
	A02	19.91	77.32	50.93	24.37	47.85	1	2	1	1	1	2	1	1	1
	A03	5.49	40.00	15.53	13.44	86.53	3	1	2	3	3	3	1	2	3
	B01	23.51	60.01	38.05	12.48	32.81	1	1	1	1	1	2	1	3	1
	B02	6.71	43.29	23.75	13.46	56.67	1	3	4	3	3	1	1	1	3
	B03	4.50	29.80	10.43	8.80	84.36	2	4	2	4	4	4	2	4	4
	B04	20.68	33.53	27.77	4.47	16.10	1	2	3	2	2	3	1	2	2
	D01	11.11	90.00	41.81	26.18	62.62	1	1	1	1	2	2	1	2	2
	D02	10.00	88.89	58.19	26.18	44.99	1	1	1	2	1	1	1	1	1
3	A101	25.00	88.89	77.33	21.58	27.91	1	2	1	1	1	1	1	1	1
	A102	11.11	75.00	22.67	21.58	95.21	2	1	2	2	2	2	2	2	2
	B101	12.50	90.00	67.50	33.00	48.89	1	1	2	1	1	1	2	1	1
	B102	10.00	87.50	32.50	33.00	101.53	2	2	1	2	2	2	1	2	2
	B201	12.50	87.50	59.37	29.44	49.59	1	1	1	1	2	2	1	1	1
	B202	12.50	87.50	40.63	29.44	72.47	2	2	1	2	1	1	2	1	2
	B301	10.00	90.00	48.44	32.59	67.28	2	1	1	2	1	1	1	2	2
	B302	10.00	90.00	51.56	32.59	63.20	1	2	2	1	2	1	1	1	1
	B401	10.49	42.12	25.85	11.95	46.22	3	2	1	1	3	1	1	2	2
	B402	17.89	46.98	32.15	10.28	31.99	2	1	1	2	2	2	1	1	1
	B403	2.48	20.00	6.26	5.95	95.15	4	5	1	5	4	5	2	5	5
	B404	10.72	49.97	21.80	12.33	56.57	2	3	1	3	1	3	1	3	3
	B405	3.21	51.24	13.94	15.95	114.39	1	4	1	4	5	4	2	4	4

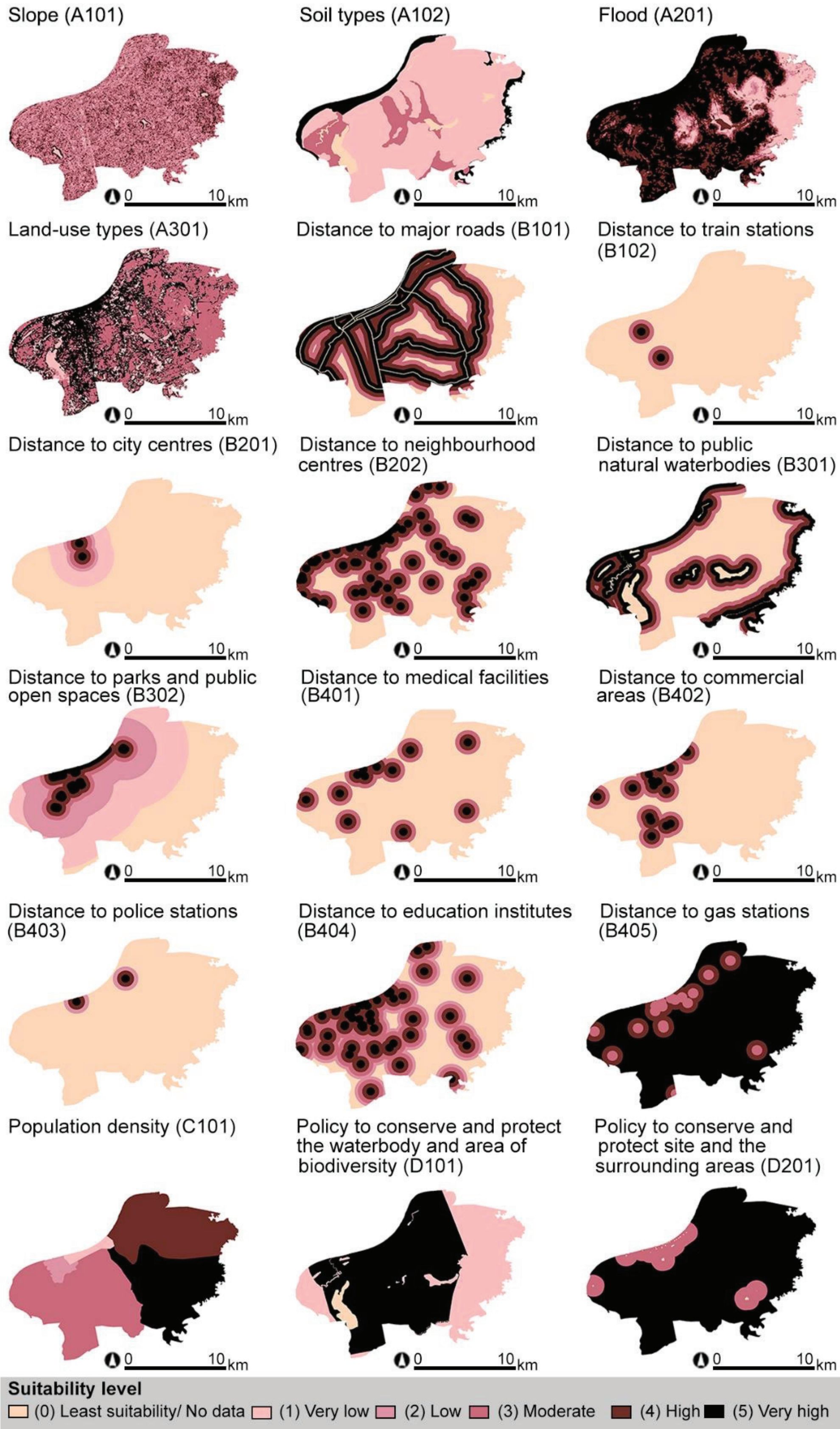

Figure 48 Rating pattern of each criterion

Considering the group judgement, Table 32 indicates that at level 1, the policy had the highest weight value at 37.49 out of 100 for urban development, followed by physical components, accessibility, and population, respectively. Regarding the overall weights, the values of all criteria range between 22.33 – 0.36. The policy to conserve and protect ancient sites and the surrounding areas had the highest overall weight value, followed by flood and the policy to conserve and protect the water body and areas with significant biodiversity, respectively. Due to the highest weight value of the policy at level 1, both criteria in the sub-levels of policy were more important than others, except flood.

Table 32

Weight value and rank of each criterion

Level 1		Level 2		Level 3		Overall Weight	
Criteria	W1	Criteria	W_2	Criteria	W_3	Value	Rank
A	30.39	A01	33.31	A101	80.15	8.11	5
				A102	19.85	2.01	11
		A02	52.83	A201	100.00	16.06	2
		A03	13.86	A301	100.00	4.21	7
B	22.33	B01	40.89	B101	71.06	6.49	6
				B102	28.94	2.64	9
		B02	21.74	B201	61.45	2.98	8
				B202	38.55	1.87	12
		B03	8.82	B301	47.35	0.93	16
				B302	52.65	1.04	15
		B04	28.55	B401	26.43	1.69	13
				B402	35.58	2.27	10
				B403	5.64	0.36	18
				B404	21.69	1.38	14
				B405	10.65	0.68	17
C	9.79	C01	100.00	C101	100.00	9.79	4
D	37.49	D01	40.43	D101	100.00	15.15	3
		D02	59.57	D201	100.00	22.33	1

For physical components, flood had the second-highest weight value, followed by slope, land-use types, and soil types in the sixth, eighth, and twelfth places, respectively, in the overall ranking. It is noteworthy that the criteria in the accessibility group had low weight values compared to the others. The moderately high weight values at level 1 and the highest number of sub-criteria at level 3 caused the weight value of each criterion in the group to have low accessibility. The distance to major roads had the highest weight value in this group; it ranked sixth, with a weight value of 6.49, and the distance to police stations had the lowest weight value for urban development.

6.4.2 Spatial characteristic of suitable areas for urban development in Nong Khai City

Figure 49 (a) presents the total suitability index is range from 2.08–4.36. Based on the Jenks natural breaks classification method, the suitable areas for urban development were categorised into five groups according to the average suitability index: very high suitability, high suitability, marginal suitability, low suitability, and very low suitability.

Figure 49 (b) shows that the areas in Nong Khai City are mainly distributed in the highly suitable areas, followed by the very highly suitable areas. The very highly suitable areas are distributed in the peri-urban area surrounding the original settlement and the current urban areas along the main roads. The highly suitable areas are distributed in the original settlement, the current urban areas, and the area surrounding the very highly suitable areas in the peri-urban area, especially in the central area. At the same time, most marginally suitable areas are adjacent to the highly suitable areas in the peri-urban area. One side of the marginally suitable area is adjacent to the lowly suitable areas. The marginally suitable areas are thus the buffer zones between the suitable and unsuitable areas, which are the waterbodies and agricultural areas at the border area on the eastern side.

As shown in Table 33, most of the criteria at every level had the highest values for the very high suitability group, followed by high suitability, marginal suitability, low suitability, and very low suitability, respectively. According to the statistical data above, the areas with higher suitability had a higher suitability index for each sub-criterion than those with lower suitability. Nevertheless, the suitability levels were classified by the scale score obtained from the sum of all the suitability of every criterion in the study, causing differences in the spatial characteristics of the areas within the same levels. Considering the spatial differences of the areas in each suitability level from the grouping analysis, the spatial characteristic patterns of the areas in the very high, high, and marginal suitability levels were different and could be classified into two subgroups. The areas in the low and very low suitability levels were limited in size, so the spatial characteristics were similar and were not classified into subgroups, as shown in Figure 50.

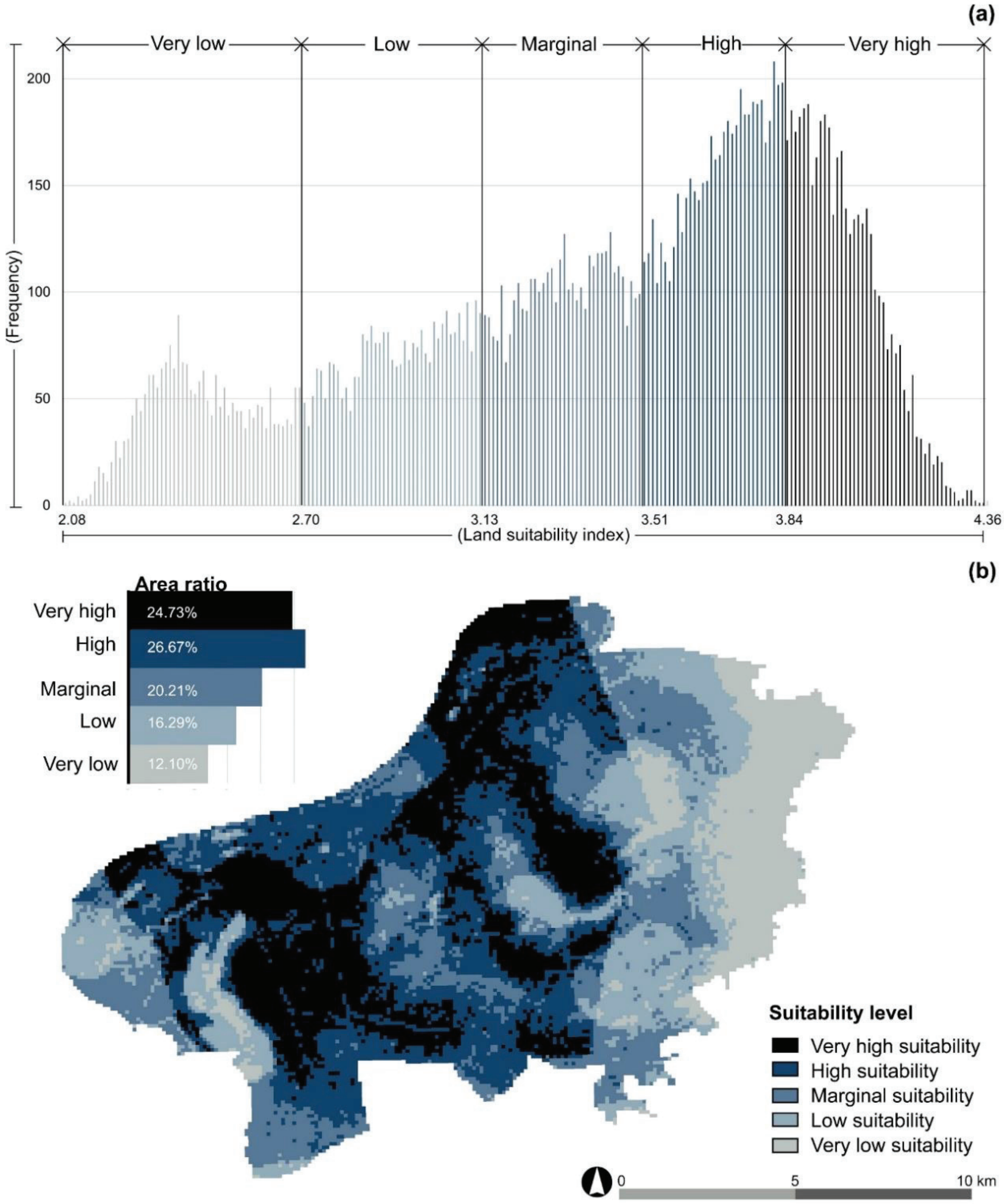

Figure 49 The suitability map for urban development in Nong Khai City

Table 33

Descriptive statistical information divided by the groups of land suitability

Criteria	Suitability Classification									
	Very high		High		Marginal		Low		Very low	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
A	1.21	0.07	1.14	0.12	1.08	0.19	1.00	0.22	0.65	0.14
A01	0.26	0.05	0.26	0.05	0.26	0.05	0.26	0.06	0.28	0.06
A101	0.23	0.05	0.23	0.05	0.23	0.05	0.23	0.05	0.25	0.06
A102	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.03
A02; A201	0.78	0.04	0.73	0.10	0.67	0.19	0.61	0.22	0.25	0.16
A03; A301	0.17	0.04	0.16	0.04	0.14	0.04	0.13	0.04	0.13	0.03
B	0.54	0.13	0.43	0.18	0.36	0.18	0.32	0.18	0.15	0.11
B01	0.30	0.07	0.24	0.09	0.20	0.12	0.18	0.12	0.07	0.11
B101	0.28	0.05	0.24	0.09	0.20	0.12	0.18	0.12	0.07	0.11
B102	0.02	0.04	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00
B02	0.08	0.04	0.06	0.06	0.04	0.04	0.03	0.04	0.01	0.02
B201	0.01	0.02	0.01	0.03	0.00	0.01	0.00	0.01	0.00	0.00
B202	0.07	0.03	0.04	0.04	0.04	0.04	0.03	0.04	0.01	0.02
B03	0.04	0.02	0.04	0.03	0.03	0.03	0.02	0.02	0.03	0.02
B301	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02
B302	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.01
B04	0.12	0.06	0.10	0.07	0.08	0.05	0.08	0.05	0.04	0.03
B401	0.02	0.03	0.02	0.03	0.01	0.02	0.02	0.03	0.00	0.01
B402	0.03	0.04	0.02	0.04	0.01	0.02	0.01	0.02	0.00	0.01
B403	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B404	0.04	0.02	0.04	0.02	0.03	0.02	0.02	0.02	0.00	0.01
B405	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.00
C	0.36	0.09	0.34	0.09	0.37	0.10	0.41	0.08	0.43	0.06
D	1.87	0.05	1.78	0.19	1.53	0.30	1.23	0.29	1.25	0.11
D01; D101	0.76	0.02	0.74	0.08	0.46	0.30	0.22	0.21	0.15	0.04
D02; D201	1.11	0.05	1.04	0.17	1.07	0.14	1.01	0.19	1.10	0.10

6.4.2.1 Very high suitability

The very high suitability group was the most suitable in almost all criteria at level 1, except for the population. Most of the areas were flood-free, and more than half were built-up lands, which were the most suitable for urban development. Regarding the accessibility group, the areas were distributed primarily in pedestrian or service areas of major roads, neighbourhood centres, public natural waterbodies, parks and public open spaces, and educational institutes. In addition, it is noteworthy that the pedestrian catchments of some criteria were in this class, such as train stations, city centres, medical facilities, commercial areas, and police stations. Furthermore, these areas are very suitable in terms of policies because approximately all areas are distributed outside the natural and cultural conservation policy zones.

Based on spatial characteristics, the areas can be categorised into two zones, as shown in Figure 50 and Figure 51. There are different characteristics between the two subgroups of the five criteria: land-use types, distance to train stations, distance to city centres, distance to commercial areas, and population density. Most of the very highly suitable areas in Zone 1 are located adjacent to the original settlement and current urban areas. The areas in this group are distributed in pedestrian catchments. Zone 2, which is very highly suitable, is located farther from the original settlement and current urban areas, making the ratio of agricultural lands in Zone 2 higher than that in Zone 1, and most of Zone 2 is less accessible. Although the areas in Zone 2 are less suitable in terms of accessibility criteria, Zone 2 is more suitable than other zones in terms of population, which is mainly in the areas with the lowest population density.

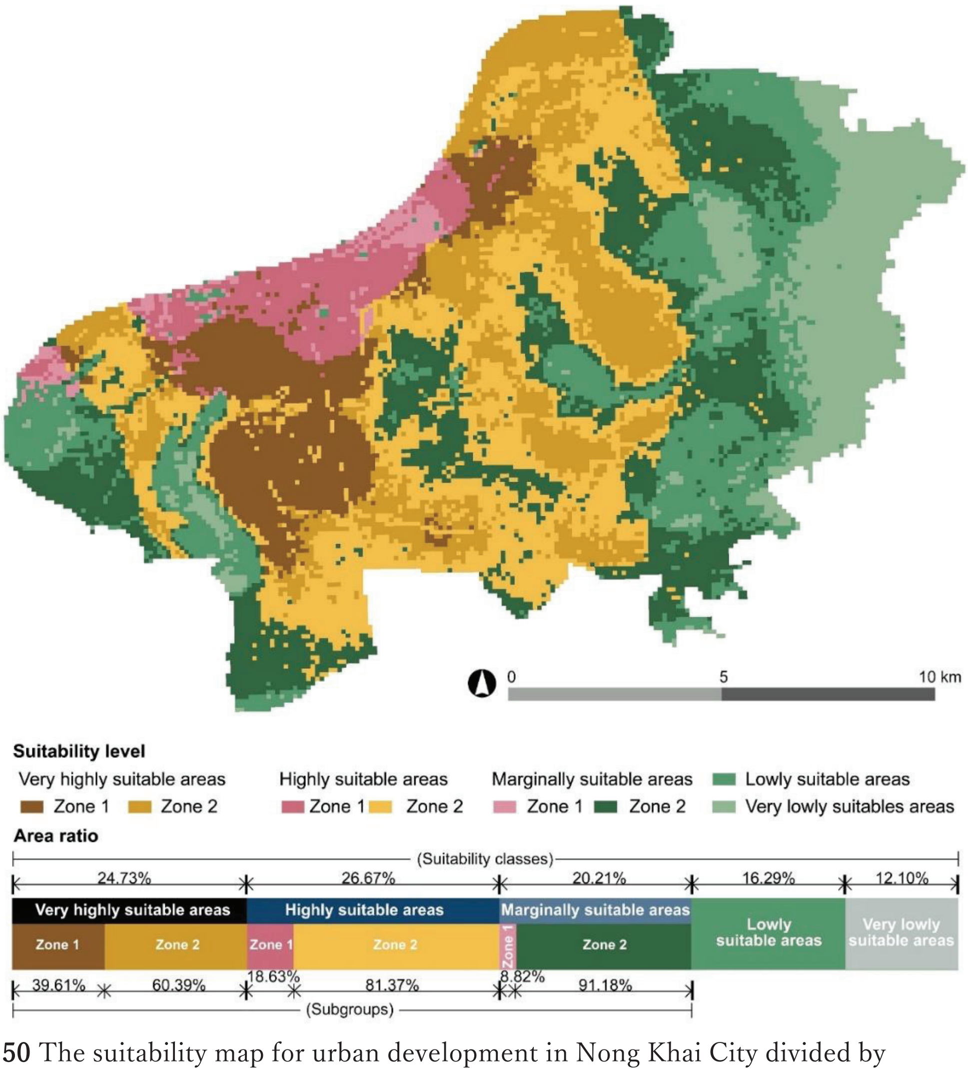

Figure 50 The suitability map for urban development in Nong Khai City divided by the spatial characteristic in each group

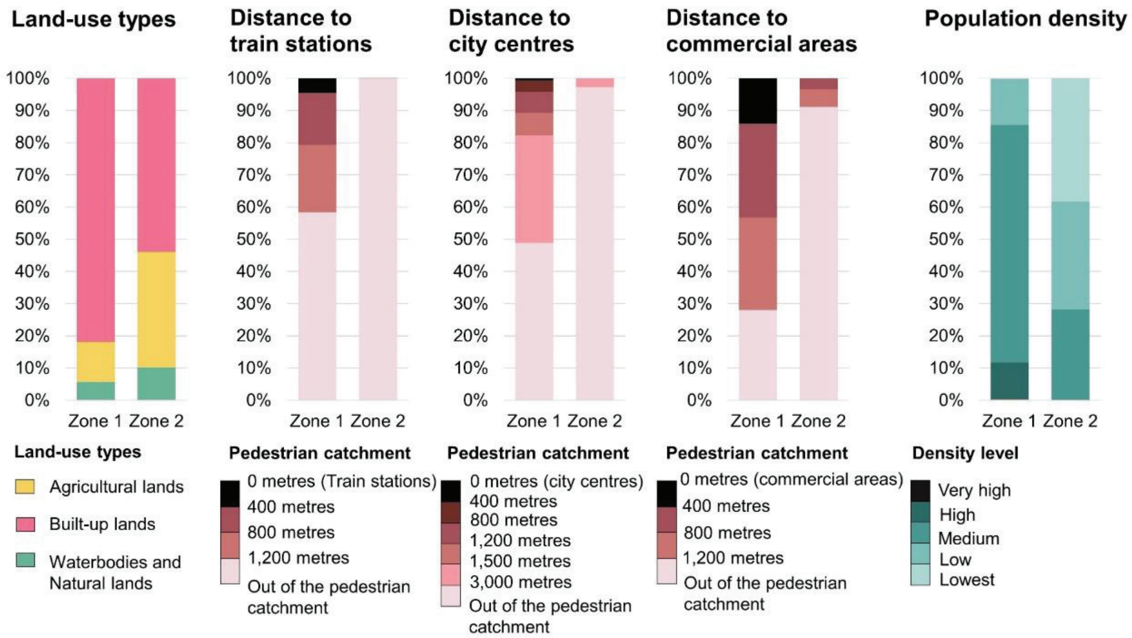

Figure 51 The different characteristics in two subgroups of the very highly suitable areas in Nong Khai City

6.4.2.2 High suitability

Overall, the characteristics of the highly suitable areas were similar to those of the very highly suitable areas, especially for the slope, distance to major roads, distance to neighbourhood centres, distance to parks and public open spaces, distance to medical facilities, distance to educational institutes, distance to police stations, distance to gas stations, and the policy to conserve natural assets. However, the major criterion that lowers the suitability index of this group to be less than that of the very highly suitable area is the policy to conserve cultural assets. The buffer zones of the ancient sites were primarily located in highly suitable areas, making the total suitability level lower than that of highly suitable areas.

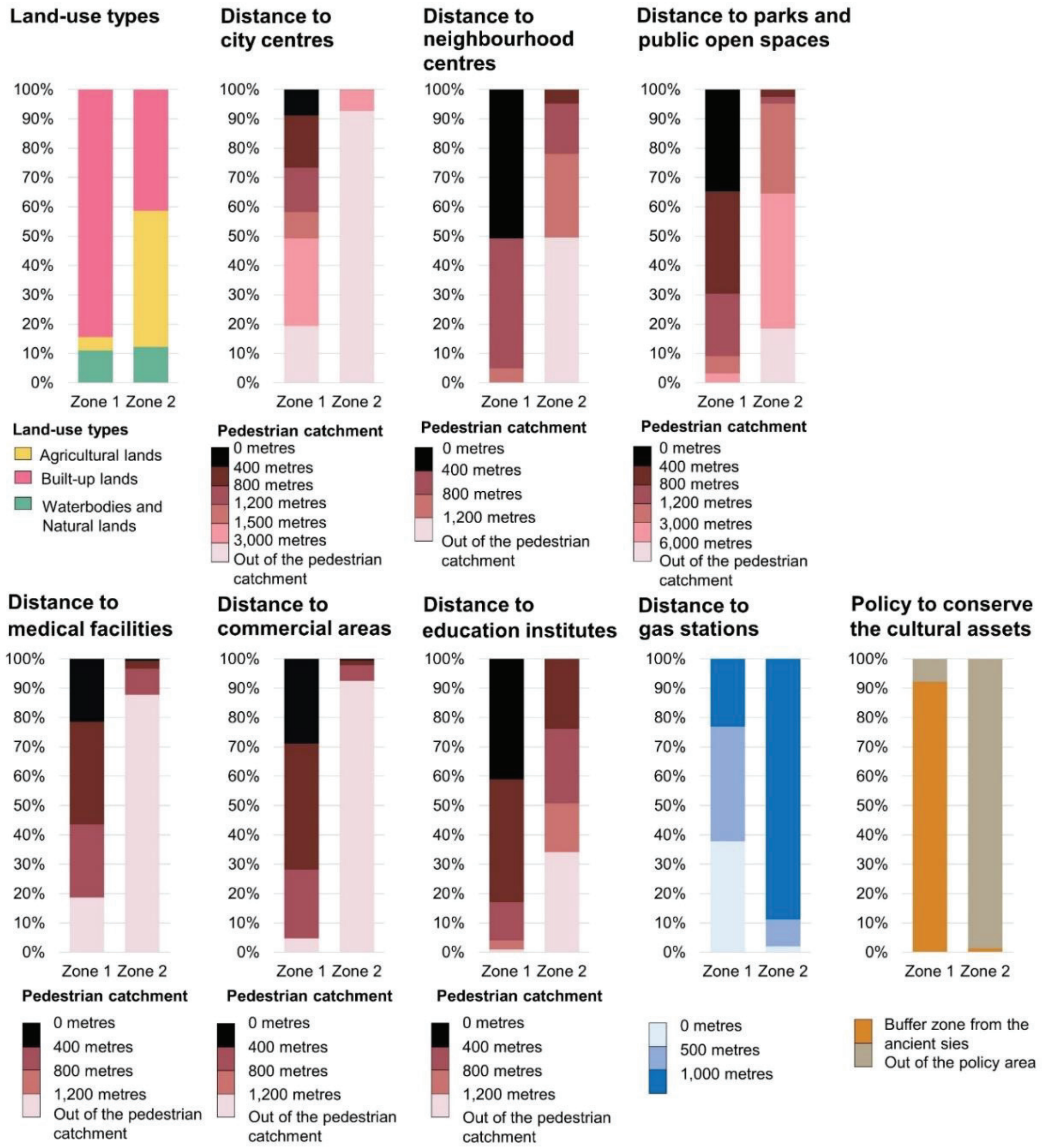

Figure 52 The different characteristics in two subgroups of the highly suitable areas in Nong Khai City

Highly suitable areas can be categorised into two subgroups based on their spatial characteristics, as shown in Figure 50. There are different patterns for the nine criteria in the two zones, as shown in Figure 52. Most of the areas in Zone 1 are located in the original settlement and current urban areas of Nong Khai City. Owing to their location, most of the areas are built-up lands and are distributed in the pedestrian catchments of city centres, neighbourhood centres, parks and public open spaces, medical facilities, commercial areas, and educational institutes. Ancient sites and buffer zones were also observed in the original settlement areas. Therefore, development is still possible due to its suitability in terms of accessibility, but it should abide by the cultural conservation policy. Zone 2 is adjacent to very highly suitable areas, which are primarily located in the peri-urban area. Therefore, the primary land use type was agricultural land. The number of areas located in the pedestrian catchment of this group was smaller than that in Zone 1. However, most of these areas are free from strict policies aimed at conserving cultural assets.

6.4.2.3 Marginal suitability

The spatial characteristics of marginally suitable areas are a mixture of those of very highly and highly suitable areas and unsuitable areas. The slope, soil type, population density, and policies to conserve cultural assets are similar to those of very highly suitable areas. The spatial characteristics of the areas in this group are also similar to the highly suitable areas in terms of accessibility, which are distributed inside the pedestrian catchment of five criteria: major roads, neighbourhood centres, public natural waterbodies, parks and public open spaces, and educational institutes. In addition, more than half of the areas are near neighbourhood centres within the pedestrian catchment. However, there are some limitations to developing areas in this group into urban areas. Although more than half of the areas are distributed in areas that had not faced floods, the largest areas that encountered floods three to five times are distributed the most in this class. In addition, this group is marginally suitable in terms of policy because approximately half of the areas are controlled by the policy to conserve natural assets.

The areas in this group can be categorised into two zones (Figure 50). Zone 1 is primarily located in the original settlement areas of Nong Khai City, whereas Zone 2 is located in the peri-urban area. As shown in Figure 53, there is large built-up land with the most suitable soil in Zone 1, while more than half of the areas of Zone 2 are agricultural land with the least suitable soil series. In addition to land-use types, policies to conserve cultural assets and some criteria regarding accessibility are also different. Zone 2 is in the lowly suitable areas in terms of accessibility compared to Zone 1. Most of the areas in Zone 1 were in the buffer zones of ancient sites and gas stations. However, most of Zone 1 is safe from flooding and is not affected by the policy to conserve natural assets. Despite being in the marginal suitability group, Zone 1 is not restricted by floods or the policy to conserve natural assets. These differences in spatial characteristics explain why Zone 1 is suitable for urban development, whereas Zone 2, with hazards and limitations on accessibility, is not suitable.

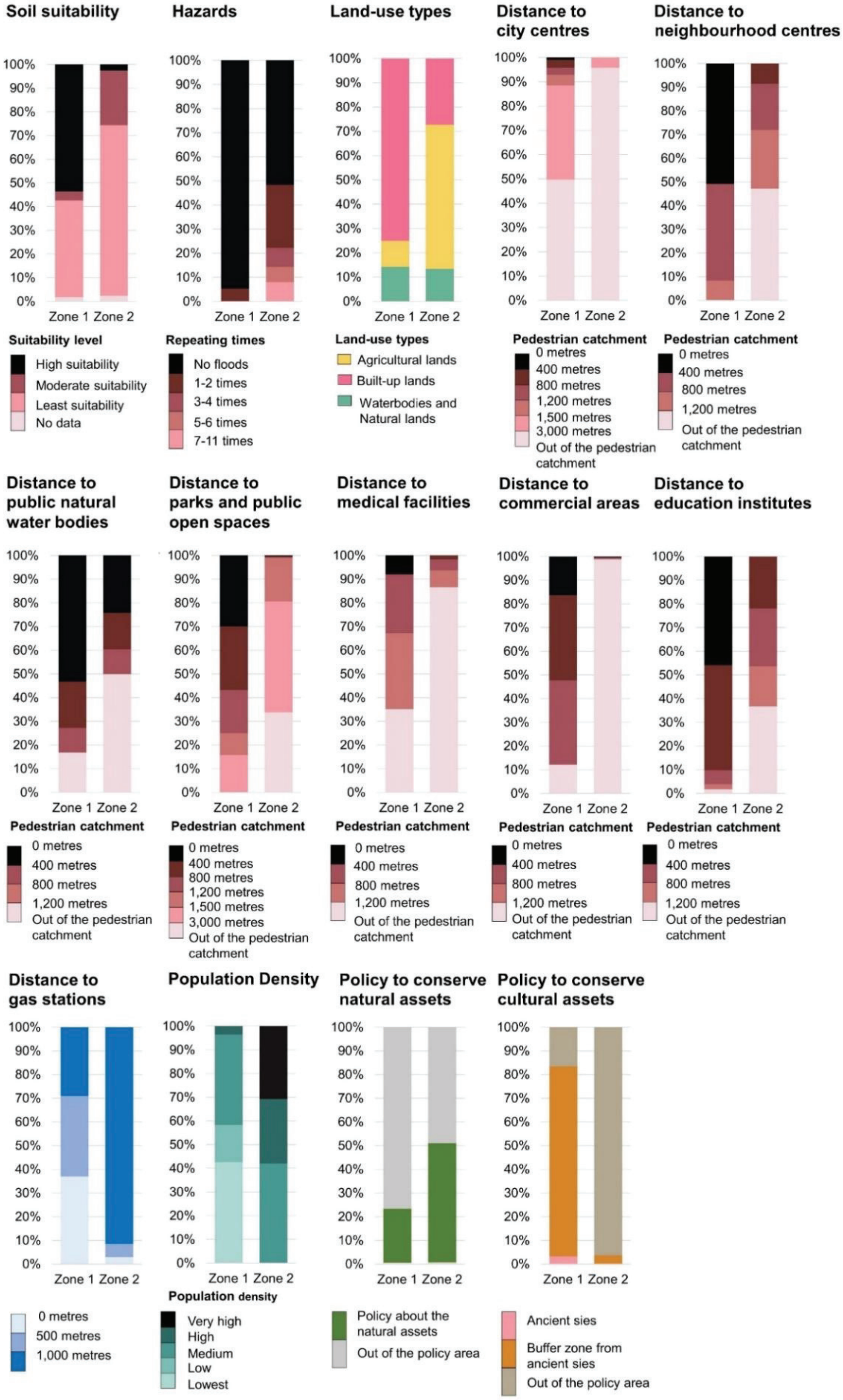

Figure 53 The different characteristics in two subgroups of the marginal suitable area in Nong Khai

6.4.2.4 Low suitability

Low-suitability areas are unsuitable for urban development. More than half of the area is agricultural land. Despite this, the areas are mainly distributed in the most suitable areas in terms of population density and policies to conserve cultural assets. However, more than half of these areas have experienced floods. Furthermore, the areas in this group lack accessibility, except for major roads and educational institutions. It is noteworthy that the most crucial waterbodies are in this group, and most areas are controlled by policies to conserve natural assets, so they are not suitable for urban development.

6.4.2.5 Very low suitability

Areas with very low suitability are suitable in terms of population density and policies to conserve cultural assets. However, most criteria were less suitable. For example, the primary soil in this group is fine, mixed, active, nonacidic, isohyperthermic Vertic (Aeric Vertic) Endoaquepts, which is the least suitable for built-up development, and large areas have encountered floods more than seven times. In addition, most pedestrian catchments in the accessibility criteria, except for public natural waterbodies, were outside. Regarding the policy to conserve natural assets, most of the areas are distributed in the rural and agricultural policy zones in the Nong Khai Provincial Comprehensive Plan B. E. 2560, resulting in their unsuitability to develop them into urban areas.

6.5 Discussion

As built-up land expansion can occur because of upcoming infrastructure development of the BRI, it is necessary to shape land policies by assessing suitable areas for urban development, especially in small cities. GIS-MCDA is a fundamental technique for analysing suitable areas for urban development. Various GIS-MCDA techniques have been developed to deal with dynamic land use systems. However, the advanced GIS-MCDA techniques are complicated and difficult to practically utilise. Hence, to apply the GIS-MCDA to assess land suitability for urban development in small cities, the GIS-MCDA technique should be simple and able to determine the influence of complicated factors. This was when AHP came into play.

In this study, the assessment of suitable areas is based on 18 crucial criteria, including physical components, accessibility, population, and policies. This is similar to the factors for predicting the pattern of urban development by White et al. (2015) and Barredo et al. (2003), who dealt with multiple factors to present a complex urban environment. The results indicate that the policy to conserve the cultural assets, flooding, and the policy to conserve the natural assets are the three biggest influences on the decision-making for urban development areas. According to the results, the area designation considers the hazard zones and sites that need to be conserved and are prone to damage by urban development. Not overlooking natural and cultural heritage while expanding the urban areas leads to sustainable urban development and is consistent with Target 11.4 in the SDGs, which aims to strengthen efforts to protect and safeguard the cultural and natural heritage of the world, as well as Target 15.1 which aims to ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services (United Nations, 2021). Some studies have considered conservation issues while identifying suitable areas for urban development, but the most used criteria are related to biodiversity and ecosystems. The criteria related to cultural heritage conservation have rarely been included, even though the study by Xiao et al. (2021) found that the world cultural heritage sites in the BRI have a higher risk of damage due to urban sprawl and infrastructure expansion. Consequently, cultural heritage sites should be protected in the urban planning policy. This study outlines an urban development plan that does not overlook cultural heritage sites that have been affected by urban development over the years and are difficult to restore. Interestingly, concern about the existence of culture amid risk factors has received the highest attention in terms of spatial planning. In addition to urbanisation, flood vulnerability also puts cultural factors at risk (Vojinovic et al., 2016).

Moreover, emphasising hazard criteria is in line with the sustainable urban development policy of the SDGs, especially Target 11.5, which focuses on reducing the death toll and the number of people affected by a natural hazard (United Nations, 2021). It is also in line with the study of Bathrellos et al. (2012), which proposed that natural hazard should be included in identifying suitable areas for urban development. In addition, many studies regarded hazard as one of the top criteria to consider when identifying areas for urban development (Luan et al., 2021; Sedigheh et al., 2009). According to the integration of the flood frequency as one criterion, the result reveals that based on the spatial characteristics of the areas in each zone, although the very highly, highly, and zone 1 of marginally suitable areas, that are assigned as the suitable zone for urban development, are not completely free from flooding, the ratio of the areas distributed on the high-frequency flood within 15 years is low. Only 0.62% of the suitable areas for urban development are located in the areas which have encountered floods more than 5 times. All of them are distributed in zone 2 of the highly suitable area. At the same time, about 88.97% of very highly suitable areas for urban development are distributed in the flood-free areas, and 10.68% are distributed in the area which was flooded 1-2 times. For the highly suitable areas, although few areas distributed in the area which was flooded more than 5 times, about 83.11% of the areas in this zone are free from flood and about 13.61% of the areas are distributed in the areas that have encountered flood only 1-2 times. While the flood-free area is the majority pattern of the suitable areas for urban development followed by the areas which have encountered floods 1-2 times, 91.82% of the areas which was flooded more than 3 times are distributed in the zone of non-suitable areas for urban development. About 50% of the areas which was flooded more than 3 times are distributed in the very lowly suitable area for urban development and cause the areas which was flooded more than 7 times to become the main pattern of this zone.

However, compared to the study by Foroozesh et al. (2022), the importance of the factors was demonstrated differently. Accessibility to urban infrastructure is more important than the other factors. The focus on the factors related to accessibility to the network and proximity to the existing development is also key to analysing the potential areas for urban development using cellular automata (Batty et al., 1999; White et al., 2015).

Although sub-factors in the accessibility group had lower importance values than the factors related to policy and hazard, accessibility was not overlooked in this study. Therefore, conservation and attempts to decrease the effects on the environment were not the only factors taken into account. Economic benefits are also maximised along the way from accessibility factors. This is in accordance with the ecological-based planning by McHarg (Collins et al., 2001) and the concept of future city development, which should support economic growth, provide infrastructure and social service efficiency, and protect environmental assets (Riffat et al., 2016) to decrease the negative effects of urban sprawl and lead urban areas to sustainable settlements (Huang et al., 2021).

Although the urban expansion situation in Nong Khai City might be described as severe (Keeratikasikorn, 2018), given the suitability map for urban development, our findings reveal that it is appropriate because more than 50 % of the built-up lands in Nong Khai City in 2017 belonged to the very highly and highly suitable areas. Only 12.64 % of them were in the lowly and very lowly suitable areas, as shown in Figure 54.

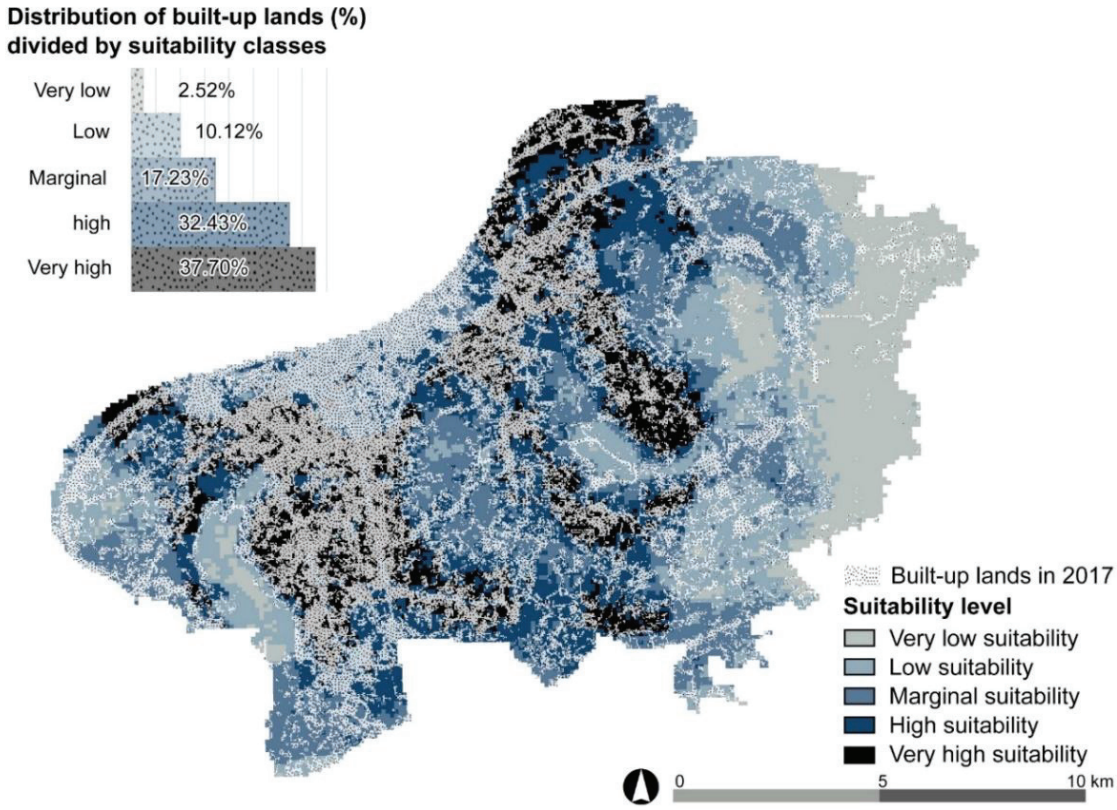

Figure 54 The comparison between the built-up lands in 2017 and suitable areas for the urban development

Although AHP is a fundamental GIS-MCDA technique, this study found that AHP can identify and manage complicated factors to classify areas into different suitability classes; 24.73 % of Nong Khai City areas are classified as very highly suitable areas. As the policy to conserve the cultural assets has the highest weight, very highly suitable areas are located adjacent to original settlement and current urban areas, which are full of ancient sites, to decrease the negative effect of urban development. While the original settlement and current urban areas have lower suitability levels, they are still classified as highly and marginally suitable. Regarding low and very low suitability, most areas are prone to flooding, lack accessibility, and are under the policy to conserve the natural assets. These spatial patterns demonstrate the capability of the AHP integrated with the GIS framework for analysing suitable areas for urban development.

The spatial characteristics of the very high and very low suitability areas for urban development in this study are similar to those of other studies that performed AHP and advanced methods. For example, the very highly suitable areas are being in the service areas of the existing infrastructure (AlFanatseh, 2021; Mosadeghi et al., 2015; Navin Ganesh et al., 2020; Ullah & Mansourian, 2016), being in the practically hazard-free zones (AlFanatseh, 2021; Liu et al., 2014;

Ullah & Mansourian, 2016), and being located near the road (AlFanatseh, 2021; Liu et al., 2014; Navin Ganesh et al., 2020) or public transportation (Ullah & Mansourian, 2016). Likewise, the very low suitability groups are usually described as prone to hazard (Ullah & Mansourian, 2016; Zhang et al., 2013), restricted by the regulation of the conservation policy to protect assets (Yang et al., 2008; Zhang et al., 2013), and lack of accessibility (Navin Ganesh et al., 2020). The similar spatial characteristics between this study and other studies that used other methods help confirm that the performance of AHP is sufficient to assess land suitability for urban development in small cities because it can determine the most suitable areas with the most suitable spatial characteristics. In contrast, the least suitable spatial characteristics were found in very low and low suitability areas.

Although the integration of AHP and GIS can create a suitability map for urban development, it is still challenging to use the final suitability map to support urban planning because of the lack of consideration for complicated spatial characteristics. Hence, this study extends the application of AHP by integrating a grouping analysis to categorise suitable areas for urban development based on spatial characteristics. The addition process of grouping analysis is a simple method that helps urban planners understand the heterogeneous spatial characteristics in each class of the suitability map, compared to other studies that present only the suitable areas with a land suitability index and the scale or ordinal value (AlFanatseh, 2021; Huang et al., 2021; Ullah & Mansourian, 2016). It also helps urban planners make decisions regarding areas with unclear suitability levels, such as marginally suitable areas which are a mixture of suitability and unsuitability for urban development. Furthermore, the clarification of the heterogeneous spatial characteristics at each level by grouping analysis enables urban planners to easily understand the spatial characteristics in terms of opportunities and constraints, which are important information for formulating spatial policies, while other studies used complicated processes to clarify these components (Liu et al., 2014).

As shown in Figure 55, based on the land suitability index and spatial characteristics from the grouping analysis, the suitable areas to implement the policy for urban development are two zones of very high, high, and zone 1 of marginal suitability areas, which cover 100.82 sq. kilometres of Nong Khai City. These areas can house a minimum of 756,150 residents according to the Standard of Residential Land Use with Low Density for Medium and Small Cities released by the Department of Public Works and Town and Country Planning (2006). Zone 1 of the very highly suitable areas should be designated as an extended urban area to respond to the growth of the original urban areas in Zone 1 of the highly and marginally suitable areas. Due to its location, it is easier to access train stations and areas with public facilities and free from the policy. Owing to the areas that surround Zone 1 of the very highly suitable areas and are located far from the city centres, the areas in Zone 2 of the very highly suitable areas should be designated as 1) the urban area supporting Zone 1 of the very highly suitable areas and 2) the urban area as the new node supporting the city centres and Zone 1 of the very highly suitable areas. Zone 2 of the highly suitable areas should be developed into built-up land to respond to the expansion of built-up land from areas of very high suitability. Zone 1 of the highly and marginally suitable areas that are distributed in the original area should be designated as urban development zones with a conservation policy to maintain the role of the city centre while conserving cultural assets from the condition of ancient sites. Finally, Zone 2 of the marginally suitable, low, and very lowly suitable areas should be designated as non-urban development zones with areas such as agricultural lands and lands under ecological conservation owing to several limitations.

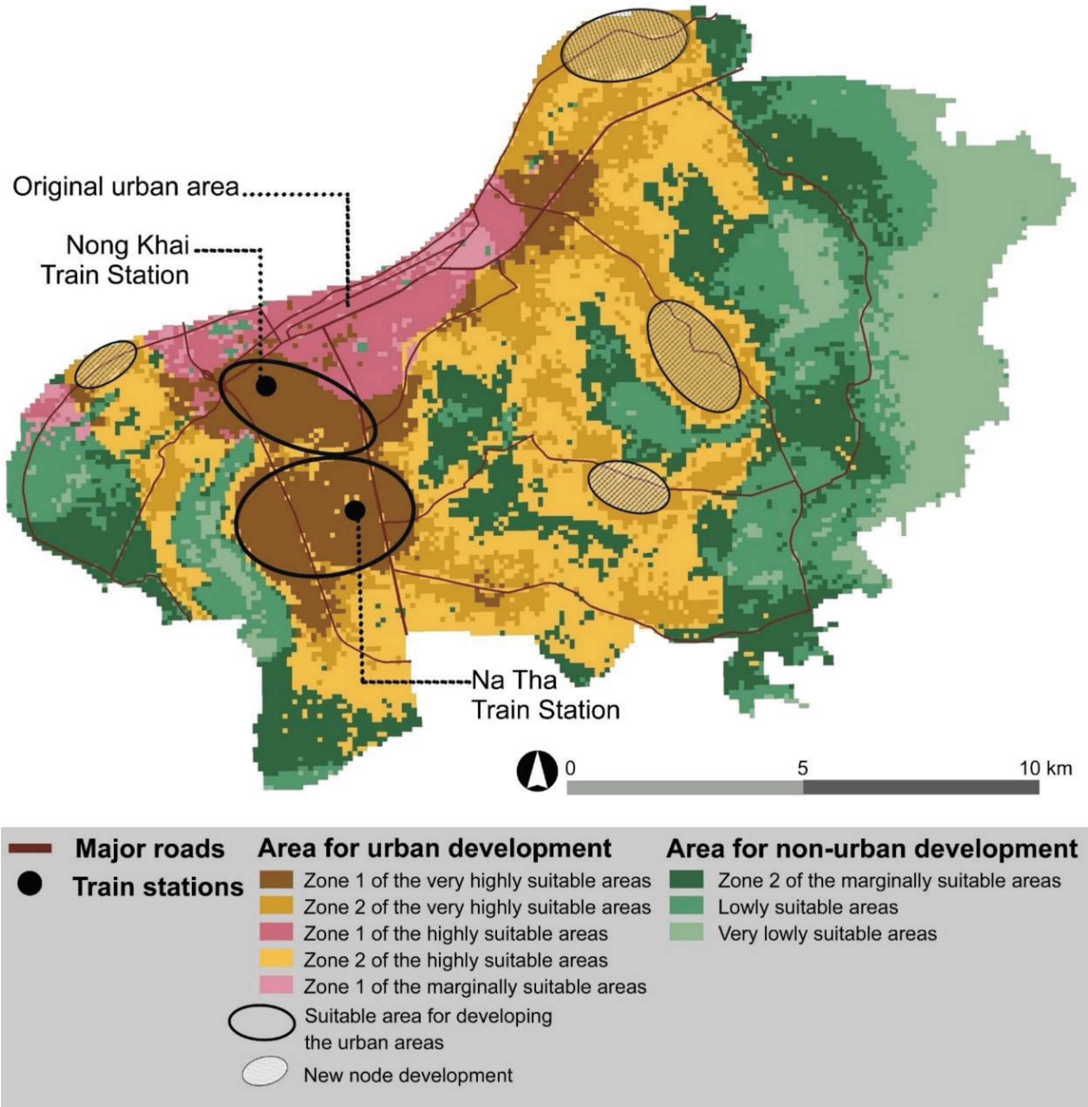

Figure 55 Map of the recommendation for urban development policies

According to the recommendations for urban development policies above, the areas for urban development surround the original settlement areas and are also found along the main road network with high accessibility and minimal damage from floods. This is consistent with the sustainable urban planning of Tierolf et al. (2021), which indicates that urban development in Thailand should not occur in the flood-prone surroundings of urban core areas.

Dividing the areas into two groups (the urban development area and non-urban development area), the comparison between this recommendation for the urban development policy and the current land-use policies reveals that 60.45 % of the areas in the recommendation are similar to the ones in the current land-use policies, especially the non-urban development areas with 88.15 % similarity. However, only 26.22 % of the urban development areas are alike. Approximately 90.71 and 90.63 % of zones 2 of the very high and high suitability areas, respectively, are similar in the current policy and the recommendation.

In addition, according to the comparison between the recommendation for the urban development policy and the land-use policy in the Building Control Act for Special Economic Zones, which is one of the land-use policies focusing on urban development, the types of urban areas in the land-use policy in the latter are consistent with the areas in the recommendation for urban development policy. A total of 97.88 % of the built-up areas in the Building Control Act for Special Economic Zones were distributed in suitable areas for urban development. Most of the new economic development zones were in zone 1 of the very high suitability area, the very highly suitable areas proposed by the recommendation to be extended as urban areas in the future. Likewise, most old commercial zones were in zone 1 of the high suitability area, the original settlement, and current urban areas. For the primary neighbourhood, the areas are densely distributed in zones 1 of very high and high suitability areas, which are the very highly and highly suitable areas for urban development.

The comparison between the recommendation policy from the suitability map and the current land-use policy shows the potential of the AHP in urban planning. The detection of the different areas between the current land-use policy and recommendation policy can be used as the fundamental database to determine the land-use policy in the next step because it reflects the gap in the current land-use policy enforcement. At the same time, it can confirm the suitability of the current land-use policy.

6.6 Conclusion

To summarise, this chapter provides a theoretical framework to analyse the suitable areas for urban development in the context of small cities from the case of Nong Khai City. It demonstrates the potential of integrating AHP and grouping analysis in urban planning as a crucial tool to shape a land-use policy for urban development in small cities. Suitability analysis by integrating AHP and grouping analysis helps city planners determine suitable areas or provide guidelines for reasonable decision-making with quantitative evidence. Practically, this study can help urban planners to find suitable areas to introduce policies that respond to urbanisation in Nong Khai City and other small cities in the BRI.

Regarding on Nong Khai City, 24.73 % of the areas were very highly suitable for urban development, most of which are flood-free with high accessibility and high suitability regarding policy. Most of them distributed in the central areas surrounding the original settlement area and the areas along the Highway no. 2 and 233. At the same time, precisely 12.10 %of the areas were very lowly suitable for urban development which are distributed mainly in the eastern area. Most of which are prone to flooding, have low accessibility, and are distributed in the zones under the policy to conserve natural assets.

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Chapter 7

Prediction of the expansion of the built-up land and the recommendation on land-use zoning policy of Nong Khai City

Contents

7.1 Introduction

Chapter 4 indicates that the built-up lands in Nong Khai City expanded into the surrounding areas between 1997 to 2017, with a high change rate in the peri-urban areas. Although the comparison between the built-up lands in 2017 and the suitable areas for urban development in Chapter 6 indicates that more than 50 % of these built-up lands are distributed in the very highly and highly suitable areas, the expansion of the built-up lands in the peri-urban areas of Nong Khai City is on the risk path because, according to Chapter 5, about quarter of Nong Khai City is in the very highly and highly flood-prone zones. Bamrungkhul & Tanaka (2022) overlaid the flooded areas (at least three times within fifteen years) with the land-use maps in 1997 and 2017 from chapter 4 and found that the expansion of the built-up lands was a significant change of land use in the repetitious flooded areas. This evidence implies that the expansion of the built-up areas has a high possibility of encountering floods and affecting sustainability in the future. However, the understanding of the expansion of the built-up lands of Nong Khai City in the future is lacking and needs clarification for the development of the land-use policy.

The prediction of the built-up land expansion is an important process to make a decision on a suitable land-use policy (Khoshnood Motlagh et al., 2021). It provides the future situations through the visual representation based on the assumptions or data trajectories (Sharma et al., 2018). The visual representation is the essential information for the models which help decrease the sprawl of the built-up lands (Mc Cutchan et al., 2020, p. 1482). Pijanowski et al. (2002, p. 556) summarises the benefits of the prediction of the built-up land expansion in order to support the sustainable planning in three areas: (1) exploring the mechanism by relating the driving factors and the changes of land use, (2) projecting potential future impacts of the land-use changes, and (3) evaluating the influence of alternative policies on the changes of land use. Therefore, the prediction of the urban expansion is a tool to support the sustainable management of urban areas (Triantakonstantis & Mountrakis, 2012) by helping the policymakers understand the directions and spatial patterns of the built-up growth, including the intervention of urban policies (Hewson et al., 2019)

The prediction of the built-up land expansion in Nong Khai City was introduced in this chapter to assess the directions and patterns of the built-up land expansion in Nong Khai City under different scenarios. Two questions were raised in this chapter to support the development of recommendations on land-use policies: (1) how will the built-up lands in Nong Khai City grow up in the future?, and what are the consequences in terms of flood-prone areas and suitable areas for urban development? (2) what are the impacts of land-use policies on the built-up land expansion in the future?. The outcome of this chapter is a crucial database to support the recommendation of land-use zoning policies in the last section of this chapter.

This chapter consists of six sections. The objective is presented in the first section to form the structure of the chapter. Then, the application and modelling of the land-use simulation are reviewed and discussed in the section of literature review. In the third section, the data and methodology including the detail of scenarios to predict the built-up lands are presented, and then the results are described in three parts to respond to the objectives: (1) the direction of the built-up land expansion (objective 1), (2) the expansion of the built-up lands in the areas susceptible to floods, (3) and the expansion of the built-up lands based on the suitability for urban development (objective 2). Next, the expansion of the built-up lands in Nong Khai City is summarised from the finding in Chapter 2 and Chapter 4 to answer questions 1 and 2, including the first main research question, in the discussion and conclusion. Last, the best scenario to reduce the sprawling of the built-up lands of Nong Khai City in the flood-prone areas is adopted to create the recommendation of the land-use zoning policy to manage and develop the city in the floodplain responding to objective 3.

7.2 Objective

1) To predict the expansion of the built-up lands in Nong Khai City between 2027–2037 under the different scenarios
2) To analyse the expansion of the built-up lands in Nong Khai City between 2027–2037 in flood-prone areas and the least suitable areas for urban development
3) To recommend the land-use zoning policy of Nong Khai City based on the best scenario

7.3 Literature review

The simulation of the future built-up lands is a part of a land-use change study. Due to the negative impact of the built-up land expansion on the biodiversity as same as the problems and losses from the expansion of the built-up lands in the hazard-prone areas, the simulation of the built-up lands that projects the expansion in these unsuitable areas is an important step to form a sustainable land-use policy. The projection of the new potential urbanised areas helps the policymakers to make decisions on suitable areas and land-use policies to reduce the impact on the biodiversity caused by the sprawl of the built-up lands into the areas with important biodiversity and to decrease the losses from the sprawl of the built-up lands into the hazard-prone areas. For example, Mesta et al. (2022) simulated the expansion of the urban built-up areas in Kathmandu Valley in 2050 and detected the built-up lands in the inundated zones. The result of the study reveals that twice of the current urban areas of Kathmandu valley will be distributed in the potentially inundated zones. Likewise, the study of Kim & Newman (2019), indicates that new built-up areas in Houston will be distributed in the flood risk areas, and the zoning regulation should be considered to control the new urbanised areas to minimise the flood damage. Li et al. (2022) and Seto Karen et al. (2012) applied the simulation of the future built-up lands in terms of the environment. The urban expansion was determined at a global scale and detected the areas which were at risk of losing their roles as natural habitats and terrestrial biodiversity due to the urban expansion. Simkin Rohan et al. (2022) indicate that the 855 species will be threatened by urban expansion by 2050. For the local scale, Mozumder & Tripathi (2014) also predicted the expansion of the urban and agricultural lands in the uplands of Deepor Beel (A Ramsar wetland) in India in order to help the policymakers to develop the land-use policies to conserve the ecology of wetlands. Zubair et al. (2017) also predicted the urban expansion into the watershed to determine the losses of wetlands in the Kansas City Metropolitan area.

The simulation of the built-up lands is applied in two scopes. First, the simulation of the built-up land expansion under the scenario of Business as Usual (BAU) (Zhang et al., 2021) simulates the expansion of the built-up lands by using the same trend as the previous times. The simulation of the built-up land expansion under the scenario of BAU is applied to forecast the effect of the built-up land expansion on specific phenomena such as the loss of agricultural land and habitats. Moreover, it is usually used to identify the directions of the built-up land expansion to reduce the expansion in the unsuitable areas. For example, Vinayak et al. (2021) predicted the expansion of the Mumbai region in 2050, indicating that the built-up lands would sprawl into the suburban region that needed the policies to minimise the negative effect of land transformation. It is similar to the study of Leta et al. (2021) that predicted the change of land use in the Nashe watershed of Ethiopia in 2035 and 2050 and found that the forestland would decrease. At the same time, the built-up lands and agricultural lands would grow, increasing vulnerabilities to various hazards. The second scope is the simulation of the built-up land expansion under the policy implementation or future conditions. In this scope, the built-up lands are simulated to determine the performances of the proposed spatial policies. To evaluate the influence of spatial policy on land-use change, this simulation usually analyses the land-use change under BAU or without the policy implementation as the baseline scenario. For example, the study of Mishra et al. (2021) compared the scenarios of the urban expansion in the Mega Manila (Philippines) with and without the enforcement of protected areas on the natural areas. The result shows that there is the urban expansion in the areas with rich biodiversity, especially in the scenario without the enforcement of protected areas. Although the protected areas are enforced, some forest lands are possibly affected by the urban expansion. The comparation between the BAU situation and the policy-implemented situation to support the biodiversity also occurs in the study of Mozumder & Tripathi (2014) that analysed the expansion of urban areas and agricultural areas in the Deepor Beel, which is the Ramsar Wetland of India. In this study, the expansion under BAU was compared with the expansion under the implementation of policies to conserve the natural wetlands, such as (1) the Conversion Restriction Policy, which doesn't allow any land-use changes for urban and agricultural lands in the green belt and (2) Wetland Restoration which attempts to relocate developed and agricultural lands out of the green belt. According to the study, the wetlands will decrease under the BAU due to the expansion of the built-up lands. At the same time, the Wetland Restoration Policy was indicated as the best scenario to conserve the wetlands. In addition, the comparative study between BAU and policy-implemented scenarios was also applied to support the management of hazard areas. For example, the study of Kim & Newman (2020) compared the expansion of the built-up lands under different scenarios — the BAU scenario, the scenario which implements the city land-use plan, and the scenario that doesn't allow the urban area to expand into the future 100-year flood plain — to determine the flood exposure in the future. From the recent works, it can imply that the comparison between the BAU scenario and the policy-implemented scenario helps the city planners and policymakers to understand the characteristics of the built-up land expansion based on what-if situations, and they can use this information to make a decision on the land-use policy planning. It provides the optimal solution to develop the land-use policy after assessing the impact of the potential scenarios associated with the planning policy (Mc Cutchan et al., 2020, pp. 1482-1483), which helps the policymakers to reasonably manage the uncertain urban areas in the future. The simulation of the built-up lands thus is a crucial tool to develop a sustainable urban area (Triantakonstantis & Mountrakis, 2012, p. 555)

Owing to the importance of land-use simulation in order to develop the sustainable development ranging from the global to local scale, the models to predict the land-use changes were developed to deal with the complexity of the spatial environment in the 1990s (Kim & Newman, 2019). The examples of the models are Cellular Automata (CA), Logistic Regression (LR), Markov Chain (MA), etc (Aburas et al., 2016). However, due to the complicated land-use changes, the integrated models or hybrid models were developed to achieve reliable results for future scenarios (Aburas et al., 2016; Guo et al., 2020; Hassan & Elhassan, 2020; Sankarrao et al., 2021). Among the various types of the models, the inductive models — which predict the potential of the land-use changes in the future scenarios from the recorded land-use data and the explanatory variables that were expected to influence the interesting phenomena (Mas et al., 2014, p. 95) — have a crucial role in leading the land-use planning.

Based on the inductive models, many pieces of software, such as the CA-Markov Chain model in Terrset and IDRISI (Abd El-Hamid et al., 2021; Hamad et al., 2018), the programs in a family of CLUE (Conversion of Land Use and its Effects) (Chang et al., 2021; Waiyasusri et al., 2016), DINAMICA EGO (Thompson et al., 2020), and Land Change Modeler (LCM)(Hasan et al., 2020; Mishra & Rai, 2016; Wang et al., 2016), were developed to help policymakers. With different benefits and limitations (Mas et al., 2014, p. 101), these programs were used by scholars as a platform, and their performances were provenly at an acceptable level. For example, Hamad et al. (2018) used Terrset to predict the land-use changes in CA-Markov Chain and achieved an accuracy of 85% for the predicted map. This is similar to the other studies that adopted the CA-Markov Chain to predict the land-use changes and achieved an accuracy of 80% (Abd El-Hamid et al., 2021, p. 1909; Jafari et al., 2016, p. 524). The programs in the family of CLUE such as CLUE-S and Dyna-CLUE — which are also popular models to predict the changes of land use based on the dynamic simulation of the competition between land uses with the allocation of rule that is grounded on empirical analysis, user-specified decision rule, neighbourhood or integrated method (Verburg et al., 2008, p. 67) — were reported by the previous studies as a good model to predict the land-use changes (Waiyasusri et al., 2016; Wang et al., 2019) , especially in the local and regional scales. Khunrattanasiri (2020) compared the performances between CA-Markov and CLUE-S to predict the land use and pointed out that the performance of CLUE-S is more outstanding than that of CA-Markov. However, the high capability to predict the land-use changes was also reported in the studies that used the LCM platform (Mishra & Rai, 2016; Wang et al., 2016) or the DINAMICA EGO platform (Cheng et al., 2020; Thompson et al., 2020).

Although each model can predict the land-use changes with acceptable accuracy, it is difficult to compare their performances to select the best model due to the different frameworks of each model (Ansari & Golabi, 2019, p. 655; Hasan et al., 2020). In addition, it involves the case and quality of input (Verburg et al., 2008, pp. 74-75). Previous studies attempted to compare the performance of each model and program. However, the result is uncertain depending on the context. For example, the performance of LCM was reportedly better than CA-Markov in the study of Nongpho et al. (2021), Ozturk (2015) and Rana & Sarkar (2021) while the study of Ongsomwang & Pimjai (2015, p. 221) indicated that CA-Markov was better. The selection of the model to predict the changes of land use thus should consider with the modelling objective (Paegelow et al., 2014) and data accessibility.

Recently, the Machine Learning (ML) has been integrated into the prediction models to develop the performance of the traditional models such as CA-Markov Chain, Markov Chain, and Logistic Regression due to the development of computer performance (Okwuashi & Ndehedehe, 2021, p. 14; Samardžić-Petrović et al., 2017, p. 2; Triantakonstantis & Mountrakis, 2012, p. 560) and the performance of the ML to predict (Aburas et al., 2019, p. 6). In addition, ML is regarded as a convenient method to create a potential map of transition because of the automated approach while the prediction models based on the statistical method such as logistic regression and weight of evidence requires the understanding of the relationship between drivers and phenomenon (Mas et al., 2014, p. 106). Hence, scholars attempted to integrate the ML to upgrade the performances of the traditional models. The previous study indicates that ML are not obstructed by the limitations of CA and Markov Chain, which is a traditional approach to predict the land-use changes with the capability to manage the driving forces of land-use changes (Aburas et al., 2019). For example, Okwuashi & Ndehedehe (2021) integrated the Support Vector Machine (SVM) into CA-Markov Chain and found that this hybrid model can predict urban expansion with a satisfactory result and is suitable to apply to other megacities. SVM was also integrated into the CA model to deal with the non-linear complex relationship between land-use changes and drivers in the study of Yang et al.(2008) which found that SVM-CA has a capability to predict the urban development with good accuracy. The comparison with the LR-CA model shows that SVM-CA was the best. The best performance of SVM was also presented in the study of Samardžić-Petrović et al.(2017) that compared the performances of three conventional ML models (SVM, DT, Neural Network; NN) to predict the land-use changes. Other ML techniques; such as SimWeight, Artificial Neural Network (ANN), ML-K Nearest Neighbour (MLKNN), Genetic Algorithm, and Decision Tree (Aburas et al., 2019, p. 15), with different advantages and limitations were also adopted to predict the changes in land use.

Although ML gets more attention from scholars, ANN is a machine learning that scholars usually integrate into the prediction models owning to its capability to create a model of the complex system of the built-up expansion in the form of non-linear relationship, its capability to manage the noisy, redundant and inaccurate data, and its simple requirement where the expert opinions and the advanced knowledge are not necessary to implement the model. This results in the quality of the generated transition potential map which is the based data to predict the land-use changes (Aburas et al., 2019, p. 15; Gharaibeh et al., 2020, p. 6). Among the various types of ANN, MLP or MLPNN is a popular technique integrated into the prediction models to enhance the performance (Mishra et al., 2018, p. 263; Pijanowski et al., 2002, p. 555; Purswani et al., 2022, p. 84). For example, Gharaibeh et al. (2020, p. 17) indicate that ANN with the MLP technique can increase the accuracy of the CA-Markov Chain to predict the land-use changes. The integrated model of the MLP-CA-Markov Chain upgraded the accuracy from 86.29% to 90.04%. Furthermore, the comparison of the performances between MLP-CA-Markov Chain, MLP-

Markov Chain, LR-Markov Chain, and LR-CA-Markov Chain by Sankarrao et al.(2021) reveals that MLP-CA-Markov was the best model. It is in accord with other studies (Gemitzi, 2021, p. 437; Leta et al., 2021) in which the performance of MLP-CA-Markov was proved as a suitable model to predict the changes in land use. The outstanding performance of MLP-CA-Markov is a result of its capability to project the dynamic phenomena, simulating the various land-use types and the suitable calibration (Leta et al., 2021). In addition, because MLP is a type of ANN called feed-forward ANN, it requires less data for training because it generates parameter values automatically (Mishra & Rai, 2016).

In addition, the comparison of the model performances between LR, MLPNN, and SimWeight in the study of Mozumder et al. (2016) shows that although MLPNN produced a large number of false alarms due to the generalisation process for the consistency with the data, it is an outstanding technique to create the transition potential model. It has the better agreement due to location and quantity. In contrast, the LR was indicated as the unsuitable technique to predict the future scenario because it cannot minimise the complex land-use change phenomena (Mozumder et al., 2016, pp. 45-46). The outstanding performance of the MLP-Markov Chain compared to other integrated models was also reported in the study of Gaur et al. (2020) that compared the performances of four integrated models — MLP-Markov Chain, LR-Markov Chain, MLP-CA-Markov Chain, and LR-CA-Markov Chain — to predict the land-use changes. It is in accord with the study of Mishra et al.(2018) which found that the MLP-Markov Chain was the best model to predict the land-use changes compared to the Stochastic Markov Chain and CA-Markov Chain. Although most studies proved that the integration between MLP and Markov Chain is the hybrid approach that has the capability to predict the land-use changes with the acceptable accuracy (Mishra & Rai, 2016; Mishra et al., 2018; Purswani et al., 2022), this technique is not recommended to predict the land-use changes with a large number of transitions (Eastman, 2020, p. 209).

Supporting the process of land-use prediction, various techniques of ML are currently integrated as an option in the prediction program. For example, LCM is combined with ML to analyse the transition potential (Eastman, 2020, p. 211). It is the same with the Land Transformation Model (LTM), which is combined with GIS and ANN to predict the changes in land use (Triantakonstantis & Mountrakis, 2012). Recently, A new machine-learning algorithm was adopted in LCM to create the potential transition, such as Support Vector Machine (SVM), Decision Forest or DF (an implementation of Random Forest) and Weighted Normalised Likelihood (WNL). However, the application of these techniques still has not sufficiently demonstrated the performance in different contexts. Most studies in the platform of LCM mainly simulated the land-use changes through MLP (Azareh et al., 2021; Chim et al., 2019; Gibson et al., 2018; Guo et al., 2020; Hewson et al., 2019; Saha et al., 2022; Sharma et al., 2018; Vilar et al., 2021; Wang et al., 2016; Zahir et al., 2021; Zhang et al., 2021). In fact, other pieces of machine learning such as DF also have a good potential to predict land-use changes. Du et al. (2018) indicate that tree-model-based ML, namely bagged trees, random forests, extremely randomised trees, and bagged gradient boosting decision trees, are better than MLP. It is similar to the study of Jun (2021), indicating that random forests have a higher capability to predict the land-use changes than ANNs. Recent studies about the use of DF in LCM indicate that the integration of random forest and Markov Chain can predict the land-use changes at an acceptable rate (Azari et al., 2022, p. 9). However, this study simulated the land-use changes only in the BAU scenario, which is lacking compared with the policy-complimented scenario that is a crucial analysis for sustainable planning.

To fulfil the gap in the application of ML in order to support the land-use planning, this chapter adopted DF in LCM as a tool to predict the built-up land expansion under different scenarios. LCM is a model applied to determine the changes and predict the land use in the future based on two components: (1) the determination of the quantity of land changes from Markov Chain analysis that is similar to other models such as CA-Markov and DINAMICA (Mas et al., 2014, p. 106) and (2) the analysis of the potential transition from the machine learning and statistical models such as MLP, DF, LR, WNL, SVM, and SimWeight (Eastman, 2020, p. 209). LCM is integrated within TerrSet. The major function of LCM consists of four areas: (1) the analysis of land-use changes, (2) the analysis of potential transition, and (3) the projection of the future land-use changes that integrates the planning intervention (Eastman, 2020, p. 207). LCM has a crucial role in supporting land-use development and urban planning to cope with the urbanisation (Kim & Newman, 2019). From the previous studies, besides the urban areas, LCM was adopted to predict the changes of other land-use types worldwide (Khoshnood Motlagh et al., 2021; Shi et al., 2022, p. 4), such as the changes in lakes and water bodies (Azareh et al., 2021), wetlands (Ansari & Golabi, 2019; Mozumder & Tripathi, 2014), grassland (Gibson et al., 2018), and deforestation (Chim et al., 2019; Hewson et al., 2019).

7.4 Materials and methods

In this chapter, TERRSET Land Change Modeler (LCM) is the main program to simulate the expansion of built-up lands in two years: 2027 and 2037. Under the LCM, DF machine learning was selected to calculate the transition potential of built-up lands from eleven factors. At the same time, Markov Chain was used to determine the quantity of the expected build-up lands in the future.

7.4.1 Data

The information of the built-up lands in 1997, 2007, 2017 and the driving factors of the built-up land expansion were derived from chapter 4 with the cell size of 100 x 100 m. Then, the land-use maps were categorised into two groups: built-up lands and non-built-up lands. The maps of the built-up lands in 1997 and 2007 were used to prepare the transition model to create a predicted map of the built-up areas in 2017 while the urban map of 2017 was used for validation.

7.4.2 Methodology

As show in Figure 56, the method to predict the expansion of built-up lands consists of three steps: (1) the analysis of the built-up land expansion, (2) the analysis of the transition potential of built-up lands, (3) the prediction of built-up land expansion and model validation.

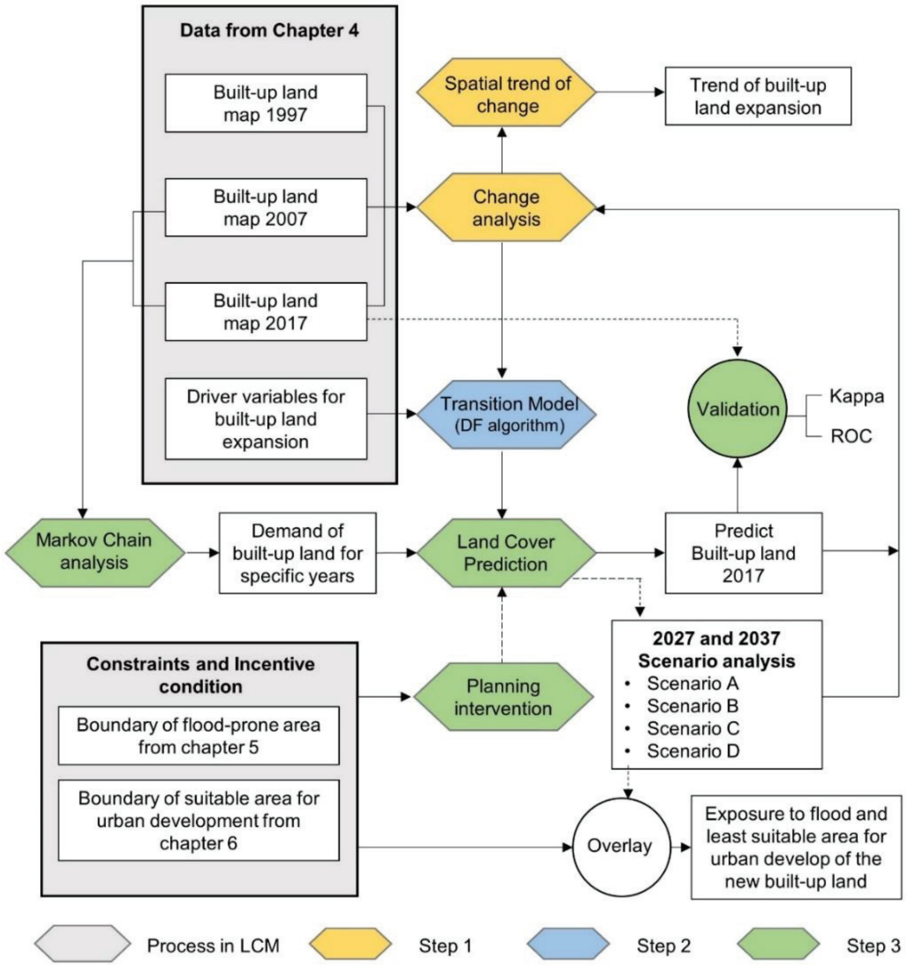


Figure 56 Methodology flow

7.4.2.1 Analysis of built-up land expansion

The land-use maps in 1997, 2007, 2017 deriving from chapter 4 were categorised as the built-up lands and non-built-up lands with the cell size of 100 x 100 m. Then, the built-up maps of 1997, 2007, and 2017 were compared to determine the expansion of the built-up lands in each period with the change analysis.

7.4.2.2 Produce the model of transition potential to built-up lands

A map of the transition potential of built-up lands is a crucial component to predict the change of built-up lands by using LCM. Creating the potential of built-up lands is related to the factors of the built-up area expansion. To create the map, the driving factors in chapter 4 were reconsidered. Although chapter 4 indicates that there are differences in the driving factors of the built-up area expansion between 1997 to 2007 and 2007 to 2017, the information from the driving factors still has limitations due to the elimination of outlier data for increased accuracy. Owing to the removal of some outliers based on Cook's distance, the findings from the Logistic Regression in Chapter 4 can only be used to describe the driving factors but are not suitable for the prediction that needs to manage all data, especially the prediction of built-up areas expansion through LCM which predicts the changes of the built-up areas by using the built-up areas from 1997 to 2007 to predict the built-up areas in 2017.

In overview, although chapter 4 indicates that some of the driving factors of the two periods are different, only 4 driving factors are different. The rest of the factors appear in both periods with different magnitude of influence. Due to this similarity, it is possible to predict the built-up areas based on the assumption that the trend of the built-up area changes in 2017 was similar to those in 2007. To use this assumption, however, it is necessary to reconsider the factors of the built-up area expansion that will be integrated into the DF machine learning. First, 11 driving factors that have an impact in both periods were integrated into the transition potential analysis to calculate the value of out-of-bag (OOB) accuracy. Then, the driving factors were revised by removing some driving factors and adding the driving factors that have an impact on the built-up area expansion in one period to the model one by one. The pattern that achieved the highest value of OOB accuracy was selected. Finally, the eleven factors that achieved the highest value of OOB accuracy of 90.79% were selected to create the transition potential model with DF machine learning in order to create the built-up areas in 2017 and predict the built-up areas in the future. The factors are elevation, the distance from Highway 2, the distance from other main roads, the distance from sub-roads, the distance from Malls, the distance from the Mekong River, the distance from big reservoirs, the distance from Khon Kaen University (Nong Khai Campus), agricultural lands, forest and natural lands, and water bodies. Most of the factors have an influence on the built-up areas in both periods except the distance from Khon Kaen University (Nong Khai Campus) which has an influence on the built-up area expansion in the second period and the distance from Highway 2 and other main roads that were reclassified from the distance from the main road in Chapter 4.

DF machine learning is the simplest method to create the transition potential map (Eastman, 2020, p. 209). It was developed from the free-standing DF modules or Random Forests (RF). RF is an algorithm of the machine learning that was introduced by Breiman (2001). This algorithm is an ensemble of classification tree which is faster and easier to understand and interpret (Azari et al., 2022, p. 3) while it can provide higher accuracy compared to other machine algorithms (Kamusoko & Gamba, 2015). In addition, RF can handle with large database and is robust in dealing with outlier and noise (Rodriguez-Galiano et al., 2012). RF Algorithm was developed and integrated in LCM, as DF machine learning. Eastman (2020, p. 211) indicates, "the number of variables to evaluate at each split defaults to the floor of the square root of the number of independent variables." Although DF is the simplest algorithm compared to other machine learning in LCM, it still provides the good results. Azari et al. (2022, p. 9) adopted DF to predict the land cover in 2030 in Selangor with the AUC of 0.84.

7.4.2.3 Prediction of built-up land expansion

To predict the built-up land expansion, there are three steps as follows:

7.4.2.3.1 Markov Chain

To predict the expansion of the built-up lands, First, the expected built-up lands that will expand in 2027 and 2037 were determined from the Markov Chain's analysis by calculating a cross-tabulation of transition between two maps of built-up lands (Azareh et al., 2021). The Markov Chain was used to calculate the expected lands based on the assumption that the probability of the urbanised areas is in a certain state at a certain time. The rate of the built-up land changes in the calibration period or the prior time (T_1 to T_2) will continue in the simulation time (T_2 to T_3) (Gibson et al., 2018, p. 8). In this study, the Markov Chain was analysed from the cross-tabulation of transition retrieving the data from the maps of the built-up lands in 2007 and 2017. Then, a simple powering was adopted to calculate the transition probability matrix (Mas et al., 2014, p. 96).

7.4.2.3.2 Model validation

Before predicting the scenarios in the future, it is necessary to assess the accuracy of the model created with Markov Chain and DF machine learning. The maps of the built-up lands in 1997 and 2007 were used as the input to generate the predicted map of the built-up lands in 2017 by integrating the results from step 2 and 3. Then, the predicted map was compared with the actual built-up lands in 2017 from Chapter 4 to assess the accuracy. Kappa statistical and relative operative characteristics (ROC) — which are the fundamental statistic information that most studies use to assess the accuracy (Hasan et al., 2020; Manonmani et al., 2017) — were adopted to indicate the performance of model in this study.

Kappa Statistics is a fundamental technique to assess the performance of the prediction (Azareh et al., 2021). The high value of Kappa coefficients indicates that this model is suitable to create the map of built-up land in 2017 and suitable to predict the scenarios in the future. The ROC is a graph to evaluate and compare the performance of classifier (Melo, 2013) by plotting the rate of true positive and the rate of false positive. The ROC was summarised through an area under the curve: it ranges between 0 and 1. 1 presents the perfect performance (Hasan et al., 2020).

The comparation between the predicted map and the actual map of the built-up lands in 2017 (Figure 57) found that the Kappa statistic resulted in 88.5% and the area under curve is 0.94. Both Kappa and area under curve from ROC confirm that the model is reliable and can be used to simulate the scenarios of the built-up land expansion in the future.

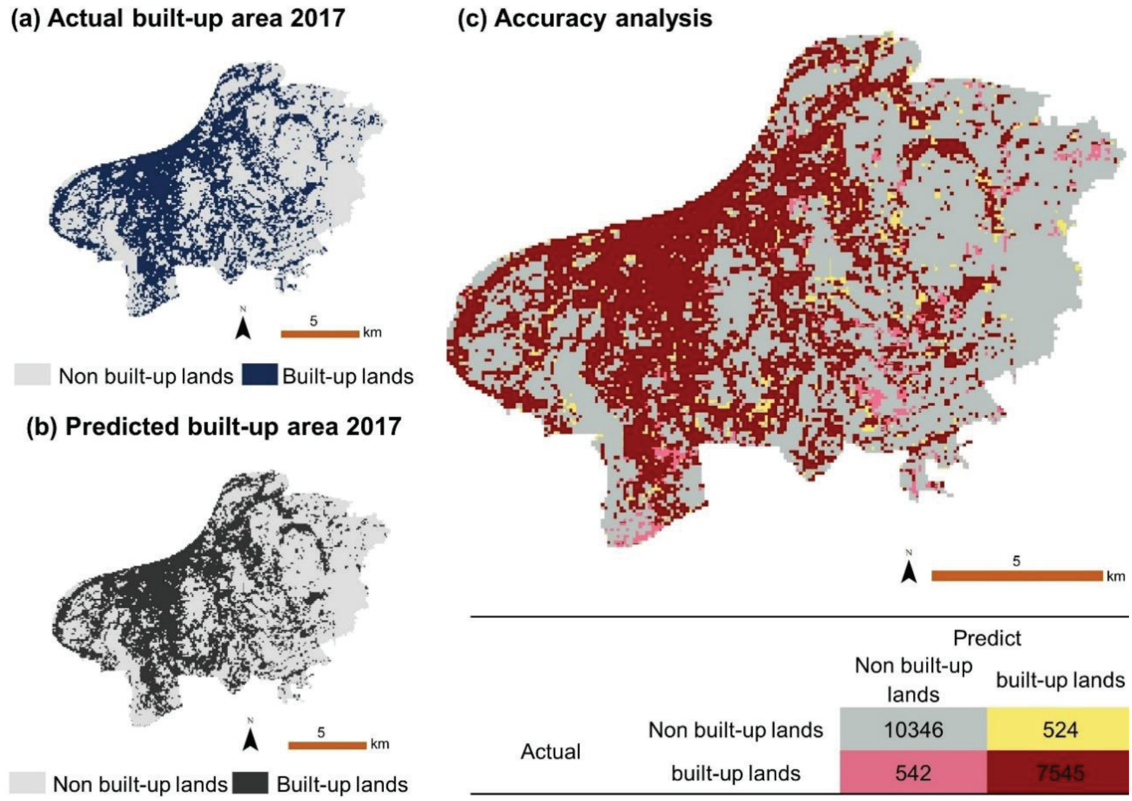


Figure 57 The actual map and the predicted map of the built-up lands in 2017: (a) actual map from chapter 4; (b) predicted map; (c) accuracy analysis

7.4.2.3.3 Scenario analysis

The transition potential maps (7.4.2.2) and transition probability matrix from Markov Chain (7.4.2.3.1) were combined to predict the expansion of the built-up lands in 2027 and 2037 under four scenarios. The scenarios were created by using the panel of the constraints and incentives which is an LCM tool to analyse the intervention of planning policy on the change of land use. The constraints involve the policy to prohibit or restrict the expansion of built-up lands while the incentives involve the policy to promote the expansion of built-up lands. The constraints and incentives were indicated through values. 0 indicates the absolute constraints. The value less than 1 but above 0 indicates the disincentives, and the value above 1 means the incentives. The values of constraints and incentives were integrated into the prediction model by multiplying with the transition potential (Eastman, 2020, p. 218). There is no specific rule to identify the value between 0 to 1 and more than 1 to reflect the influence levels of constraints and incentives. Hence, for constraints in this study, each value from 0 increasing by 0.2 was identified as the levels of constraints. For incentives, each value from 1 increasing by 0.2 was used. The exception is scenario

C1 in which its constraint value was 0.5 and its incentive value was 1.5. This is due to the assumption that the boundary of the suitable and unsuitable areas of this scenario was generalised, combining various suitability levels. If it had used the same values as other scenarios with specific boundaries, the impact of the unsuitable areas would have been close to 0 or 1 reflecting the absolute constraints or no incentive, respectively. To correctly show the impact of the suitable areas, the median value of 0.5 was used as the constraint value, and the value of 1.5 which increased from 1 by 0.5 was used as the incentive value.

To create the maps of constraints and incentives for each scenario, the areas susceptible to flood from chapter 5 and the suitable areas for urban development from chapter 6 were used as the base boundary. The constraint and incentive values for each scenario are various as shown in Figure 58.

- **Scenario A: Business-as-Usual (BAU)**

The analysis under scenario A is the change with the business-as-usual (BAU). The changes of the built-up lands in 2027 and 2037 were assumed by previous trend that the built-up lands will expand uncontrollably without the policy or planning. Hence, to predict the expansion of the built-up lands, there is not constraint and incentive integrated to the model.

- **Scenario B: Flood resilience growth**

Flood is a local natural disaster in Nong Khai City. Chapter 5 indicates that about a quarter of the total areas is distributed in the very highly and highly flood-prone areas that should not be developed into the urban areas to decrease the exposure to flooding in the future. The prohibition of urban development or construction in the flood-prone areas is the fundamental policy to manage the floodplain (American Planning Association, 1953, p. 326; Asian Development Bank, 2016, p. 28; Berke et al., 2006) for limiting the exposure to flood-prone area (Hudson & Botzen, 2019, p. 2). Hence, this scenario aims to predict the growth of built-up lands under the policy to retard the development in the flood prone area by using the very highly and highly flood-prone areas from Chapter 5.

The prediction of the built-up land expansion in the scenario of flood resilience growth consists of two sub-scenarios: (B1) The strict prevention of the built-up land expansion in the flood-prone areas which means that the new built-up land constructions are not allowed in these areas of Nong Khai City and (B2) the flexible prevention of the built-up land expansion in the flood-prone areas which means that the small sizes of the built-up lands are allowed in these areas if they support the agricultural activities in the rural contexts. Hence, 0 and 0.2 were set as the constraint values for scenarios B1 and B2, respectively.

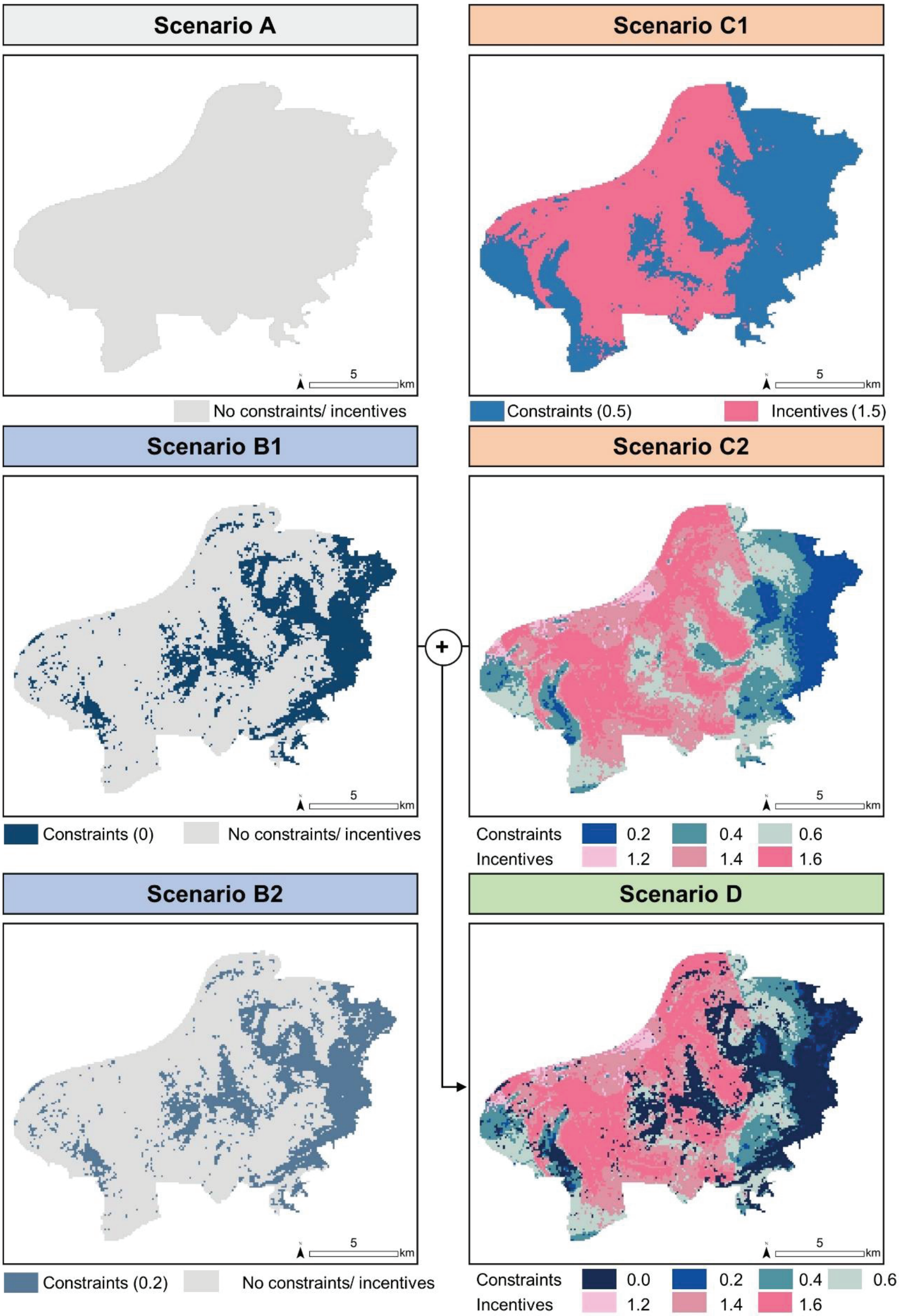


Figure 58 The constraint and incentive to predict the expansion of the built-up lands under the different scenario.

- **Scenario C: Growth under the urban development zone**

In this scenario, we assume that the built-up lands will grow under the policy to support the development of built-up lands in the zone of suitable areas that is better for the accessibility, the safety from hazard, and the conservation of natural and cultural assets in Nong Khai City. At the same time, the built-up lands will be discouraged to grow in the zone of unsuitable areas that are less accessible, prone to hazards, and under the condition of natural and cultural assets conservation. The zone of suitable and unsuitable areas for urban development was from Chapter 6.

This scenario consists of two sub-scenarios based on the pattern of constraints and incentives: Scenario 1 (C1) represents the scenario of the built-up land expansion under the generalised boundary of suitable areas for urban development. The areas in Nong Khai City were set into two zones: the suitable areas and the unsuitable areas for urban development. The suitable areas were set as the incentive zone with the value of 1.5 and the unsuitable areas were set as the constraint zone with the value of 0.5. Scenario 2 (C2) represents the scenario of the built-up land expansion under the strict boundary of suitable areas for urban development. All the zones of the very highly and highly suitable areas and zone 1 of the marginally suitable area for urban development were set as the incentive zone with the value of 1.6, 1.4, and 1.2, respectively. The zones of the very lowly and lowly suitable areas together with zone 2 of the marginally suitable areas for urban development were set as the constraint zone with the value of 0.2, 0.4, and 0.6, respectively.

- **Scenario D: The integrated growth**

In this scenario, the incentives and constraints of scenario B and scenario C were integrated to represent the simulation the built-up land expansion under the integration of the policy to prevent the expansion into flood-prone areas, the policy to reinforce the expansion into suitable areas, and the policy to decrease the expansion into unsuitable areas in other dimensions such as the accessibility and the cultural assets. The incentives and constraints of scenario D were formulated from the integration of scenario B1 and scenario C2 where the built-up lands are distributed in flood-prone areas and the least suitable areas in each group. The flood-prone area from scenario B1 was set as the constraint with the value of 0. Other areas were set following scenario C2.

After the built-up land expansion maps of 2027 and 2037 under different scenarios were produced, the spatial trend of change in LCM was adopted to create the contour map of the trends of the built-up land expansion with the maps of 1997, 2007, and 2017. At the same time, the predicted maps were combined in ArcMap to analyse the patterns of expansion in the flood-prone areas and the zone of suitable areas for urban development to project the exposure to flood and least suitable areas for urban development of Nong Khai City in the future.

7.5 Results

According to the analysis, the patterns of the built-up land expansion and the land allocation from every scenario are generally similar (Figure 59-Figure 62). There will be 46.63 % and 20.45% of the built-up land expansion in 2027 and 2037.

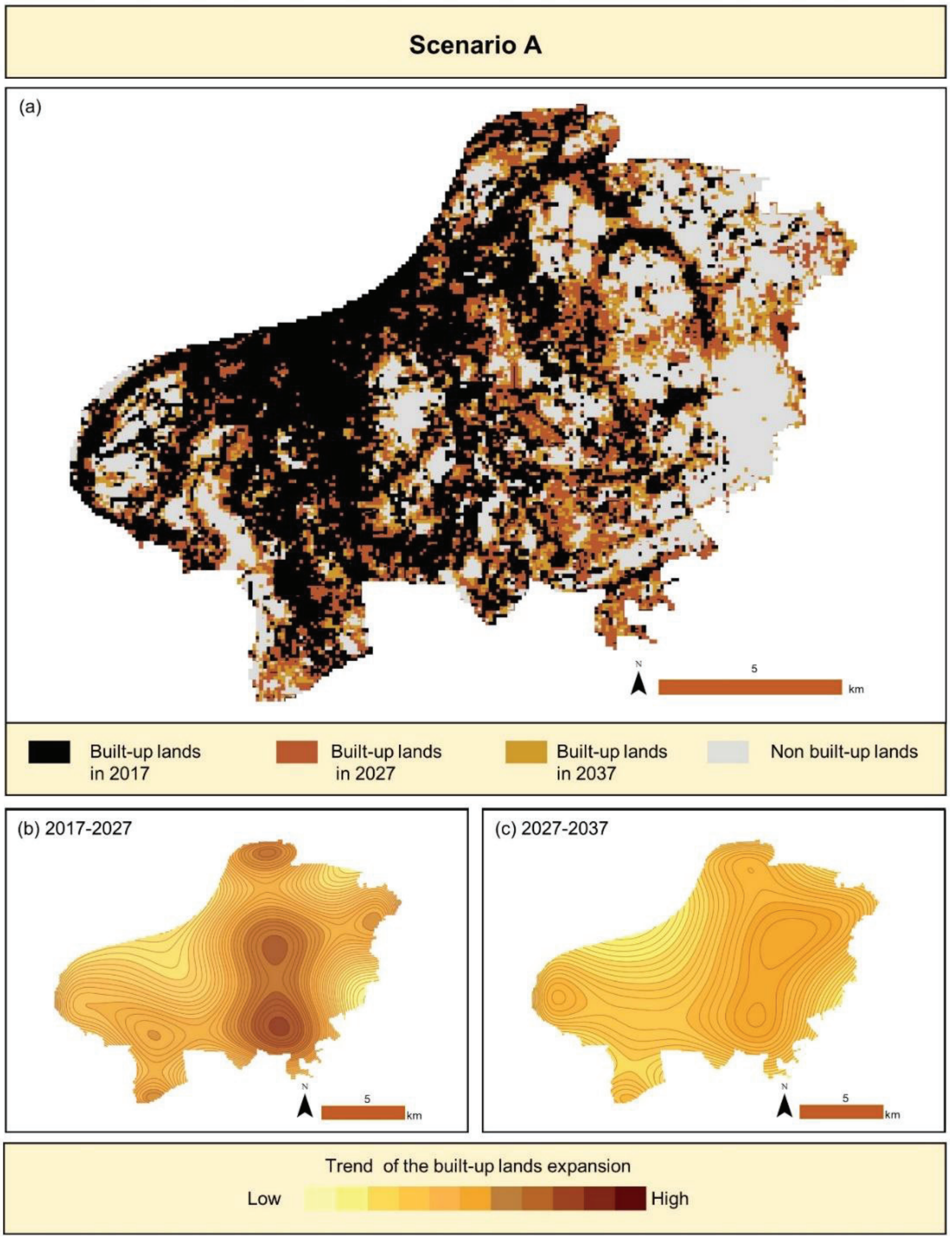


Figure 59 The expansion of the built-up lands in 2027 and 2037 from scenario A

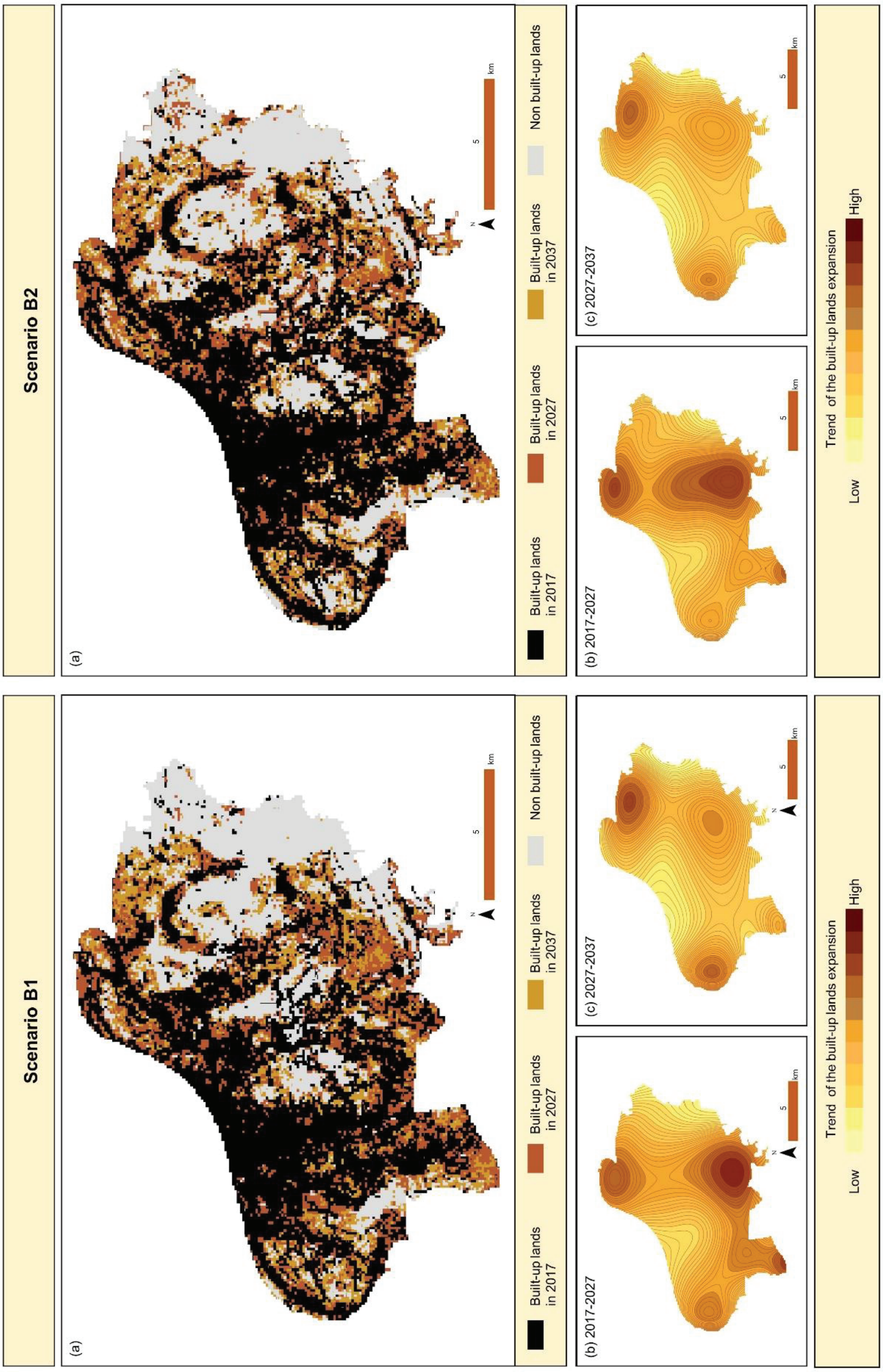


Figure 60 The expansion of built-up land in 2027 and 2037 from scenario B

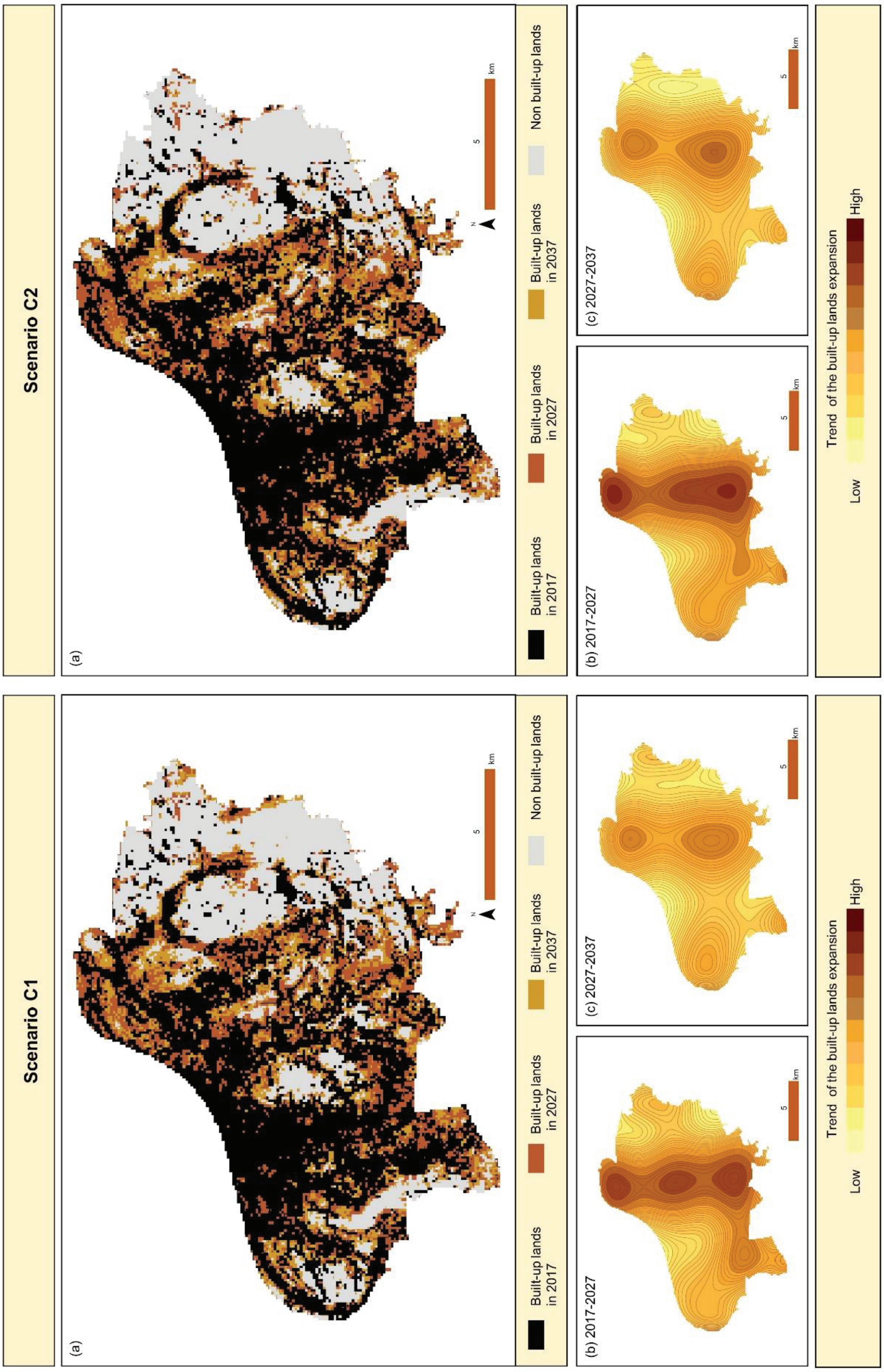


Figure 61 The expansion of built-up land in 2027 and 2037 from scenario C

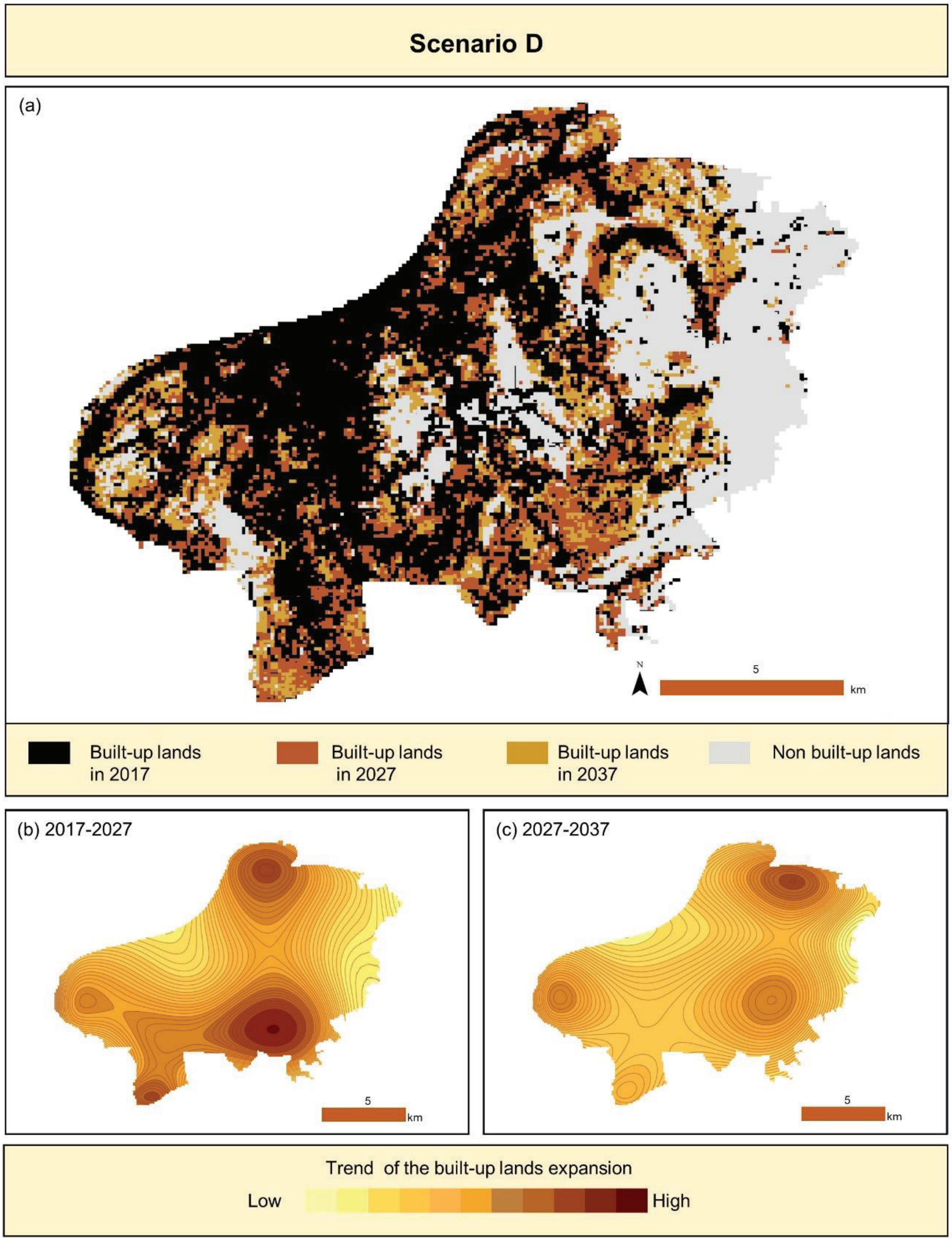


Figure 62 The expansion of built-up land in 2027 and 2037 from scenario D

7.5.1 The direction of the built-up land expansion

Figure 63(a) shows that the directions of the built-up land expansion in 2027 and 2037 are not vastly dissimilar in each scenario. The built-up land will increase significantly in the eastern and south-eastern areas in both periods, compared to other directions. Interestingly, the number of the built-up lands will also increase moderately in the southern and north-eastern in 2027 but extremely decrease in 2037.

Considering the expansion rate of the built-up lands, the patterns between the scenario A and other scenarios — which predict the expansion of the built-up lands under the promulgation of the land-use policies to protect the urbanisation in the unsuitable areas — are dissimilar. From the analysis, under scenario A, the built-up land expansion in the eastern areas will show the highest rate in 2027. For 2037, the highest expansion rate for scenario A will also be in the eastern areas like scenario B and Scenario D. This is different from scenario C where the highest expansion rate will be in the south-eastern areas. It is noteworthy that the expansion of the built-up lands in the southwest areas will be more significant in 2037 for scenario B1 and Scenario D. The expansion rate of these areas will rise into the second rank. The important reason is the strict protection of the built-up expansion in the flood-prone areas in the south-eastern areas, disenabling the built-up lands to expand in these areas and to be expanded in the southwest areas, which is flexible in terms of the constraints.

Considering the expansion rate of the built-up lands based on the boundary of subdistricts, in the overview, the number of built-up lands and the expansion rate of each scenario are similar each year, as shown in Figure 64. The original settlement, Nai Mueang and Mi Chai Subdistricts will show a small expansion. At the same time, Wat That and Hat Kham Subdistricts on the eastern side will grow highly in terms of the number of the areas and the expansion rate. However, it is noteworthy that under the scenario that controls the built-up expansion, the subdistricts on the western side, such as Mueng Mi and Kuan Wan Subdistricts, will see a high expansion rate, especially in 2037, despite the small total areas. Mueng Mi Subdistrict will hit the highest expansion rate for Scenario B1 and D. Other scenarios will be in the second place in the expansion rate ranking. The high expansion of Mueng Mi Subdistrict is in accord with the pattern of the built-up land based on the direction. The high expansion rate of Mueng Mi, which is on the western side, reflects the influence of the promulgation of the policy to prohibit the built-up lands, which are mainly distributed in the eastern areas due to floods, on the expansion of the built-up lands. However, owing to the size of the areas in the eastern side, the subdistrict is a significant area of the built-up land expansion for Nong Khai City.

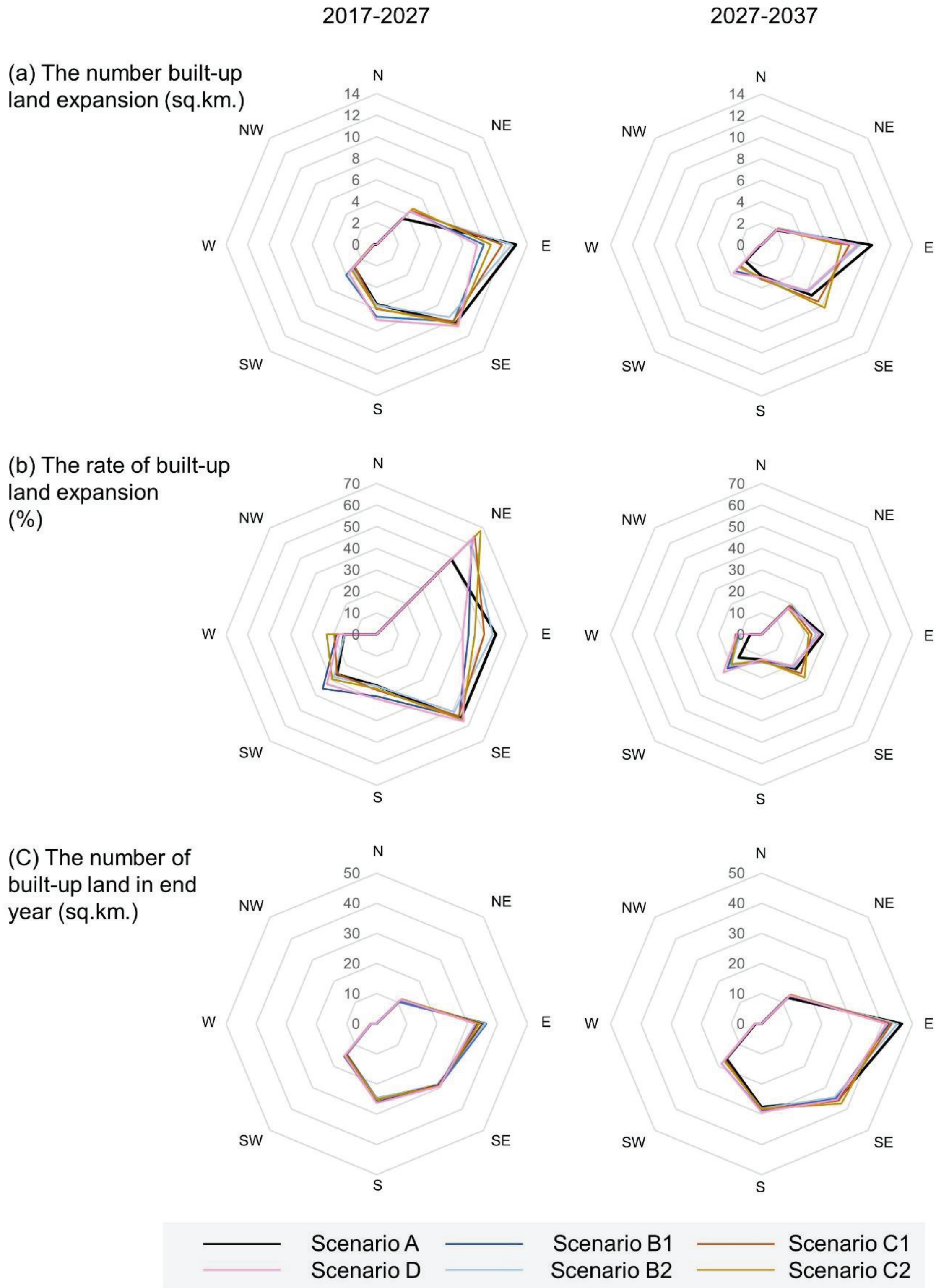


Figure 63 The number of the built-up land expansion (a), the rate of the built-up land expansion (b), and the built-up land (c) in 2027 and 2037, divided by directions

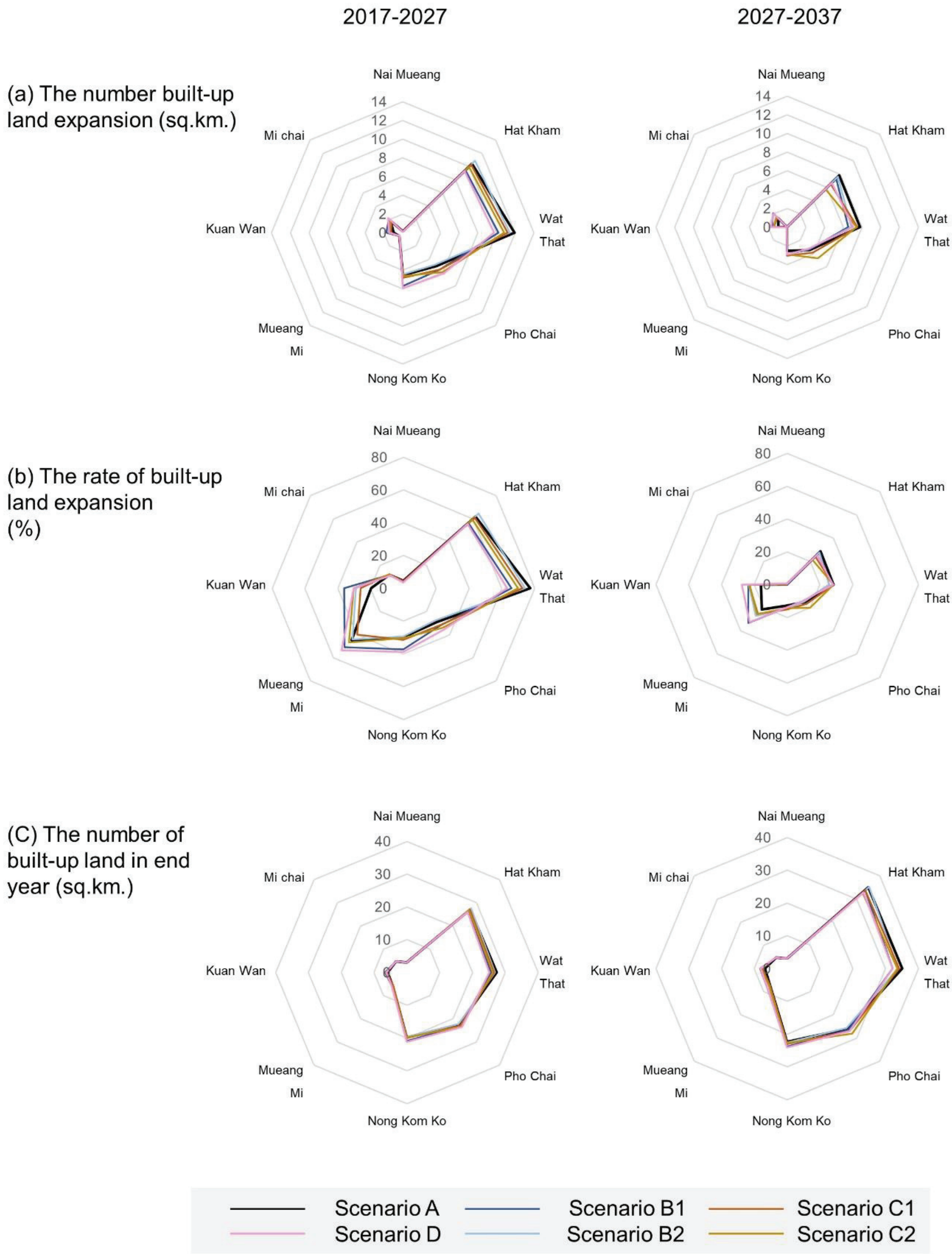


Figure 64 The number and the rate of the built-up land expansion in 2027 and 2037, divided by subdistricts

7.5.2 The expansion of the built-up lands in the areas susceptible to floods

The analysis of the built-up land expansion in the very highly and highly flood-prone areas in Chapter 5 shows that the number of the built-up lands in those areas will increase from 11.21 % in 2017 to 28.67 % and 45.19 % in 2027 and 2037 under the analysis of scenario A, as shown in Table 34.

Table 34

The distribution of the built-up lands divided by the levels of flood susceptibility (%)

		Ratio of built-up land in the flood susceptibility class					Ratio of flood-prone area (High and very high flood susceptibility class)	Ratio of Flood-prone area and moderate flood susceptibility class
		Very low	Low	Moderate	High	Very High		
Built-up lands in 2017		77.19	56.41	32.51	14.62	5.05	11.21	21.17
Built-up lands in 2027	A	90.99	77.53	52.97	33.07	20.70	28.67	40.03
	B1	94.12	83.72	61.59	14.62	5.05	11.21	34.77
	B2	92.91	80.68	57.82	23.35	11.56	19.15	37.23
	C1	91.27	78.90	54.24	31.16	15.67	25.64	39.01
	C2	92.17	79.44	54.62	29.83	13.49	24.01	38.32
	D	93.94	84.03	61.30	14.62	5.05	11.21	34.63
Built-up lands in 2037	A	96.36	88.68	68.73	49.74	36.96	45.19	56.20
	B1	99.74	98.43	90.93	14.62	5.05	11.21	48.48
	B2	98.62	95.10	81.16	30.48	14.31	24.72	51.11
	C1	95.98	90.40	72.07	48.51	25.69	40.38	55.20
	C2	97.02	91.55	72.97	45.52	22.86	37.45	54.06
	D	99.69	98.63	90.69	14.62	5.05	11.21	48.37

Regarding scenario B, which was set for decreasing the exposure to flood, scenario B1 is a representative of the strict policy to control the expansion of the built-up areas in the flood-prone areas, indicating that the number of the built-up lands in 2027 and 2037 will be similar to those in 2017. The same phenomenon appears in scenario D, which was also set under the same policy to protect the expansion of the built-up areas. While the B2 was set as the more flexible approach to expand the built-up lands in the flood-prone areas, the built-up areas will increase by a small number from 11.21 % to 19.15% and 24.72% in 2027 and 2037, respectively.

Regarding scenario C, the expansion of the built-up lands in the flood-prone areas will be higher than in scenario B but remain lower than in scenario A. Comparing scenarios C1 and C2, the built-up lands in the flood-prone areas in C1 will be higher than in scenario C2. For scenario C1, 25.64% and 40.38 % of the flood-prone areas will be covered by the built-up areas in 2027 and 2037. For scenario C2, 24.01% and 37.45% will be covered by the built-up areas in 2027 and 2037.

7.5.3 The expansion of the built-up lands based on the suitability for urban development

The analysis of the expansion of the built-up lands based on the suitable areas for urban development derived from chapter 6 demonstrates that the built-up lands will sprawl in 19.96 % and 35.53 % of the least suitable areas in 2027 and 2037 under the scenario A. Like the built-up land expansion in the flood-prone areas, the number of the areas that expand in the least suitable areas from other scenarios will be lower than scenario A. Table 35 shows that in scenario D the number of the least suitable areas for urban development will be the lowest while the number of those areas in Scenario C1 will be the highest in both periods.

Table 35

The distribution of the built-up lands (%) divided by the suitability for urban development (%)

		Ratio of built-up land in the classes of suitable area for urban development							
		Very low	Low	Marginal		High		Very High	
				Zone1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2
Built-up lands in 2017		**4.43**	23.29	78.98	30.41	87.65	45.71	85.04	59.43
Built-up lands in 2027	A	**19.96**	46.03	91.89	53.19	97.38	66.93	93.15	78.12
	B1	**8.35**	44.22	94.00	53.83	97.46	70.75	95.63	81.26
	B2	**13.23**	46.02	93.42	53.16	97.91	68.75	93.59	80.32
	C1	**13.79**	39.74	92.53	47.94	97.79	74.49	94.66	84.28
	C2	**9.17**	38.62	91.76	49.68	97.83	74.68	95.99	86.04
	D	**6.93**	38.92	92.82	55.84	96.78	73.24	96.56	81.88
Built-up lands in 2037	A	**35.53**	61.18	94.32	69.52	99.13	80.90	97.51	89.02
	B1	**12.11**	63.47	97.20	71.50	98.79	86.48	99.35	93.50
	B2	**19.51**	64.33	96.46	70.68	99.47	83.54	98.41	92.31
	C1	**21.64**	49.26	96.35	64.38	99.67	94.69	99.52	97.89
	C2	**11.93**	48.20	98.12	69.64	99.88	95.05	99.82	99.44
	D	**9.34**	60.05	96.65	73.97	98.79	88.12	99.54	94.01

7.6 Discussion and conclusion

According to the patterns of the built-up land expansion in 2017, 2027, and 2037 from the prediction in this chapter and the patterns of the land-use changes between 1997 to 2007 in chapter 4, the characteristics of the built-up land expansion can be summarised as follows to be used as a database in land-use policy development of Nong Khai City as shown in Figure 65.

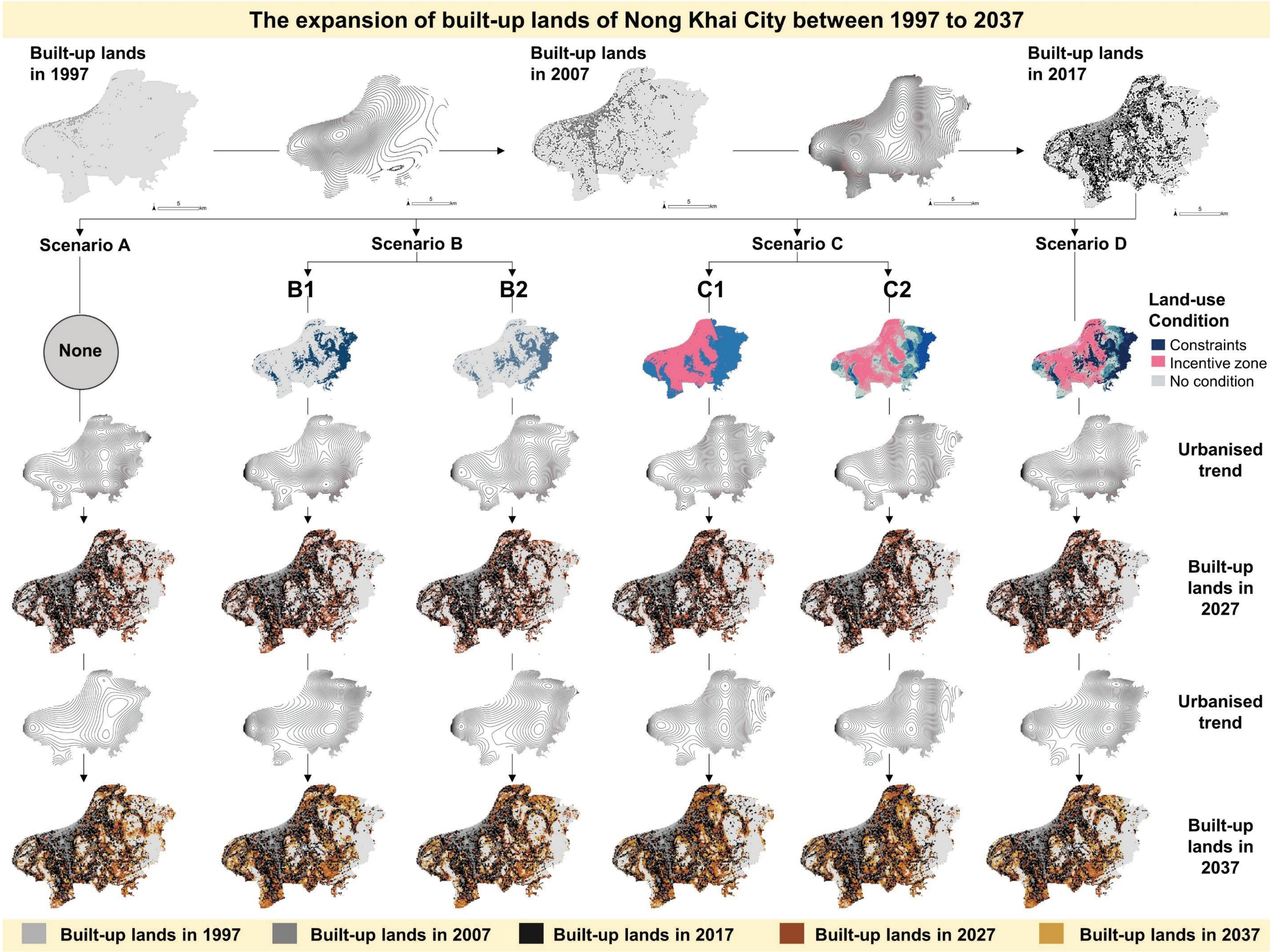


Figure 65 The expansion of the built-up lands of Nong Khai City between 1997 to 2037

To answer the question 1 which is about the growth of the built-up lands in Nong Khai City, in this chapter, although Nong Khai City has a long history as a settlement area, Figure 65. shows that in 1997 the built-up lands had only clustered along the Mekong River before the lands in the southern side sprawled along Highway 2, especially in the areas around the Government Complex, between 1997 to 2007. This resulted in the change of the shape of the city from rectangular into a T-like shape. The expansion in the southern side along Highway 2 and 233 carried on until 2017. Besides this expansion, between 2007–2017, more built-up lands expanded along the transportation networks, especially in the eastern side where the expansion was apparent in the area next to the original settlement. The conceptual section of urban development in Nong Khai City between 1997 to 2017 was summarised in Figure 66.

The prediction about the future changes under BAU pattern as shown in scenario 1 found that despite the tendency to expand into the southern side over these years, in 2027 the areas will not be able to support more built-up land expansion leading to the expansion to be less intense than that in the eastern side, especially the southeastern side. As the built-up lands in the eastern side expanded further from the original areas in 2017, the expansion between 2027–2037 will be further and further away from the city centre and the areas along Highway 2 and 233 where the expansion had happened. This will lead the new expansion into the eastern side where there are many flood-prone areas and unsuitable areas discussed in chapters 5 and 6. Generated from the analysis of the built-up land changes between 1997–2037, Figure 67 found that the areas in Nong Khai City in the normal scenario has been expanded into the flooded areas increasing flood exposure to the city.

To reduce the impact and the damages which will happen to the communities in the flood-prone areas, it is necessary to plan the land uses for future urbanisation in the peri-urban areas of Nong Khai City by slowing down the expansion into the flood-prone areas in the eastern side. **Here, the answer to question 2 about the impact of land-use policy on the trend of built-up land expansion was discussed.** The simulation of the built-up land expansion under scenario B, which was set with the land-use policy to prohibit the built-up land expansion into the very highly and highly flood-prone areas, reveals that marking the very highly and highly flood-prone areas as the constraints on city development in both strict and flexible manners, where the slight expansion is allowed, can decrease the built-up land expansion in the flood-prone areas. The decrease of built-up land expansion due to the restriction of settlement in flood-prone areas reflects the influence of conservation policy as green belt or prohibited areas to shape the city. The result of scenario B is similar to the case of scenario C where the constraints were applied in the unsuitable area and the incentive to develop the built-up lands in the suitable areas in chapter 6 was given.

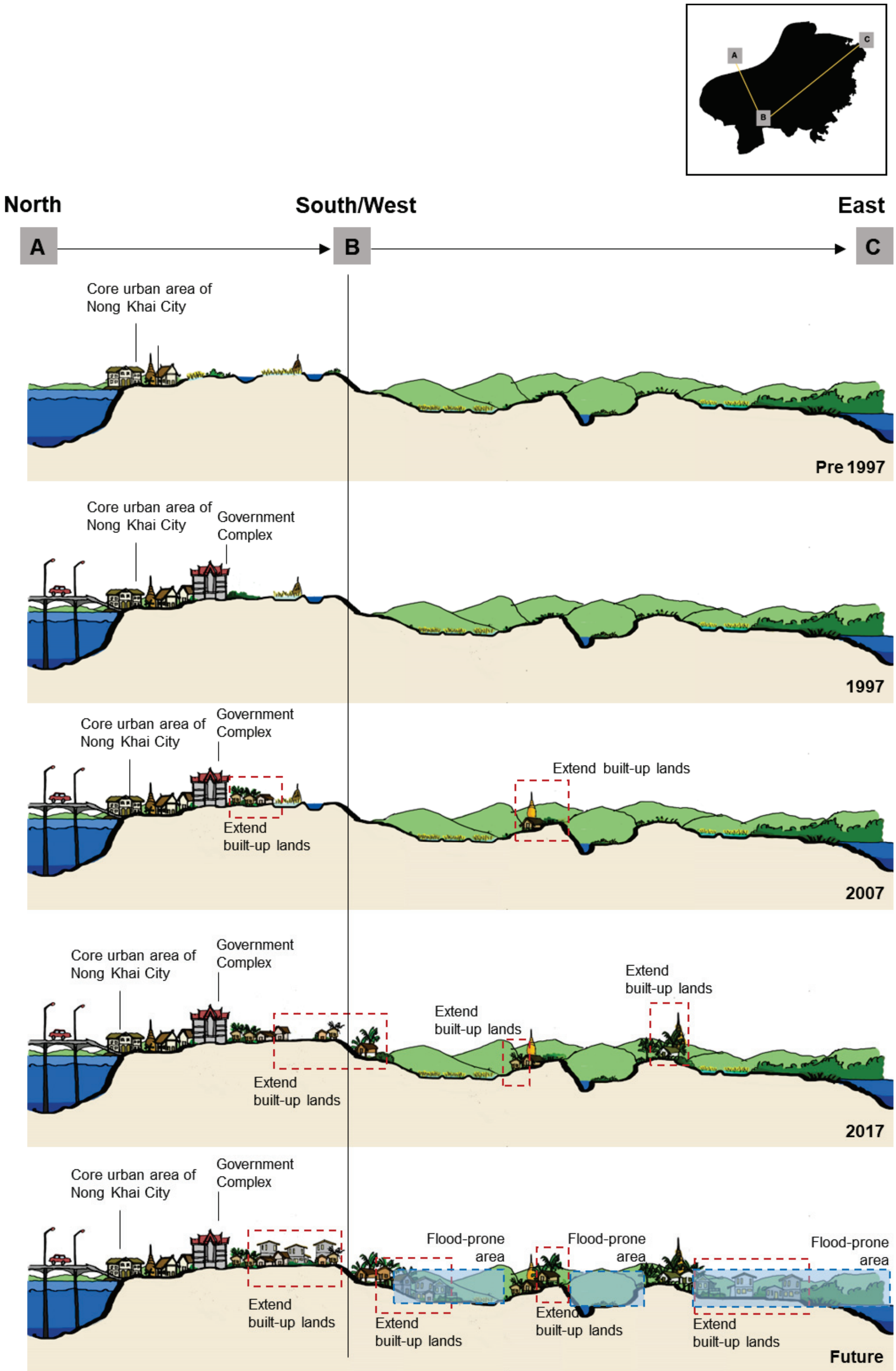


Figure 66 Conceptual section of urban development in Nong Khai City between 1997 to 2017

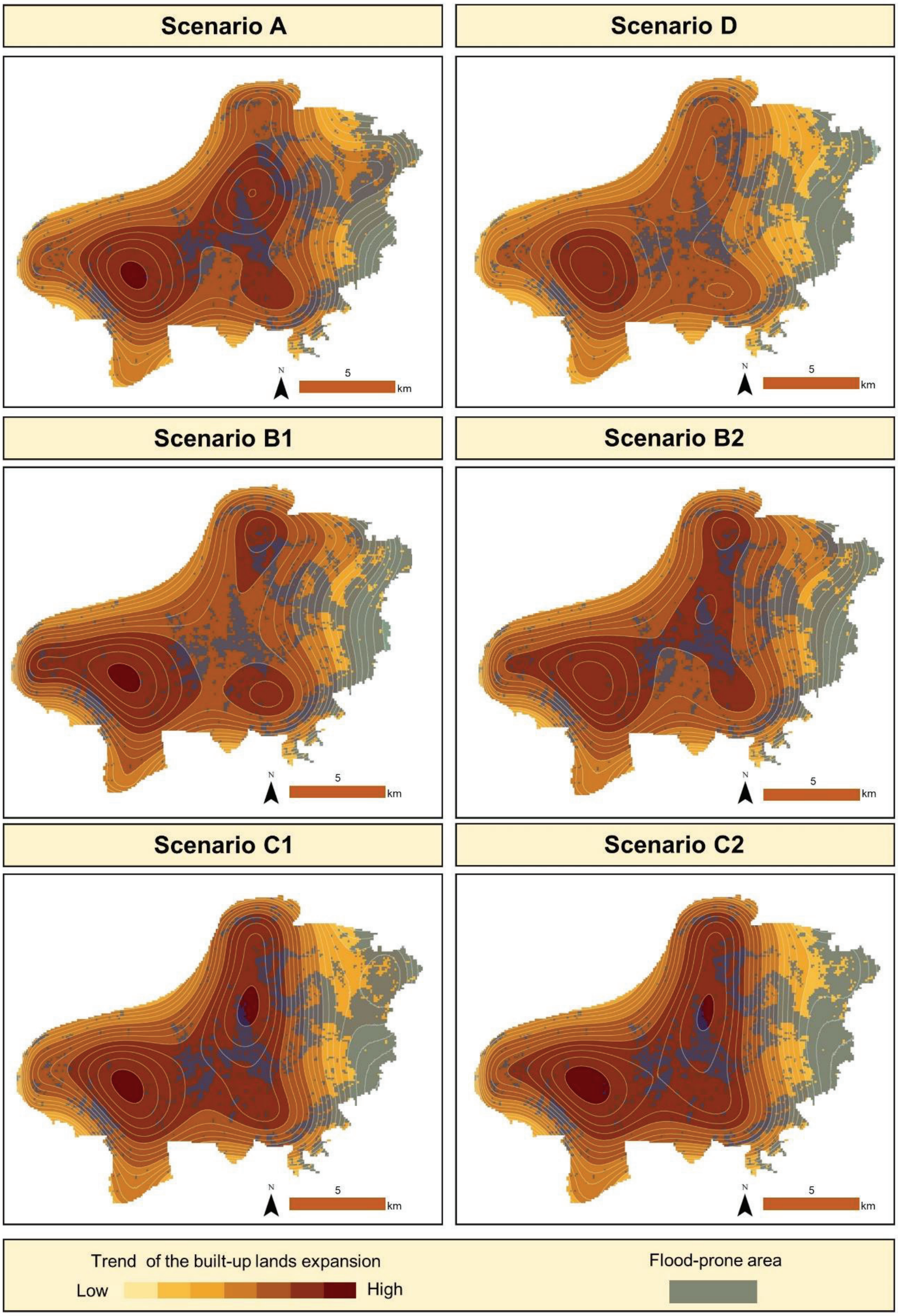


Figure 67 The urbanisation trend during 1997–2037 in the flood-prone area of Nong Khai City

Although the expansion in both scenarios sprawls into the flood-prone areas in the eastern side less than the usual scenario, other contexts indicate the limitations on the patterns of the built-up land expansion. For example, in terms of suitable areas for urban development, more built-up lands in both scenarios expand into the least suitable area.

The integration of policy under scenario D combines land-use conditions of scenario B1 and scenario C2 where the built-up lands are distributed in flood-prone areas and the least suitable areas in each group. This scenario was set to simulate the built-up land expansion under the integration of the policy to prevent the expansion into flood-prone areas, the reinforcement of the expansion into suitable areas, and the policy to decrease the expansion into unsuitable areas in other dimensions such as the accessibility and the cultural assets.

The analysis of the built-up land expansion under scenario D in Figure 67 found that the expansion clusters in the western along Highway 2. Compared with other scenarios, this is different because in other scenarios the expansion happens in both western and eastern sides. Moreover, the built-up land expansion in scenario D shows the lowest number in the least suitable areas. The number of the built-up lands in flood-prone areas in scenario D is also lower than that of other scenarios except for scenario B1 which uses the same land-use policy to prohibit the settlement in the flood-prone areas. After including the areas that are moderately susceptible to floods as parts of flood-prone areas to analyse the differences between scenario B1 which only uses the policy to prevent the built-up land expansion and scenario D which also reinforces the expansion into suitable areas, the result shows that the number of the built-up lands of scenario D in those areas is still lower. This implies that despite using the same policy, the integration of the policy to reinforce the built-up lands in suitable areas and the attempts to slow down the expansion into unsuitable areas which are seen in scenario C2 causes the expansion in scenario D to be more compact than scenario B1. In addition, the comparison between the built-up land expansion in scenario D and in scenario C2 which use the same policy to reinforce the land uses in suitable areas and prevent them in unsuitable areas reveals that the integration helps decrease the exposure to flood and the settlement in the least suitable areas in scenario C2. This is all because of the policy to prohibit the built-up land expansion into flood-prone areas — the policy that is integrated in scenario D.

The decrease in the built-up lands due to the integration of the policy used in scenario B1 and C2 shows that it is ineffective to develop only the policy to prevent the expansion into flood-prone areas when planning policies for urbanisation in the floodplain that overlap with flood-prone areas. Another necessary move is to develop other land-use policies so that the expansion will distribute to suitable areas, controlling the direction of the urban expansion in the vicinity. The integration between the policy to prevent the development in the flood-prone areas and the policy to support the urban development in the suitable areas is in accordance with the recommended solutions of urban land-use planning which considers the disaster risk and the benefits of policies (Asian Development Bank, 2016, p. 31).

To summarise the impact of land-use policy on the trend of built-up land expansion, the patterns of the built-up areas of BAU and the policy-integrated scenario are similar in terms of the spatial distribution. However, Table 34 and Table 35 show that the expansion of the built-up areas in the least suitable area for urban development and flood-prone area are 3 times and 4 times higher than scenario D which is the best scenario. The lowest ratio of the built-up areas in the least suitable area for urban development and flood-prone area is caused by the strict policy of urban development in the flood-prone areas and the policy to support the urban expansion in the suitable area and prevent the urban expansion in the unsuitable area. These policies cause the urbanisation trend of Nong Khai City in Scenario D to be the most compact among every scenario as shown in Figure 67.

7.7 Recommendation on land-use zoning policy

Land-use zoning is an important tool for urban growth management in the floodplain. It provides the policies to restrict the use of the floodplain in various degrees, ranging from completely prohibiting uses to permitting some uses in the floodplain (American Planning Association, 1953, p. 3). To reduce the flood risk, which is a natural disaster in the floodplain, zoning policy is an effective tool to manage the development regulation in the hazard-prone areas to reduce the exposure to hazards (Asian Development Bank, 2016, p. 43). Under the expansion of the built-up lands in the flood-risk areas in the future, the zoning regulation should involve controlling the new urbanised areas to minimise the flood damage (Kim & Newman, 2019) with building code, the transformation of land use to natural type, relocation policy and raising awareness (Hudson & Botzen, 2019, p. 2). Hence, the land-use zoning to control the development is not only a tool for managing the urban growth but also an important non-structural flood measure (Correia et al., 1999, p.2; World Bank, 2017, p. 4).

In this section, to provide an overview of the understanding of built-up area expansion management of Thailand from the government policy perspective, the situation of land-use zoning policy to manage the built-up area in the country and Nong Khai City level was presented, Then the recommendation on the land-use zoning policy for Nong Khai City was described to support the built-up area expansion management in the future.

7.7.1 Situation of land-use zoning policy to manage the built-up area expansion in Thailand

The concept of the built-up area expansion management occurred officially in Thailand after Bangkok and its surrounding areas encountered massive immigration due to industrialisation, which caused the capital city to be clustered with industrial and urban activities, resulting in pollution and social problems (Pongprayoon, 1997). The concern about these problems was shown through the second National Economic Development Plan (B.E. 2510-2514) and led the Thai government to create the measure to manage the urban sprawl. However, the measures more concentrated on allocating and providing public utilities to support quality of life of people in the sprawling areas than on mitigating the expansion of the population and the built-up areas in the peri-urban areas. Even with these policies, the sprawling of built-up areas was still increasing.

The measures to mitigate the increasing population in Bangkok and the surrounding areas first officially appeared in the Third National Economic and Social development plan (B.E. 2515-2519). The decentralisation policy with the growth pole development was adopted to mitigate the immigration of the population. Under the decentralisation policy, the provincial cities were developed as the economic and social provincial centres. At the same time, some provincial cities were selected as the regional cities. The development of the cities in regional areas to mitigate the urban sprawl in Bangkok caused the provincial cities to encounter the sprawl of built-up areas. Many cities designated agricultural lands and unused lands along the road networks as the built-up areas to respond to the built-up area expansion and boost the economic growth while the surrounding areas were designated to be the rural and agricultural lands to control the urban boundary. In fact, although these areas were assumed to be agricultural areas with the prohibition to be developed into industrial area; hotels; theatres; and row houses, the restriction still left some rooms for government offices, utilities, and others to be constructed in the areas. The detached houses and other buildings were still spread in the agricultural lands together with the expansion of built-up areas in the built-up zones, causing the disorderly sprawling built-up areas in the peri-urban areas. Under these situations, it can imply that the designation of rural and agricultural lands as a tool to control the sprawl of the built-up areas are not enough. Apart from the flexible prevention of built-up area expansion in the zone of rural and agricultural lands, the city plan expiration is also a crucial factor in the sprawling of built-up areas. The difficulty in city plan creation caused the tardiness and the discontinuity of promulgation of land-use zoning policy, leading to the lack of policies to control land use (Auttarat, Boonyanupong & Boakla, 2014).

It is interesting that although flood is the local hazard of floodplain area which is the major space of provincial cities in Thailand, flood-prone zone, which is crucial land-use zone to support the flood risk management, was neglected in city planning, Thailand. There is no specific designation of flood-prone zoning: the zoning of flood-prone areas was defined through the zone of conserved rural and agricultural areas which required different conditions to manage land use.

Despite the restriction policy on the built-up area expansion, it is a flexible restriction similar to the zone of rural and agricultural areas, resulting in the built-up areas still expanding in the flooded areas. In addition, the designation of conserved rural and agricultural land is limited despite the provincial cities settling on the floodplain areas and having the potential to encounter floods. Based on the last provincial cities plans, only 9 out of 76 plans designated the zone of conserved rural and agricultural areas. There are only 3 plans that designated this zone in the flood-prone area. Furthermore, some city planning also assigned the flood-prone area to the built-up zone (Piromruen, 2009, pp.75-76).

From this situation, it can be summarised that although most provincial cities of Thailand have settled on the floodplain, the flood-prone areas were excluded from the land-use policy zoning to manage and prevent the built-up area expansion. To control the built-up area expansion in the peri-urban area and the flood-prone area, the zoning of rural and agricultural areas thus has a crucial role in the provincial city plans. However, the flexible prevention of built-up area expansion under the regulation of this zone and the discontinued of land-use zoning policy caused the built-up areas to still expand, implying that the expansion of built-up area is haphazard and needs the restricted land-use zoning policy to shape the built-up area expansion.

Based on the purpose of the provincial cities which focus on supporting urban growth, the management of built-up land expansion was neglected in practical terms and caused the sprawling of built-up areas in flood-prone areas and unsuitable areas. Promphakping & Ponbumrung (2022, p. 77) evaluated the performance of local government organisations in order to develop the urban area. They indicated that the local government organisations have the highest capacity to construct road network to support the urban growth while the capacity to manage flood to respond to the urban growth is lowest. In fact, a local government organisation has an important role to control and shape the built-up areas into suitable areas that are safe from floods. Based on the Town Planning Act B.E. 2562 (2019), the local government organisation can formulate and prepare their town plans in order to support urban development and resolve the problems that involve the impact of the inconsistency of land uses to prevent the possibly arising disaster. In addition, the local government organisations also have the role to allow construction or land use in accordance with the town plan in order to control the sprawling built-up area. However, although the central government decentralises the ability to create the city plan to the local government organisations, due to the limitations on budget and specialised staff in urban planning including the intricacy of the boundary of local governments, it is difficult for the local government organisations to create the city plan. The limitation on the government staff of the local government organisations prevent them from efficiently controlling the built-up areas and land-use in accordance with the town planning (Auttarat, Boonyanupong & Boakla, 2014, p.124; Piromruen, 2009, p.74). Piromruen (2009 pp.69-70) also indicated that the concept of town planning which focused on 'controlling' instead of 'promoting' is also an important factor in obstructing the local government organisation to implement town planning to achieve a productive outcome, causing the sprawling of built-up areas in the unsuitable areas.

7.7.2 Situation of land-use zoning policy in Nong Khai City

Despite being established in 1827, Nong Khai City promulgated the first land-use zoning policy in 1989 through the Nong Khai City plan. So far, the land-use zoning policy of Nong Khai City consists of four city plans: Nong Khai City plan in 1989, Nong Khai City plan in 1999, Nong Khai City plan in 2011, and Building Control in the special economic zone of Nong Khai City in 2017. Currently, the lands in Nong Khai City were controlled by the integration of the land use zoning policy in Nong Khai City plan in 2011 and Building Control in the special economic zone of Nong Khai City in 2017.

From Figure 68, the first city plan of Nong Khai City controlled the area surrounding the original settlement. The centre was assigned as the highest density of the residential area. Then, the density of residential area decreased respectively in the surrounding area. All residential areas were surrounded by the zone of rural and agricultural areas, as the buffer zone of the urban areas. In overview, the first city plan of Nong Khai City was influenced by the monocentric model in which the core areas are highly concentrated with the population, jobs, and public amenities due to the spatial conditions of the original settlement area. However, although the city plan attempts to attract the population and lead commercial zone into the centre area, it pushes the government offices into the border area in the low-density residential areas and rural and agricultural lands.

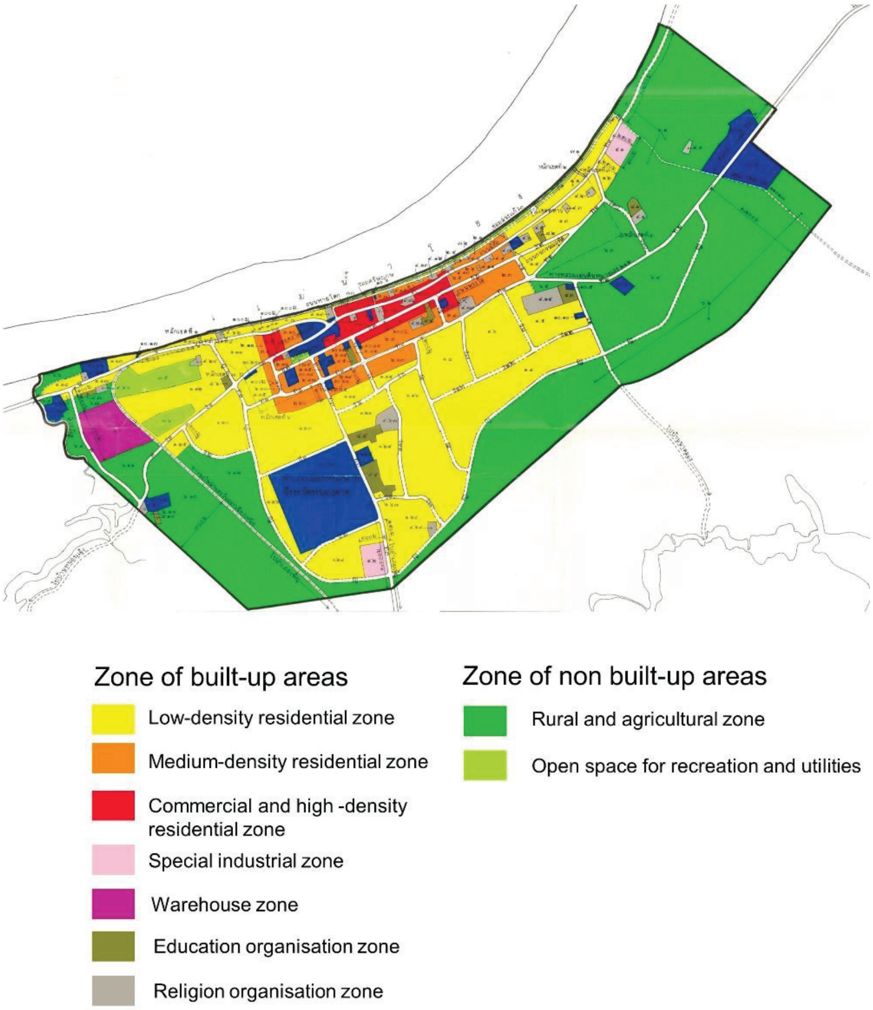


Figure 68 City plan of Nong Khai City in 1989

Regarding the second city plan (Figure 69), the boundary of the city plan was extended from the first plan on every side, especially on the southwestern side. Despite most extended areas being assigned as the zone of rural and agricultural lands, the zone of built-up areas extended into the border edge, and the low-density residential zone near the centre was upgraded to be the medium-density residential zone, especially on the eastern side. In addition, the built-up areas like cargo areas were assigned on the southern side surrounding the train station to support the Thai-Lao friendship bridge. Although the planning of Nong Khai City is still under the monocentric model using the original settlement of Nong Khai City as the core area, the small node of residential areas with a medium density was added on the western side. Considering the extension of the built-up areas in terms of density, boundary, and the addition of a small node to a residential area, urban planning was created to support urbanisation.

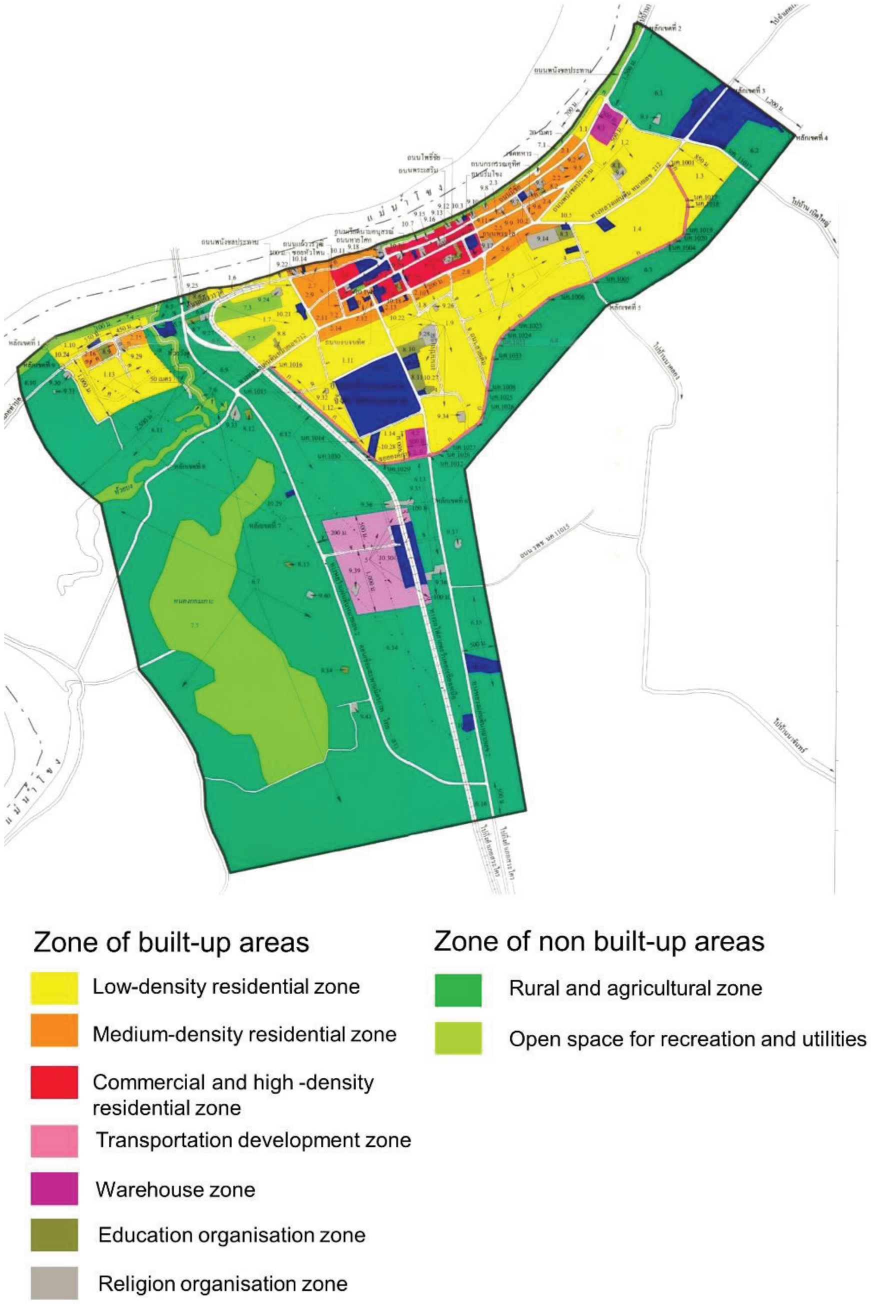


Figure 69 City plan of Nong Khai City in 1999

The third city plan (Figure 70) is similar to the second city plan. The original settlement areas were assigned as the core area with the highest density of population. However, the third city plan extends the boundary of city planning towards the southeastern side and designated it as the rural and agricultural area zone. In addition, it also transformed the rural and agricultural lands on the southern side into the low-density residential areas to support the development of Khon Kean University. The addition of low-density residential areas was a new node to support urbanisation.

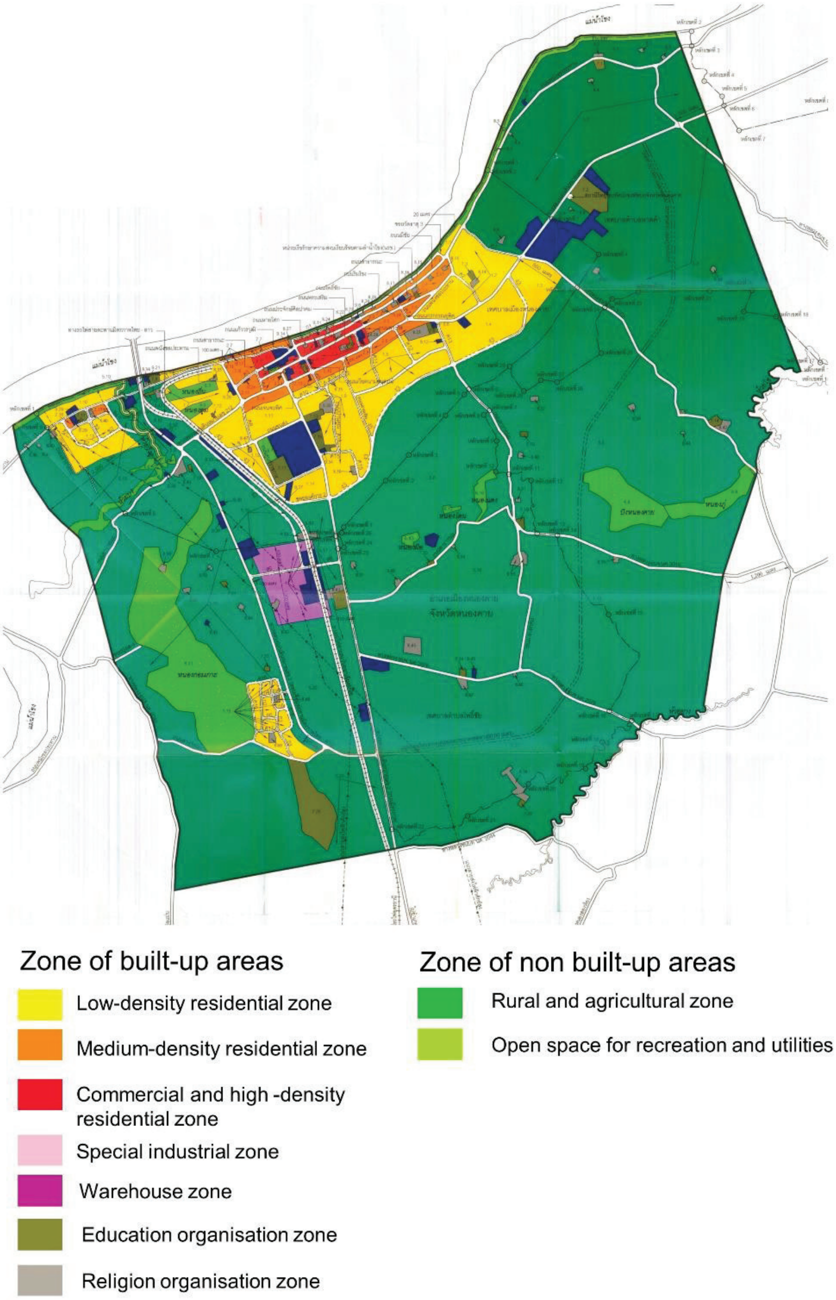


Figure 70 City plan of Nong Khai City in 2011

The concept of urban planning in Nong Khai City can be summarised as follows. Based on the city plan, firstly the governments attempted to make the urban areas concentrate in the original settlement area as the monocentric centre. However, due to the pressure on urbanisation, urban planning in the second plan needs to extend the boundary and increase the density of the built-up areas in the core areas. In addition, a small node of the built-up area has been added although all of the areas are still rural and agricultural areas. The addition of a small node in the peri-urban also continued to be the method to respond to the urbanisation in the third city plan together with the expansion of rural and agricultural zone. The characteristics of the built-up zone in the core area are the same as in the previous plan. In the overview, the city planning of Nong Khai City is based on the concept of a monocentric centre with small nodes to support urbanisation. These city plans attempt to concentrate on the core area and decrease the sprawling built-up areas in the peri-urban area by assigning the rural and agriculture zones with the small node of built-up area to retard the increase of population in the core area. As discussed in Chapter 4 about the driving factors of the built-up land expansion, the zone of built-up area in the city plan has a positive relationship with the built-up area expansion, implying that the built-up area expanded in the zone of built-up areas, and the zone of the built-up area helps shape the expansion of the built-up areas in Nong Khai City. However, the limitation of the zone of built-up areas, which were designated since 1999, in the core area cannot cope with the urbanisation, as shown in Chapter 4 that the agricultural areas had a high impact on the built-up area expansion and cause the built-up area sprawling into the zone of rural and agricultural areas and flood-prone areas without the land-use zoning policy to manage the urbanised area on the flood-prone zone.

7.7.3 Recommendation on land-use zoning policy for Nong Khai City

In general, the land-use management and planning in the floodplain to reduce the flood risk should balance between the reduction of exposure to flood by avoiding or preventing the development in the flood-prone areas and the maximisation of the efficient use of the floodplain to respond to the needs by promoting growth in the suitable areas with the regulations and incentives (Asian Development Bank, 2016, p. 35; Associated Programme on Flood Management, 2016, pp. 8, 25; World Bank, 2017, p. 2). It is in accordance with the expansion of built-up land under the policy of scenario D — which integrated the policy to protect the expansion of the built-up lands in the flood-prone areas with the policy to support the settlement in a suitable area which provides a good environment in term of safety, accessibility and policy to conserve the assets.

In this section, the recommendation on land-use zoning policy thus was introduced as the guideline to manage the floodplain areas by synthesising the findings from each chapter to develop the land-use zoning policy of Nong Khai City based on scenario D, which was indicated as the best scenario to reduce the sprawling of the built-up lands of Nong Khai City in the flood-prone areas. To develop the recommendation on the zoning of land-use policy for Nong Khai City based on scenario D, firstly, the importance waterbodies were eliminated as the restricted zone or conservation zone from the development. Then remaining areas were considered based on flood resilience growth and urban development zone. In this study, the policy of flood resilience growth was developed from the information on flood-prone areas in Chapter 5. It was categorised into three groups based on the class of flood susceptibility, as shown in Figure 71.

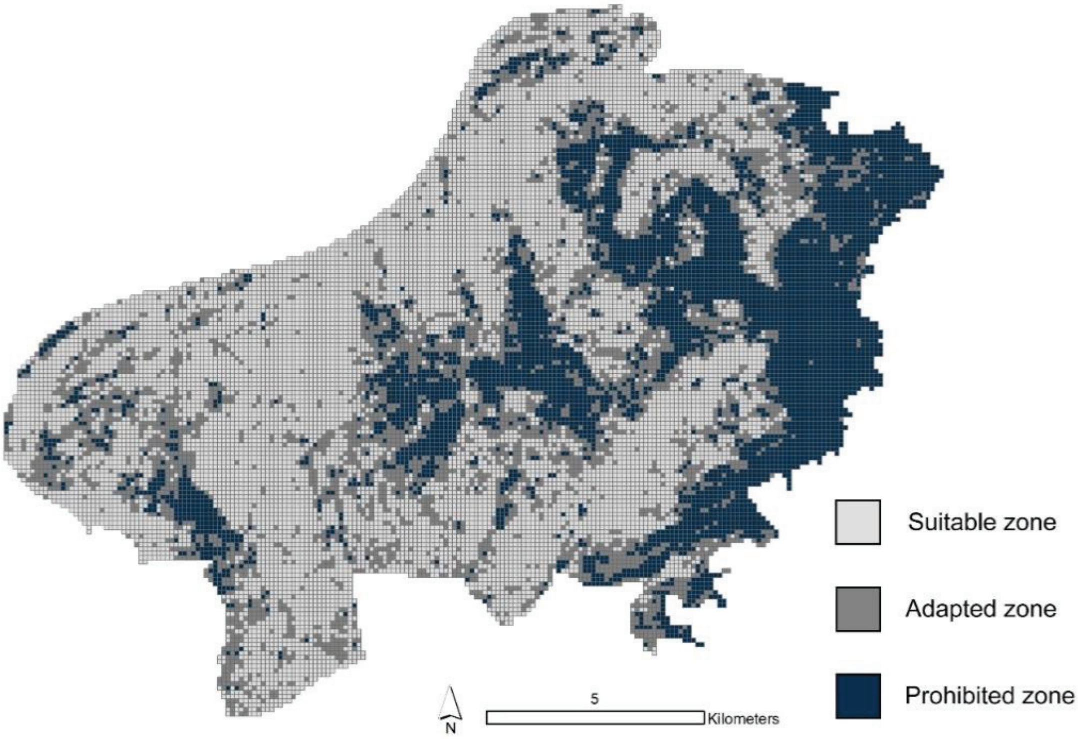


Figure 71 Zoning based on flood-prone areas

From Figure 71, the lowly and very lowly flood-prone areas were grouped into the suitable construction zone. The moderately flood-prone areas were set as the adapted construction zone, and the highly and very highly flood-prone areas were set as the flood-prone areas with the construction prohibition zone. To enhance the flood resilience by reducing the exposure to floods in the floodplain, the land-use policy and construction guideline were recommended based on the susceptibility level that is usually used as the reference to construct the land use policy (World Bank, 2017, pp. 6,10), as shown in Table 36.

Table 36

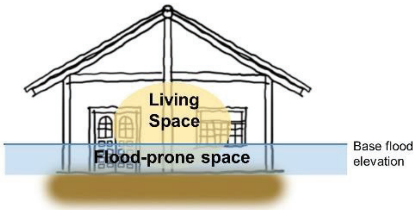
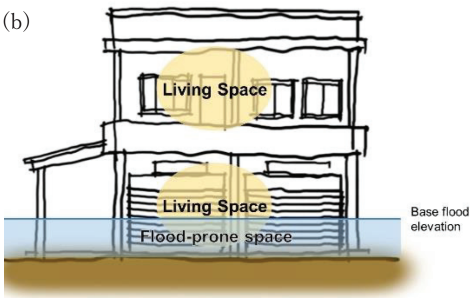
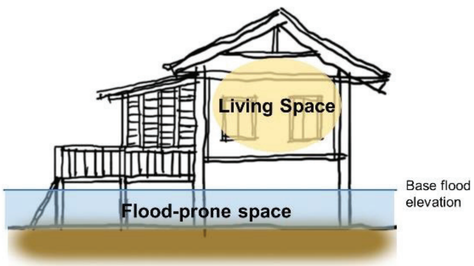
The recommendation on land use and construction based on the flood-susceptibility zones

	Zone		Recommendation
Non- flood-prone area	The suitable zones	Land use	Both urban development and non-urban development zone. For urban development, the built-up lands, including the highly vulnerable infrastructure such as hospitals and schools, should steer in these zones the most.
		Construction	Consideration about flooding is not required for the construction in this zone.
	The adapted zones	Land use	Both urban development and non-urban development zone.
		Construction	The construction in this zone should consider the flood-resistant design and materials, such as a one-storey house with the enclosure floor and flood opening. Moreover, elevated houses should be developed for a new building to lift the living space level from the ground floor. The existing one-story house on the ground floor should prepare the space or construct an additional story to store important assets during the flooding. In addition, the facilities should be set up at a high level to protect them from the flooding.
Flood-prone area	The prohibited zone	Land use	• The construction for the new urban development is not allowed in this zone to mitigate the loss due to flooding. The existed built-up lands, such as the residential areas, should be encouraged to relocate into other safer zones (World Bank, 2017, p. 6) • The areas in this zone should be used as the open spaces, recreation spaces, and rural areas (Associated Programme on Flood Management, 2016, p. 47). • Currently, most areas are agricultural lands. To decrease the negative effects of flooding on the agricultural lands during the rainy season, the multi-functions of land uses by integrating between agricultural lands and flood-retention areas should be considered with local agricultural routine.
		Construction	The built-up lands that cannot be relocated should be adjusted to mitigate the effects of flood by considering three factors to resist a flood: the minimum ground floor height, foundation of building and material. • **For minimum ground floor height**, a one-storey house should be avoided and reconstructed into an elevated house without liveable space and an enclosure area on the ground floor to allow the water flow. The based flood elevation should be used as the reference minimum ground floor height • **For the foundation**, a pile foundation was recommended to support the strengthening of buildings during the floodings (Nimsamer & Ramasoot, 2015). • **Flood resistant materials** should be considered for the parts that are likely to sink in the flood, such as the basement.

As shown in Table 37, these buildings were from the housing style in the Northeast of Thailand that were constructed according to the formation factor and chronological order (Satiennam & Thungsakul, 2016). However, the styles based on the formation factors and chronological order cannot reflect the capacity to cope with floods. Hence, the building styles since 1930 was recategorised based on characteristics of elevated floors: the one-storey building on the ground, one-storey building with enclosure floor and flood opening, elevated houses with (a) the partial and (b) completely wall, and elevated house without the living space on the group floor.

Table 37

The recommendation on construction types based on the flood-susceptibility zones

	Types of buildings		Zone		
			Non flood-prone area		Flood-prone area
			The suitable zones	The adapted zones	The prohibited zone
A	A one-storey building on the ground		Recommended	Recommended with space to store the important assets	Not recommended
B	The one-storey building with enclosure floor and flood opening		Recommended	Recommended	Not recommended
C	Elevated house with (a) the partial and (b) complete wall	(a)  (b) 	Recommended	Recommended	Not recommended
D	Elevated house without the living space on the group floor.		Recommended	Recommended	Recommended for the case that cannot be relocated

The elevated floor was selected as the index to categorise the building types in this study because the architecture components reflect the capacity to cope with a flood by supporting the living space during flood. The elevated building thus is a building type that was fundamentally recommended for construction and renovation in the flood-prone areas to lower vulnerability (Hudson & Botzen, 2019; World Bank, 2017, p. 10). Due to the importance of the elevated building to the flood resilience, the previous study about the flood-resilient houses and the settlement in the flood-prone areas usually adopts an index of the elevated floor which reflect the elevated building to categorise the buildings. For example, Tikul (2015) categorises the buildings of low-income people in Chiang Mai to analyse the flood-resilient into eight styles using the structure and floors. Based on the floor, the low-income people's buildings can be categorised into one-floor houses, one-floor houses with high space under the house (elevated buildings), and two-floor houses. Nimsamer & Ramasoot (2015), which studied the capacity of architecture to cope with floods, also categorised the buildings in Ayutthaya based on the styles, materials, and floors. In this study, the floor was categorised similarly to the study of Tikul (2015), such as a one-floor house, a one-floor house with high space (elevated building), a two-floor house, and a two-floor with high space. That is similar to the study of Mongkonkerd et al. (2013), which categorised the building styles into three groups based on the floors: a pillar house, a two-storey house, and a one-story house.

Although the northeast region frequently encounters floods, the studied about flood-resistant buildings and suitable buildings in flood-prone zones are limited. However, we can get the general idea about the appropriate building styles in each flood zone from the previous studies that included the riverine floods and similar architectural styles based on the characteristics of the elevated floor. Most studies indicated that a one-storey house had a high risk because the architectural component and structure sank under the water, and the locals could not live during the flood (Mongkonkerd et al., 2013; Nimsamer & Ramasoot, 2015; Tikul, 2015). This building style is not recommended in flood-prone areas in this study. For the adapted zones —which was indicated from the marginally flood-prone areas that are unlikely to encounter floods but need preparation, this building style was recommended with space to store the important assets. In this study, a one-storey building with an enclosure floor, a popular architectural style, is also recommended for the non-flood prone area. Because the elevation of the adapted zone is higher than the flood-prone areas, the added enclosure floor with the flood opening supporting the building is higher resilient than a normal one-storey floor on the ground. However, the usage of the higher level of living space due to the enclosure floor is still limited in the flood-prone areas. Hence, the building style is not recommended in the areas.

Regarding the elevated buildings, it was categorised into two styles based on the space on the ground. An elevated buildings without the living space is a traditional architecture style in the northeast region, as shown in Chapter 2. Owing to the modernisation since 1957, the elevated buildings with partial and complete walls on the ground floor turned into a popular house style in the northeast region (Satiennam & Thungsakul, 2016, p. 9). The elevated buildings without the living space were regarded as the most suitable building style to construct in the flood-prone areas (Nimsamer & Ramasoot, 2015; Siriponnoppakun, 2012; Tikul, 2015) . '*Taithun*' or the open space under the elevated floor was indicated as an important architectural component to enhance the flood-resilience of the buildings (Nimsamer & Ramasoot, 2015). It decreases the damage of floods to construction and assets. Nimsamer & Ramasoot (2015) indicated that the elevated concrete house on the column without the living space on the ground floor has the least damage to the structure and architectural element during the unusual flooding. It is in accord with the study of Konisranukul et al. (2013, p. 99) and Tikul (2015), indicating that the elevated house with the open space on the ground floor has smaller damage from floods than other building types. Regarding the monetary perspective, the study of Promsaka Na Sakonnakron et al. (2012, p. 519) also found that the repair cost for elevated houses is lower than the non-elevated houses. From the considering the efficiency of the elevated buildings without the living space at the ground level, it was recommended to construct this type of bounding in non-flood-prone zone and flood-prone areas if the relocation is impossible.

Although the elevated building without the living space was recommended as the choice for renovation in the flood-prone areas, the elevated building with the partial or full wall was not recommended because this style also encountered the damage from the flood and required an amount of financial support after the flood. Mongkonkerd et al.(2013, p. 334) indicated that the average repair cost from flood damage of an elevated house with the wall is similar to the one-storey house while repair cost of the pillar house is obviously lower. In addition, Siriponnoppakun (2012, p. 104) indicates that the wall added to the elevated houses makes the buildings more at risk because the living space on the ground floor is low and the water will flood into the enclosure boundary. For this reason, this building style was not recommended for construction in the flood-prone areas.

Regarding zoning based on the suitable areas for urban development in Chapter 6, the areas in the flood-prone areas were set as the flood-prevention zone. The remaining areas were divided into two groups: the zones for urban development and non-urban development. The recommendation for each zone was synthesised from the findings in Chapter 3 and 6, as shown in Figure 72 and Table 38.

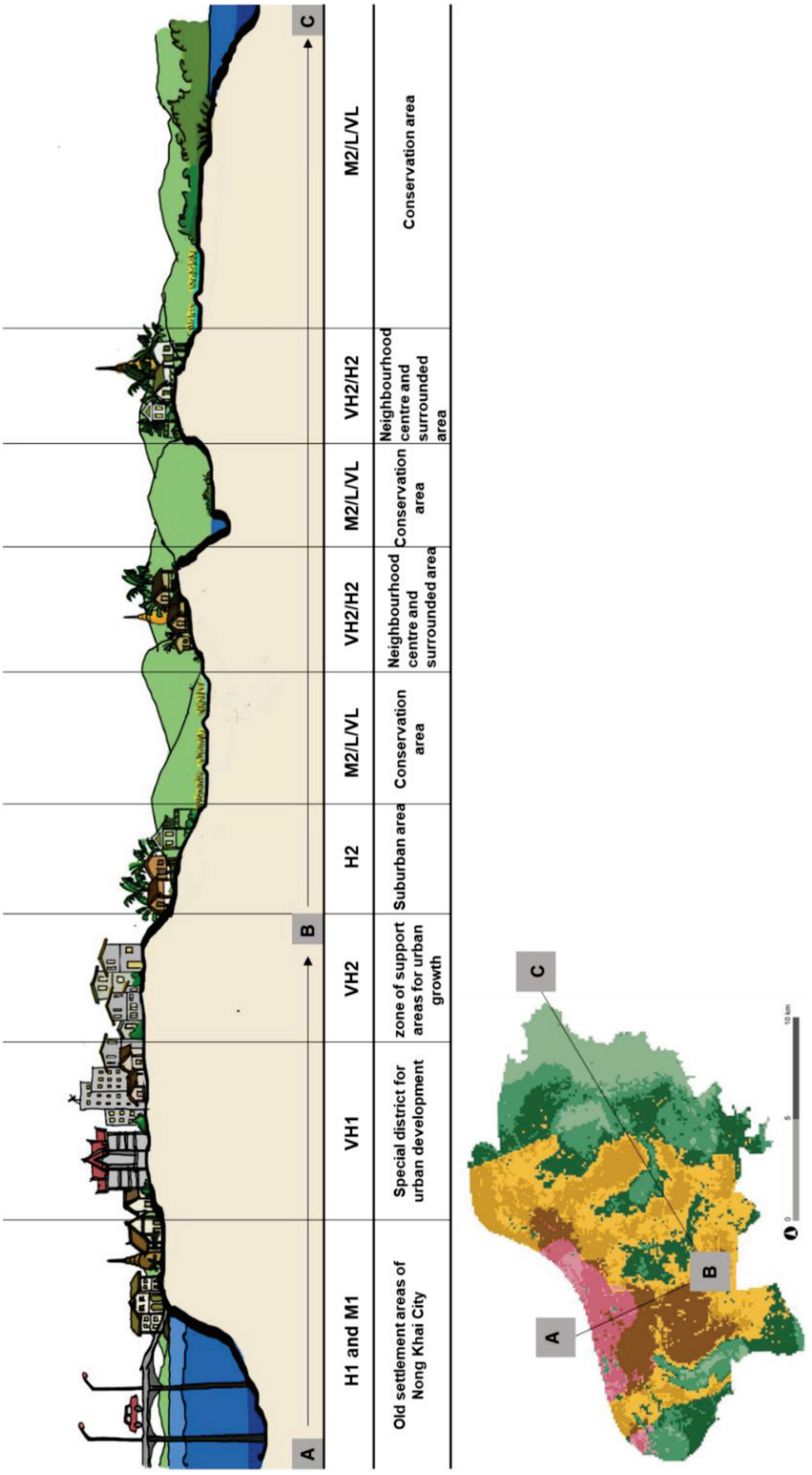


Figure 72 The urban transects of Nong Khai City

Table 38

Recommendation on land-use policy for urban development and non-urban development zones

Land-use type	Zone		Recommendation of land-use policy	Level of Constraint and incentive
Urban development	VH	1	**A special district for urban development:** the areas in this zone should be developed as the new node of urban development of Nong Khai that expand from an existing urban areas to respond to the growth of the original urban areas, which has a limitation on the policy for cultural asset conservation. Considering the location that is free from the hazard and limitations of the cultural and natural asset conservation policy together with the high accessibility to public infrastructure and train stations, the feasibility studies about transit-oriented development (TOD) in the surrounding areas of the train stations should be done to manage the areas to be the special district of urban development maximising the economic benefits and developing the built-up lands in the suitable areas.	High incentive policy
		2	**Neighbourhood centre and the supporting zone for urban growth 01:** the areas in this zone should be used as the supported zone for the expansion of residential areas from the new node of the urban area (zone 1 of very highly suitable areas). It should be used as a neighbourhood centres in the peri-urban area.	
	H	1	**Old settlement areas of Nong Khai City:** the areas in this zone covered the original settlement and the existing urban areas of Nong Khai City. Currently, this area is the urban core area which is a centre of economy and trading at the provincial level. Owing to the characteristics of the original settlement, the ancient sites and cultural heritage are also distributed densely in this zone. Chapter 3, explores the changes of population by Thesaban 's boundary that covers most areas of this zone, indicates that the urban population of the province is distributed densely in this area. However, the change rate of the population is static with a negative rate. At the same time, the population in the surrounding area increased. From this situation, to reduce the future shrink of this city's population, the area in this zone should still be used as the urban areas with the economic policy to attract more people to settle in this area and mitigate the sprawling of the population into the zone of non-urban- development. However, due to the spatial context, the policy of urban development in an old settlement area consisting of various cultural assets should involve the policy to promote cultural assets to support the economy and the cultural conservation.	Moderate incentive policy
		2	**Suburban area: the supporting zone for the built-up areas 02:** the areas in this zone should be used as the extended built-up areas when the settlement in other zones is full, but the demand for urban development still remains. The areas in this zone thus are the sub-urban areas that connect the urban development zone and the non-urban development zone.	
	M	1	**Old settlement areas of Nong Khai City:** Same land-use policy with H1 but provide the lower incentive support	Low incentive policy
Non-urban development		2	**Conservation area for agricultural and ecological purposes in the rural context as '*Thung*':** the areas in these zones should be as the agricultural lands, water bodies, and wetlands based on the current context and existing conditions, to support the food security and enhance the urban livelihood from the ecological benefit. The idea of *'Thung'* in Chapter 2 should be adopted in the non-suitable areas for urban development. Thung is a toponym found in the premodern time. It means a plain area that reflects the multi-using based on spatial and time, including the local disaster that has a role in shaping the settlement in the premodern time. The non-suitable areas for urban development should be conserved as Thung with the use as agricultural lands and unused land for water retention during the flooding. The water bodies and wetlands should be conserved as well.	Low constraint policy
	L			Moderate constraint policy
	VL			High constraint policy

From Table 38, the constraints and incentives to support the expansion of the built-up lands in each zone are still the challenges for urbanisation management. Because the efficiency of constraint and incentive policy to support the urban development and protect the settlement in the flood-prone areas is varied based on the administrative efficiency, participation of stakeholders, and governance system (Bengston et al., 2004, p. 281; OECD, 2018, p. 148). It is also related to the regulatory structure and fiscal status of each administrative. In addition, the influence of policy has more than one dimension, both positive and negative effects on the urban sprawling and other aspects of economic and society's perspectives (Hudson & Botzen, 2019, p. 5; OECD, 2018, p. 144). Based on the different spatial context in each city, the constraint and incentive policy is challenging and needs to be studied in detail. Hence, this study doesn't provide the details of the constraint and incentive policies for Nong Khai City. The level of constraints and incentives was proposed conceptually from the level of suitability based on the assumption that the zone of a very highly suitable areas should be more supported to develop the built-up lands than the zone of the marginally suitable areas. At the same time, the zone of a very lowly suitable areas should be controlled by the constraint policy to slow the expansion of the built-up lands. The level of these constraints and incentives can be applied to the rate of property tax. Ermini & Santolini (2017) provide the function of property tax to shape the urban expansion in Italy and found that the increase of property tax in the suburban areas enables the city to be more compact. It can imply that the increased tax in the unsuitable zone is a solution to reduce the urban sprawl. Furthermore, Asian Development Bank (2016, p. 37) provides two groups of incentives to encourage people to settle in the desired urban development area: financial and non-financial incentives. The financial incentives are monetary rewards such as a grant, tax credits, tax rebates, public subsidies, and accessibility to loans or credits. The non-financial incentives are a nonmonetary reward such as the density bonus and the advice on design and construction. The constraint policies should be promulgated in the undesired land for urban development. For example, the conservation areas and hazard-prone areas should be under the restricted policy; the price should be increased and the public subsidies should be denied to encourage the development outside these areas (Berke et al., 2006, p. 324). In addition, the constraint policy to develop the urban areas can be promulgated by supporting the agriculture lands such as the incentive to support the agricultural activities by adopting the concept of Right-to-Farm laws and Agricultural district or the purchase and transfer of development right (PDR, TDR) (Bengston et al., 2004, pp. 277–278). Miyazaki & Sato (2022) indicate that preferential property tax treatment is a quality tool to preserve the farmland from the transformation to residential lots in the urban promotion area of Japan. If the preferential property tax treatment had not been promulgated, most of the farmlands would have been changed into residential lots.

Based on the two policies — the land-use policies based on the flood resilience growth and urban development, the areas can be categorised into five main zones (Figure 73). Zones A and B were set as the zones for urban development with and without the policy of adapted construction to cope with the flood. Zones C and B were set as the zones for non-urban development with and without the policy of adapted construction to cope with the flood. Last, zone E was set as the zone for flood prevention areas with the construction-prohibited policy.

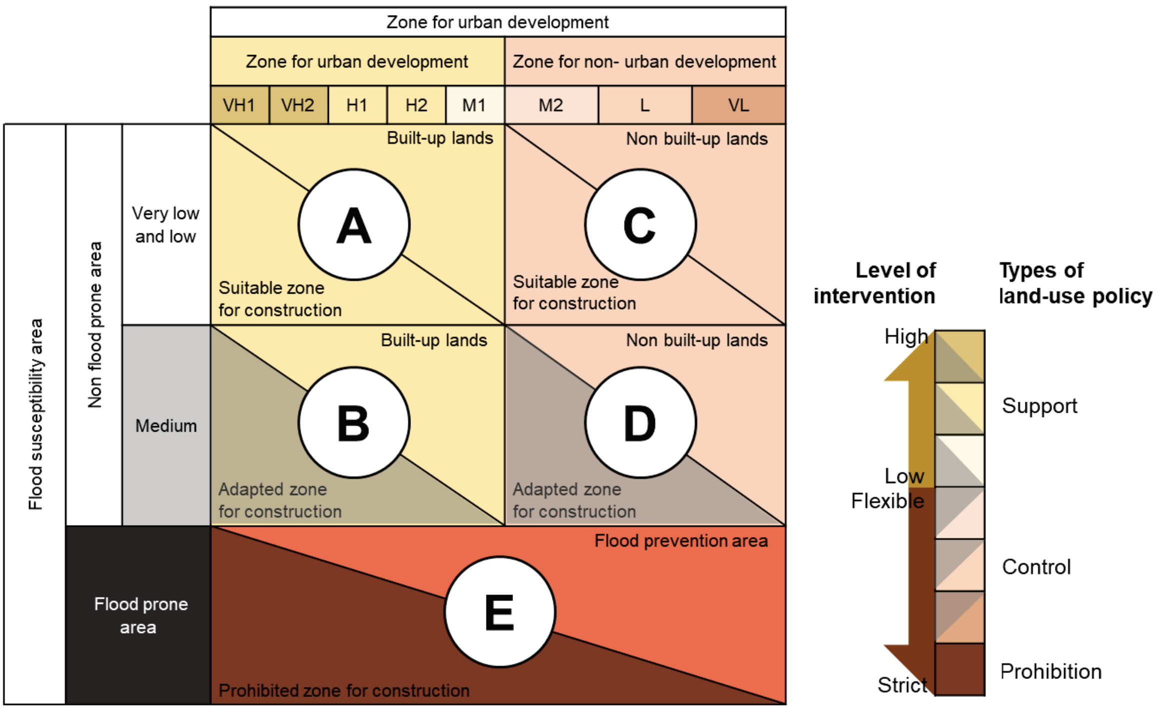


Figure 73 Matrix of land-use policy recommendations

Based on the structures of land policy which were categorised into three groups: the urban development, the rural use or non-urban development, and the conservation areas (Berke et al., 2006, p. 320), five zones of land-use policy and the water bodies that were set as the restricted zone of Nong Khai City can be categorised into three zones as shown in Figure 74 : Urban development zone, non-urban development zone, and restricted zone.

Figure 74 presents the urban development zone that covers the highest ratio of 47.18. It consists of five sub-zones. Most areas in each sub-zone are distributed in group A which does not require the policy to mitigate the loss from floods. The non-urban development zone covers the least areas equivalent to the ratio of 22.56. Last is the restricted zone that covers the waterbodies and the areas for flood prevention. In the overview, about 50% of the total areas in the non-urban development zone do not require the policy to mitigate the loss from floods as the adapted zone. At the same time, 76 % of the urban development zone also do not require the policy to mitigate the loss from flood as the adapted zone. About 50% of the adapted zone for flood of the urban development zone are in the zone of H2 that was assigned as the suburban area for the supporting zone of the built-up areas. The adapted zone covers about 34 % of the total areas of Zone H2.

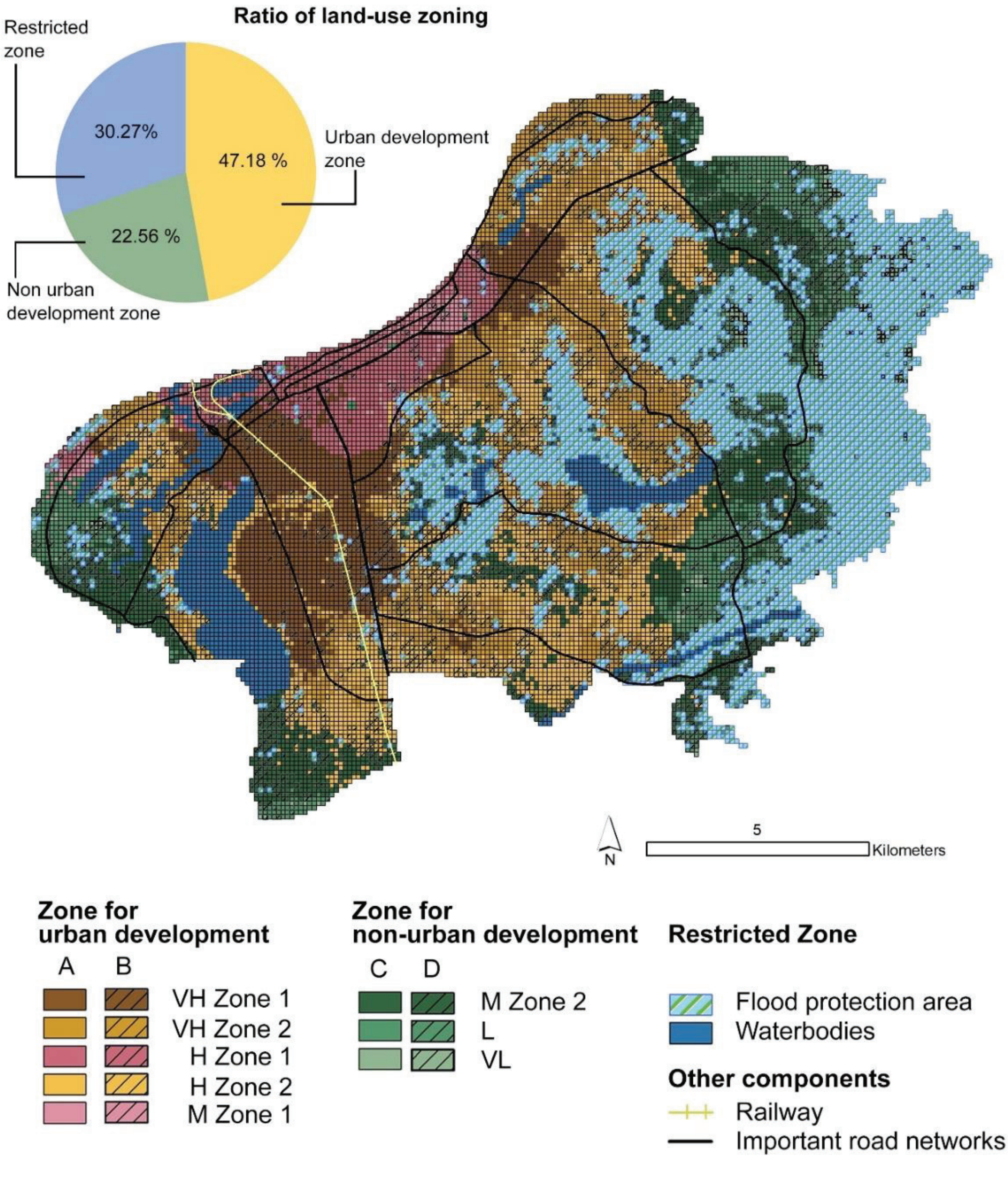


Figure 74 Land-use zoning of Nong Khai City

Figure 75 presents the comparison between the land-use policy zoning in the city plans (Figure 68-Figure 70) and the recommended land-use policy zoning of Nong Khai City created from scenario D (Figure 74). It indicates that the previous city plan attempts to shape Nong Khai City to be a monocentric city with the small node by concentrating the built-up areas around the core area and use the small node of built-up areas to retard the increase of the built-up area in the centres. However, (1) the limitation of the space for built-up areas due to the out-of-date city plan, (2) the lack of the guideline for the suitable area for built-up areas, and (3) the lack of the control of the built-up areas in the unsuitable area like the flood-prone area cause the population to sprawl into the peri-urban area. The built-up areas sprawled uncontrollably into the rural and agricultural lands and overlapped with the flood-prone area unavoidably. This situation implies that under the suburbanisation process, the monocentric growth cannot manage the built-up area expansion in the peri-urban areas.

Under this situation, the study recommended that new city plan (Figure 74) needs to guide and promote the development of built-up areas into the suitable area and control the expansion of built-up areas in the unsuitable area. Scenario D updated the city plan by assigning Nong Khai City as the multicentric city. Due to the limitation of space to respond to the built-up area in the old centre and the limitation of the cultural assets that obstruct the built-up area development, the second node was assigned on the very highly suitable area for urban development at the southern side to make the built-up areas cluster in the areas along the main road and train stations in order to retard the sprawling of the built-up areas on the eastern side which contain the agricultural areas and flood-prone areas. In addition, the small node of built-up areas is still assigned to support the growth of the built-up areas in both centres. While the previous city plan did not consider the flood-prone area on the eastern side, the city plan under scenario D recommended avoiding the new settlement. The restriction of the built-up area expansion on the flood-prone area will retard the expansion of the built-up area on the eastern side causing the area in both centres to be more compact.

While the previous city plan focused on controlling the built-up areas in each land-use type without the promotion to support the settlement in the suitable areas, the sprawling of the built-up areas in the rural and agricultural lands indicates that this method in the previous city plan is ineffective. The recommendation in scenario D recommended the promotion of the settlement into the suitable area such as in the core area and the node for built-up areas to attract development whereas the zone of rural and agricultural lands should apply the controlling policy to retard the sprawling. Likewise, the flood-prone area should be designated as the restricted area for urban development.

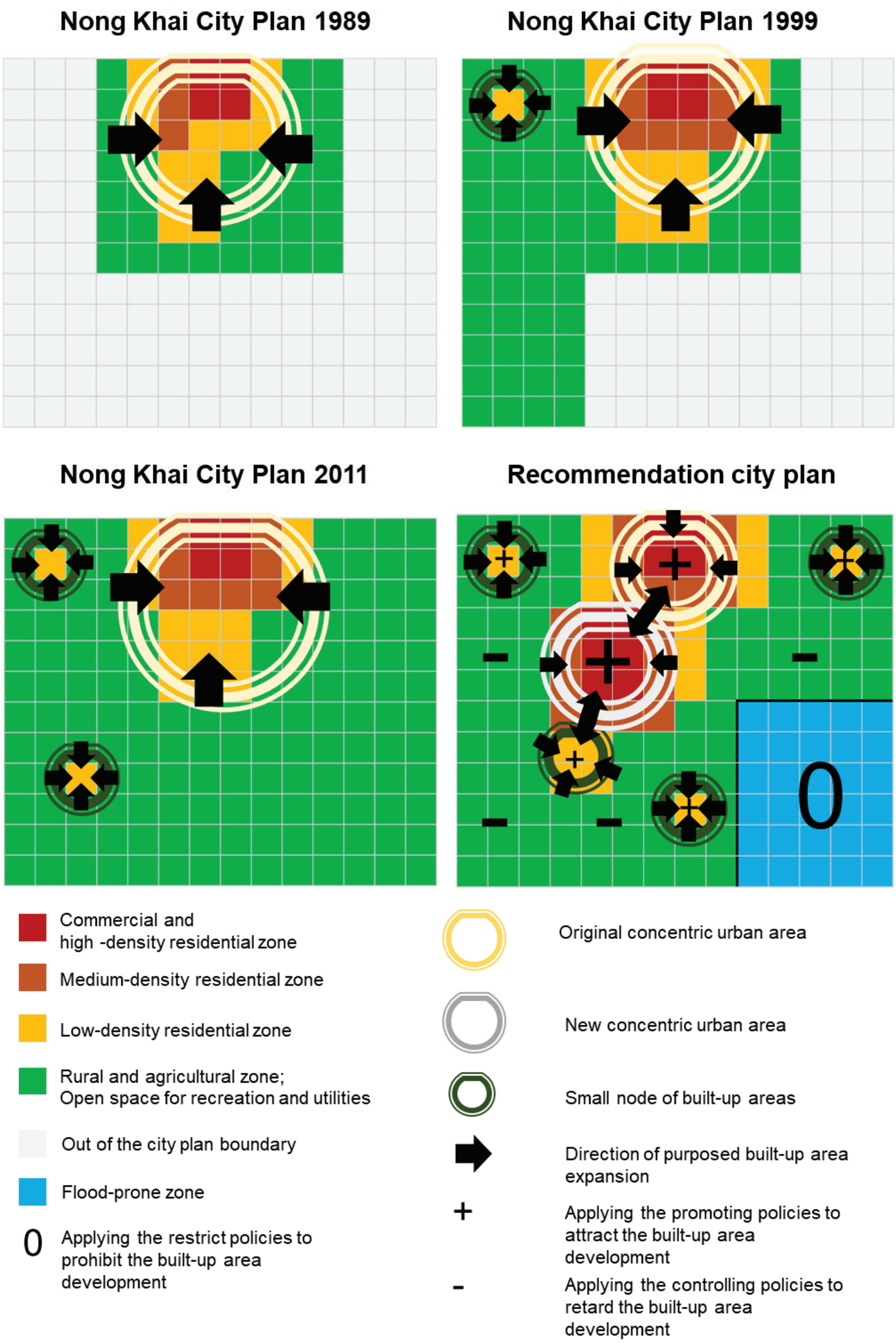


Figure 75 Concept of Nong Khai City plan

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Chapter 8

Conclusion

Contents

In this chapter, the summary was described in two sections. The first section is chapter summary where the information of each chapter was summarised individually. The second section is dissertation summary where the findings of each chapter were combined to construct an understanding of the built-up area expansion and the suitable policy to manage the built-up area expansion in the data-scarce environment. These understandings were divided into two parts: the case study perspective and the generalised perspective to fulfil the understanding of the built-up area expansion in a small provincial city on the floodplain. Then, the direction of future study was presented in the last section.

8.1 Chapter summary

To summarise the findings of this dissertation; the objectives; main methodologies; significant findings; and the implication of each chapter from Chapters 2 to 7 were concluded as shown in Table 39.

Table 39

Chapter summary

Chapter	Title	Detail
2	Objective	To describe the pattern of settlement and land-use of north-east in premodern time, when no mapmaking or developed survey methods were available, through *Nirat Nongkhai* and related historical documents
	Main methodology	Narrative approach and conceptual cross-section
	Significant findings	1) The characteristics of the settlement and land use of northeastern Thailand in the nineteenth century are under the influence of geographic conditions. 2) Natural hazards like drought and flood are the crucial driving factors forming and controlling the settlement and land-use pattern of the northeast in the nineteenth century. 3) Most of the settlements in the northeast are on the plateau while the settlements in the Khorat marginal highland are distributed near the forest edges. The settlement on the plateau is the island village or nucleated settlement: the communities spread over low-hill areas while flat areas around the foothills were rice fields, large unused lands, and forestlands. 4) The land uses can be classified into five types: forestlands, built-up lands, water bodies, unused lands, and agricultural lands. (1) Forestlands were dense in the area of Khorat marginal highland while the forestlands on the plateau were distributed on the low-hill areas across the flat plain. (2) The distribution of the built-up lands is similar to the forestlands. They are distributed in the low-hill areas due to floodings, but the location is also not far from a big waterbody due to drought and daily life. The built-up lands can be classified into five groups to reflect the settlement in the northeast. The city walls, moats, glacises, and archaeological sites were used as evidence of the settlement in the northeastern region in the past while the religious sites, residences and shops were used as the evidence of the settlement in the premodern time (nineteenth century). It is interesting that although they settled in the low-hill areas, their residential buildings are the Ruan Kruang Phuk, which is a stilt house. The floodings were assumed as one of the reasons why the architectures were in this style. (3) Numerous water bodies are distributed on the plateau. It consists of two types based on toponyms: the waterways and reservoirs. Although there were numerous water bodies on the plateau, the water was still limited in the dry season in terms of quality and quantity. This why the

Table 39 (Continued)

Chapter	Title	Detail
		settlement was distributed near the water bodies while the flat lands were mainly the unused lands. (4) The unused land is a common land-use type in the northeast. It overlapped with the dried water bodies and agricultural lands. Due to drought; flood; and soil quality, flat lands in the northeast were abandoned and transformed into grasslands. (5) Agricultural lands were short of information about them. They were distributed in the low hills near the communities and in the garden yards. 5) The settlement and land use of Nong Khai City were similar to other communities in the northeastern region. The city was located on a natural levee that was higher than the surrounding plains, and the land uses there were thung which were vast empty lands, agricultural lands, water bodies, and forestlands on small hills.
	Implication	1) Provide the evidence to fulfil the knowledge of the landscape and settlement patterns in the northeastern region of Thailand during the nineteenth century. 2) Clarify the significance of *Nirat NongKhai* as a historical account of the landscape and settlement in the premodern time.
3	Objective	To analyse and categorise the provincial cities in Thailand based on the patterns of the urban population changes and the urban population concentration and changes.
	Main methodology	1) Content analysis to identify the patterns of the urban population change and concentration based on three indices: annual change rate of the population (ACP), urban population concentration (UPC), and changes in the urban population concentration (CUPC). 2) Cluster analysis to categorise the provincial cities based on the patterns of the population changes.
	Significant findings	1) Under the urbanisation trend at the national level, most provincial cities in Thailand are stagnant cities, followed by shrinking cities and growing cities, respectively. The relation between the population size and the change rate in the provincial cities does not occur. 2) The urban populations are scattered to other urban areas in the provinces; there are only four provincial cities where the urban populations account for more than 50% of the total urban populations. Most provincial cities have an urban population between 15.90-50 %, which is the general ratio. 3) At the national level, the urban population concentration decreased, implying the growth of the urban population outside the provincial cities and the loss of the role as the urban centres of the provincial cities. The replacement of the neighbour cities or the district cities, owing to the process of suburbanisation and the decentralisation policies, shows that the settlement at the province level tends to change from one settlement centre in each provincial city to multi-settlement centres. 4) The provincial cities were categorised into three clusters with 13 sub-clusters. 5) The development outside the provincial cities to respond to globalisation and suburbanisation was assumed to be a crucial factor in creating the shrinking cities in Thailand. At the same time, the accumulation of economic activities in the provincial cities was assumed to be a crucial factor to support the growing population. 6) The population in Nong Khai City increased in the last decade. However, based on the population in the provincial city, it is a stagnant city with the negative trend of population change while the population in the peri-urban area outside the provincial city increased. It implies that Nong Khai City is in the suburbanisation stage. Based on the population trend, the land-use policy should maintain and enhance the economic activity in the provincial city and control the sprawl of population in the peri-urban area.
	Implication	1) Point out the topic of shrinking and stagnant cities in Thai academic contexts. 2) Provide the conceptual guideline to manage the cities in terms of population change.
4	Objective	1) To clarify built-up land expansion patterns. 2) To demonstrate the driving factors of built-up land expansion of Nong Khai City during the 1997–2017

Table 39 (Continued)

Chapter	Title	Detail
	Main methodology	1) Supervised classification with the maximum likelihood classifier (MLC) algorithm and combine function were used to clarify the built-up land expansion. 2) Logistic Regession was used to demonstrate the driving factors of built-up land expansion.
	Significant findings	1) The built-up areas of Nong Khai City were dense in the old settlement area along the Mekong River in 1997, and then they have expanded along the roads, especially the southern area of Nong Khai where the Highway no. 2 and no. 232 are located connecting Nong Khai to the Thai-Lao Friendship bridge and the surrounded provinces. The expansion of the built-up lands along the main highways is in accord with the increasing population in the peri-urban area. 2) The logistic regression model reveals that the expansion of the built-up lands in Nong Khai City was driven by various factors, not just the road network and Thailand's National Economic and Social Development Plan. The biophysical factors, socioeconomic factors, spatial policy, and neighbourhood and spatial interaction factors significantly affected the expansion in different patterns and magnitudes. 3) An access to malls was the most influential driving factor during the first period while agricultural land was the most influential driving factor during the second period.
	Implication	Clarify the driving factors of the built-up land expansion of Nong Khai City in terms of quantitative analysis.
5	Objective	To create the flood susceptibility map of Nong Khai City under three objectives: 1) To clarify the effects of the conditioning factors of flooding in Nong Khai City, 2) To implement the satistical modelling methods to create the FSMs of Nong Khai City, and 3) To compare the performance of each model from AUC and create the FSMs
	Main methodology	**Four standalone models of the statistical modelling method**: • Frequency ratio (FR) • Modified frequency ratio (MoFR) • Weight of Evidence (WoE) • Logistic Regression (LR) **Three ensemble models**: • Ensemble LR-FR • Ensemble LR-MoFR • Ensemble LR-WoE
	Significant findings	1) The conditioning factors of flood occurrence in each model vary in terms of magnitude and patterns. TWI, SPI, drainage density, and flow accumulation have a positive relationship with flood occurrence. Like flat areas, agricultural lands; back swamps and alluvial terrace; and the geology of KTpt which consists of mudstone, siltstone, and fieldstone were also indicated as a positive impactful conditioning classes of flood occurrence in Nong Khai City. In contrast, the elevation has a negative correlation with flood occurrence. Interestingly, the relationship between the flood occurrence and the conditioning factors in terms of the waterways is varied and random. 2) WoE achieves the highest overall accuracy and prediction accuracy to produce the final FSM while the model of ensemble LR-FR achieves the highest success rate to produce the final FSM. Finally, the FSM of WoE was selected as the most suitable FSM. 3) The areas with very low flood susceptibility cover 18.08% of the total areas. These areas surround the original settlement area and are also distributed in Nong Kom Ko Subdistrict near the government centre of Nong Khai Province. 4) The areas with very high and high flood susceptibility are in the southeastern part of Nong Khai City. These areas cover 26.25% and are mainly back swamp, low elevation, high drainage density, and agricultural lands. They are located near the Mesuai River which the most impactful factor for flood susceptibility analysis.
	Implication	1) Confirm that the performances of the models to create the FSMs vary based on the target and the data. It is necessary to compare the efficiency of each model and then select the best models to create the FSMs. 2) Test the performance of MoFR, that usually used in landslide hazard, in order to produce the FSM.

Table 39 (Continued)

Chapter	Title	Detail
		3) Produce the FSM of Nong Khai City to support the urban planning and flood risk management in the data-scarce environment.
6	Objective	To assess the land suitability for urban development in Nong Khai City using AHP in order to determine the suitable and non-suitable areas for urban development in the future.
	Main methodology	Analytical Hierarchy Process (AHP) and grouping analysis
	Significant findings	1) The policy to conserve and protect ancient sites and the surrounding areas had the highest overall weight value, followed by flood and the policy to conserve and protect the water body and areas with significant biodiversity, respectively. At the same time, the distance to police stations had the lowest weight value for urban development. 2) Nong Khai City are mainly distributed in the highly suitable areas, followed by the very highly suitable areas. The very highly suitable areas are distributed in the peri-urban area surrounding the original settlement and the current urban areas along the main roads. The highly suitable areas are distributed in the original settlement, the current urban areas, and the area surrounding the very highly suitable areas in the peri-urban area, especially in the central area. At the same time, most marginally suitable areas are adjacent to the highly suitable areas in the peri-urban area. One side of the marginally suitable area is adjacent to the lowly suitable areas. The marginally suitable areas are thus the buffer zones between the suitable and unsuitable areas, which are the water bodies and agricultural areas at the border area on the eastern side. 3) Based on the spatial characteristic, Nong Khai City can be categorised into eight zones: five are suitable areas for urban development, and three are unsuitable areas for urban development.
	Implication	1) Confirm the performance of AHP to assess land suitability for the urban development in the data-scarce environment. 2) Enhance the performance of AHP to support the urban planning by integrating the grouping analysis to categorise the zones of the urban development based on their characteristics. 3) Propose using AHP to support the urban planning in the small cities in BRI.
7	Objective	1) To predict the expansion of the built-up lands in Nong Khai City between 2027-2037 under the different scenarios. 2) To analyse the expansion of the built-up lands in Nong Khai City between 2027-2037 in flood-prone areas and the least suitable areas for urban development. 3) To recommend the land-use zoning policy of Nong Khai City based on the best scenario.
	Main methodology	Decision Forest Machine Learning and Markov Chain were adopted to predict the expansion of the built-up lands within four scenarios. Overlay techniques using the prediction map, the flood-prone area, and the least suitable area for urban development were adopted to assess the performance of each scenario.
	Significant findings	1) Directions of the built-up land expansion in 2027 and 2037 are not vastly dissimilar in each scenario. The built-up land will increase significantly in the eastern and southeastern areas in both periods, compared to other directions. Interestingly, the number of the built-up lands will also increase moderately in the southern and north-eastern in 2027 but extremely decrease in 2037. 2) The number of the built-up lands will increase in the flood prone area from 11.21 % in 2017 to 28.67 % and 45.19 % in 2027 and 2037. 3) The built-up lands will sprawl in 19.96 % and 35.53 % of the least suitable areas in 2027 and 2037. 4) The most suitable scenario to mitigating the built-up lands in the flood-prone areas and least suitable areas is the integration of policy to prevent the expansion into flood-prone areas, the reinforcement of the expansion into suitable areas, and the policy to decrease the expansion into unsuitable areas in other dimensions such as the accessibility and the cultural assets.

Table 39 (Continued)

Chapter	Title	Detail
		5) The land-use policy categorises the areas in Nong Khai City into five zone under the three groups of the urban development, the rural use or non-urban development, and the conservation areas. Urban development zone that covers the highest ratio of 47.18. Most areas in each sub-zone are distributed in group does not require the policy to mitigate the loss from the flood. The non-urban development zone covers the least areas equivalent to the ratio of 22.56. It consists of three sub-zones. More than 50% of the total regions need the policy to mitigate the loss from the flood. Last is the restricted zone that covers the waterbodies and the areas for flood prevention.
	Implication	1) Provide a case study of Decision Forest machine learning to predict the built-up land expansion in order to support the urban planning. 2) The recommendation on land-use zoning policy thus was introduced as the guideline to manage the city in the floodplain.

8.2 Dissertation summary

8.2.1 The built-up area expansion of Nong Khai City and the suitable policy to manage the built-up areas in the future

From the findings of each chapter, the patterns of the built-up area expansion of Nong Khai City were summarised to answer the first research question as shown in Figure 66 and Figure 76, From the historical documents and the satellite images, the built-up lands in 1997 had only clustered on the natural levee along the Mekong River before the lands on the southern side sprawled along Highway 2, especially in the areas around the Government Complex and malls, between 1997 to 2007. The expansion on the southern side along Highway 2 and 233 carried on until 2017. Besides this expansion, between 2007-2017, more built-up lands expanded along with the transportation networks, especially on the eastern side, where the expansion was apparent in the area next to the original settlement. The prediction about the future changes found that despite the tendency to expand into the southern side over these years, in 2027, the areas will not be able to support more built-up land expansion leading to the expansion being less intense than that in the eastern side, especially the southeastern side. As the built-up lands in the eastern side expanded further from the original areas in 2017, the expansion between 2027-2037 will be further and further away from the city centre and the areas along Highway 2 and 233 where the expansion had happened. Based on the boundary of the flood-prone areas and the suitable areas for urban development that were analysed in the data-scarce environment to respond to the research question 2, the sprawling built-up areas of Nong Khai City on the eastern side in the future cause higher exposure to floods in Nong Khai City. At the same time, it also sprawled on the least suitable areas for urban development that are considered with other perspectives like accessibility.

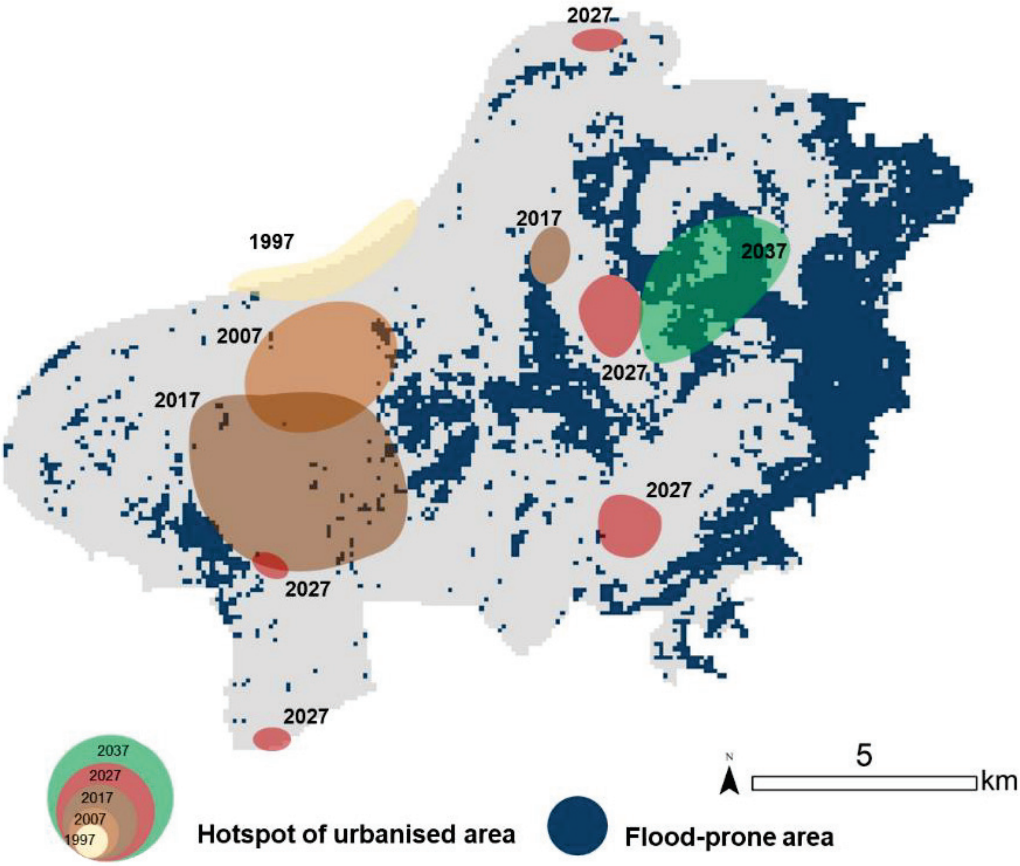

Figure 76 The changes of the built-up areas from 1997 to 2037

Although the expansion of built-up areas has a relationship with the zone of built-up areas in the previous city plans, the limitations of the area in the zone of built-up areas due to the old city plan caused the built-up areas to sprawl into the zone of rural and agricultural areas that overlapped with flood-prone areas on the eastern side. Hence, to manage the built-up area expansion of Nong Khai, it is necessary to identify the areas for urban development to shape the new settlement in a suitable area. According to the prediction of built-up areas with the integration of policy based on the flood-prone boundary and suitable area for urban development, the land-use policy zoning of Nong Khai City should prevent the development in the flood-prone areas and maximise of the efficient use of the floodplain to respond to the needs to promote growth in the suitable areas with the regulations and incentives, together with the discouragement of the settlement in the unsuitable areas for urban development. Due to the policy to conserve cultural assets that was applied in the original settlement that is the city centre, the concept of city planning should be adjusted from being monocentric with small nodes that are saturated with built-up areas to being multicentric with small nodes. The very highly suitable areas, located around the train station which will become the terminal of high-speed railway, should be designated as a new centric node to support the built-up area expansion and gain the maximum benefit from high-speed railway. At the same time, the small node should be assigned to support the built-up area expansion in another direction. In addition, not only should the city planning make the built-up areas compact within the centric node and small node surrounding the city based on the suitability level, but it should also consider the restricted area for built-up area development. The flexible restriction of the policy of the zone of rural and agricultural areas and the absence of a policy on flood zoning in Nong Khai City causes the built-up areas to spread into the least suitable areas for urban development and flood-prone areas, so the land-use policy should be adjusted by designating the flood-prone areas as the restriction zone for built-up area development, together with the promulgation of the policy to control the built-up areas in the non-suitable areas based on the suitability level to retard the urban development in the non-suitable areas for urban development.

8.2.2 The built-up area expansion of small provincial cities on the floodplain and the development of suitable policy to manage the built-up areas in the data-scarce environment

As stated in the introduction, the current understanding of the built-up area expansion on the floodplain has two crucial gaps: (1) the understanding of the expansion of the built-up areas in the small cities on the floodplains in Thailand and (2) little evidence on the application of GIS to support the land-use policy of the small cities on the floodplains in the data-scarce environment. In this section, the findings in each chapter were generalised to fulfil the current understanding of the built-up area expansion on the floodplain as the following summary.

8.2.2.1 The understanding of built-up area expansion of the small provincial cities on the floodplain

The expansion of the built-up areas in Nong Khai City was summarised to support the limited understanding of the built-up areas in the small provincial cities on the floodplain along the Mekong River. The model of the built-up area expansion in the small provincial city on the floodplain were developed and break down into three stages: the before urbanisation, the urbanisation, and the saturated urbanisation.

From Figure 77, Stage 1 is the built-up area expansion before urbanisation. Due to the limitations of population pressure, at this stage, the built-up areas are clustered on a low hill and natural levee which is a safe area from flooding. The new built-up areas expand in the communities as the infilling or near the old built-up areas because of the limitation of transportation. The surrounding areas are agricultural lands and unused lands which overlap with the flood-prone areas. As a result of this condition, the city at this stage is compact and has less flood exposure.

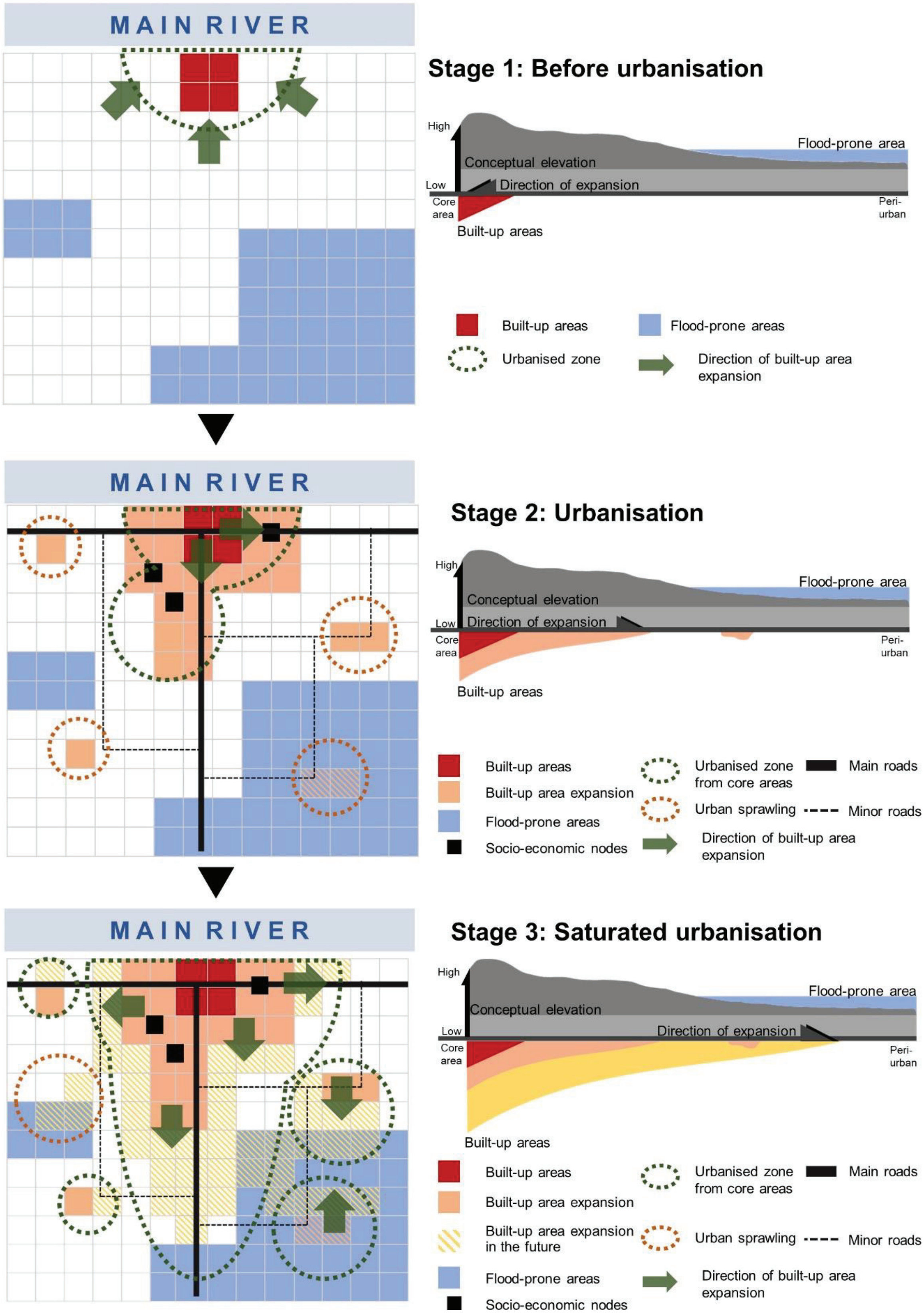

Figure 77 The model of the built-up area expansion in the small provincial city

Stage 2 is the built-up area expansion in the urbanisation process. The pressure of population caused the built-up areas to expand around the old city and along the developed road network in the peri-urban areas, especially the area around the hub of social and economic such as government complexes, and malls. However, these hubs are usually located densely along the main roads in the peri-urban area because these land-use activities require the amount of space which is limited in the original settlement. Due to the location of the cities — which usually is in the waterfront area — and the size of economy which is smaller than the big city, the main road that is dense with the economic and social hubs is usually a single road, causing the change of urban area to look like T-Shape that is different from big cities or the cities on the plain area that can expand into the surrounding areas.

Stage 3 is the built-up area expansion with the saturated urbanisation and the encroachment of built-up area on the flood-prone area. The built-up areas are still expanding into the peri-urban area around the old city and the main roads. While the continuation of population pressure caused the built-up areas in the core area and the main road to be saturated, the population and built-up area spread into the agricultural lands along the minor roads. The built-up areas along the minor roads in the prior period also expand. The spread of the built-up areas leads to more severe encroachment of built-up areas on flood-prone areas.

The expansion of other small provincial cities along the Mekong River like Nakhon Phanom and Bueng Kan provincial cities was adopted to support this model in the general term. From Figure 78, the built-up areas of Nakhon Phanom provincial city in 2004, 2015, and 2021 were extracted from Google Earth. In 2004, Nakhon Phanom City was a monocentric city. The core urban lay along the Mekong River. The figure shows that the built-up areas expanded around the core urban areas in every period. In the first period, the built-up areas were dense in the core urban area and expanded around the hubs of society and economy with the little sprawling built-up area around the main roads. In this stage, it can imply that Nakhon Phanom was in the early stage 2 in the model of built-up area expansion in the small provincial city on the floodplain. Nakhon Pronom moved completely to stage 2 as shown in the built-up area expansion in 2015. The built-up area was still increasing in the surrounding area and densely expanded around the economic hub along the main roads. The shape of the urban areas of Nakhon Phanom in this year was like a T-Shape. In addition, the sprawling built-up area was also found in the agricultural area along the minor road. For the built-up area expansion in 2021, less built-up area along the main road in the prior period was saturated and expanded compared to the earlier period. Then, most of the built-up areas expanded along the minor roads around the earlier sprawled area and

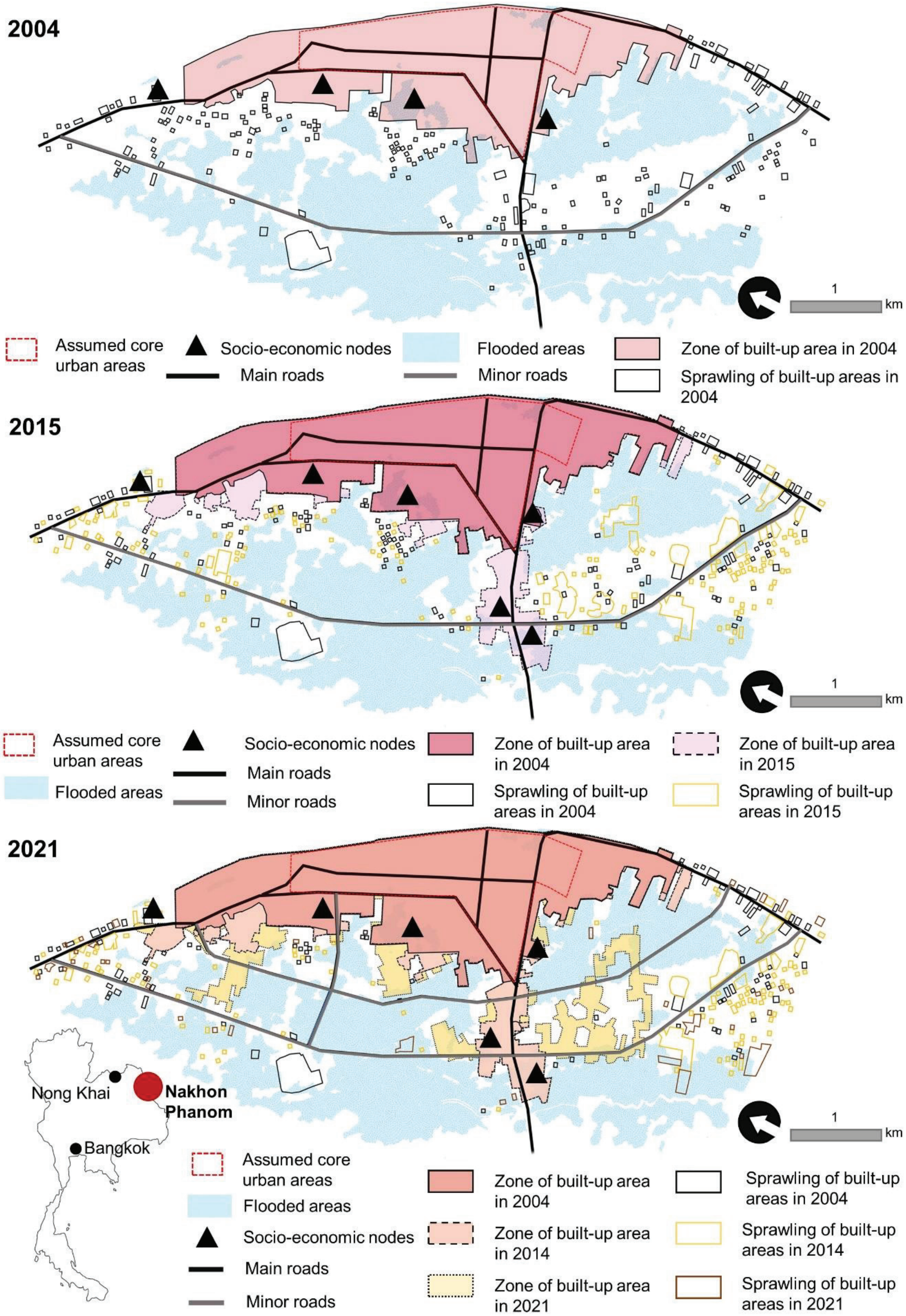

Figure 78 the expansion of the built-up areas in Nakhon Phanom provincial city

overlapped with the floodplain areas. In the overview, the Nakhon Phanom provincial city was in stage 3 and required a plan to retard the built-up areas in the flood-prone area.

For Bueng Kan Provincial city, as shown in Figure 79, this city is a small provincial city compared to Nong Khai and Nakhon Phanom. In addition, the land use was not controlled by the land-use policy. From the Figure 79, Bueng Kan is a monocentric city. The expansion of the built-up areas in 2003 was similar to other provincial cities in that the built-up areas expanded around the core urban area, especially around the economic and social hubs. At the same time, there was a sprawling built-up area along the main road and minor roads. From this characteristic, it can imply that Bueng Kan city was in the early stage 2 according to the model of the built-up area expansion in the small provincial city on the floodplain.

The built-up area of Bueng Kan Provincial city still expanded from the old edge around the economic hub and overlapped with the flood-prone area in 2011. In addition, the built-up area also sprawled along the main and minor roads as same as the first stage. The shape of Bueng Kan was similar to T-Shape, which is the character of stage 2 in the model of built-up area expansion in the small provincial city on the floodplain, in 2018 after this city was established as the provincial city in 2011. The built-up area still expanded along the main road and connected with the previous built-up area which had sprawled in the prior time. With the expansion of the built-up areas in 2011 and 2018, many areas overlapped with the flood-prone areas.

The similarities between the patterns of the built-up areas in Nakhon Phanom and Bueng Kan and the model of the built-up area expansion in the small provincial city created from Nong Khai City support the model's ability to explain the patterns of the built-up area expansion in the small provincial cities which need more knowledge to support the urban planning in the future.

According to the model, under the pressure of population, the built-up area in the small provincial city will expand into flood-prone areas especially after the built-up areas in the core areas and around the main roads near the economic hub are saturated. In the long run, the small provincial cities need the planning to make the cities in the original settlement and economic hub compact to retard the built-up areas in the flood-prone areas.

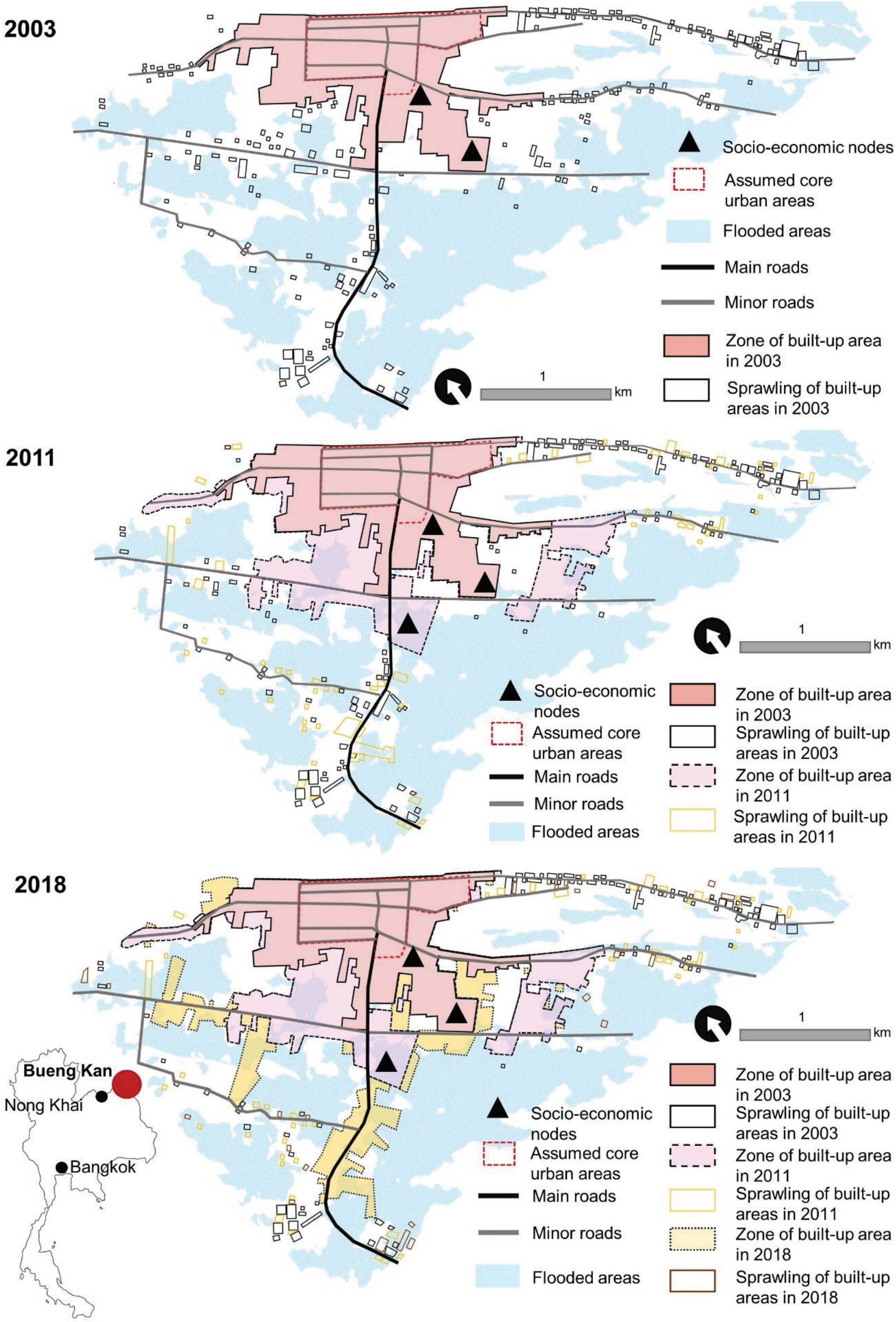

Figure 79 the expansion of the built-up areas in Bueng Kan provincial city

8.2.2.2 The development of suitable policy for built-up area expansion management in the data-scarce environment

To support the built-up land expansion management in the floodplains in the data-scarce environment, in this study, GIS was applied in four scopes: the analysis of the patterns of the built-up land expansion, the delineation of flood-prone areas, the suitable areas for urban development, and the prediction of the built-up land expansion. The analysis of the patterns of the built-up land expansion is a traditional approach to study the land-use change. The analysis of flood-prone areas, the analysis of the suitable areas for urban development, and the prediction of the built-up land expansion were additionally applied in this study to support the city planning in the floodplain area.

In the data-scarce environment, the accessible data from the government and public organisation were combined and applied to create the crucial features, as shown in Table 40. Based on the input data and the spatial information created from GIS functions, this dissertation proves that under the limitation of spatial data, the statistical model and the multi-criteria decision-making modelling related to the statistical models have the potential to be applied with GIS to support urban planning with acceptable accuracy, compared to other models that require intense data and advances knowledge which are usually limited in developing countries. For the analysis of flood-prone areas, although the statistical model cannot inform the flood height and velocity and the performance of the best model is varied based on the input data and spatial context, the mapping from the statistical model can set the boundary of flood-prone areas through the level of flood susceptibility which is sufficient to support the land-use zoning policy that requires only the boundary information rather than the velocity and flood height that are related to the architecture development and can be collected from the field survey in the next step. At the same time, the limitation like the instability of the best model to create the flood-prone map can be dissolved by using the potential statistical models to produce the flood susceptibility map and selecting the high accuracy at the last step. The dissolution of the limitation causes the statistical model to be a suitable method to create the flood-prone map in the data-scarce environment instead of the physically-based model method that requires intense data.

Table 40

Accessible input data in data-scarce environment

	Input data	Spatial information	
		The analysis of flood-prone areas	The analysis of suitable area for urban development
1	DEM	Elevation	-
		-	Slope
		TWI	-
		Curvature	-
		Distance to stream	-
		Drainage Density	-
		Flow accumulation	-
		Stream Power Index	-
2	Landsat Satellite Images	Land use	Land use
		Distance to the Mekong River	Distance to public natural waterbodies
		Distance to the Mesuai River	
		-	Distance to major roads
		-	Distance to train stations
		-	Distance to city centres
		-	Distance to neighbourhood centres
		-	Distance to parks and public open spaces
		-	Distance to medical facilities
		-	Distance to commercial areas
		-	Distance to police stations
		-	Distance to education institutes
			Distance to gas stations
3	Population data from Department of Provincial Administration	-	Population density
4	Geology data from Department of Mineral Resource	Geology	-
5	Soil data from Land Development Department	Geomorphology	Soil types
6	Repeatedly flooded area from Geo-Informatics and Space Technology Development Agency	Flooded area	Flooded area
7	Current city planning	-	Boundary of important waterbodies
8	National wetland from the Office of Natural Resources and Environmental Policy and Planning	-	Boundary of national wetland
9	Ancient sties from the Fine Arts Department	-	Ancient sites and buffer zone

For the analysis of suitable areas for urban development that helps the policymakers to detect the suitable and non-suitable areas in the land-use policy zoning, the accessible spatial data related to the urban development was selected and the AHP was adopted to support the importance of each spatial data on the urban development. In data-scarce environment, AHP is capable to determine the importance of accessible factors by using expert judgement. The suitability map for urban development was developed from the weight value. The mixture of spatial characteristics in suitability classes was categorised by integrating the grouping analysis to support the land-use policy development.

Under the prediction about the built-up land expansion with the decision forest machine learning —which is a simple method in the Land Change Modeller, the flood susceptibility maps and suitability map for urban development can help the policymakers to track the suitability of the built-up land expansion in the future. In addition, based on the integration of the boundary of flood-prone areas and the suitable areas for urban development as the policies, the finding points out that the management of the city on the floodplain should consider how to avoid flood hazard and support the settlement in suitable areas to maximise the benefits of floodplain uses. Hence, the flood susceptibility map and the suitability map for urban development created from the statistical model in the data-scarce environment can be used as the tools to support the creation of a land-use zoning policy for the region that is lacking the spatial data.

To apply the finding in other data-scarce regions, this dissertation provides the framework in Chapters 5 and 6 to create the policy to support the built-up area expansion through the flood-prone areas with the statistical model and the suitable areas for urban development with AHP to facilitate the policymakers in order to develop the land-use policy. The accessible spatial data that is easy to access in Table 40 can be used as the starting point of the spatial database to be checked and added in the local context in the first step. Then, the accessible spatial data is integrated to create the spatial information in the GIS framework. Because the model to produce the map of flood-prone areas and the map of suitable areas for urban development is the statistical-based model, the advanced programme is not required and the policymaker can use the fundamental programme like the Microsoft Excel to produce the weight values by using the equation in this study. Although, the AHP analysis requires judgement from experts. The policymakers can collect the judgement by collaborating with the urban planning expertise staff at the local organisation, the experts from local education organisation, and locals to enhance the participation. After that, they can integrate the weight values into GIS Framework with the spatial database to produce the map of flood-prone areas and the map of suitable areas for urban development. The summarised process to apply the method to create the flood-prone map and suitability map for urban development in the data-scarce environment was presented in Figure 80.

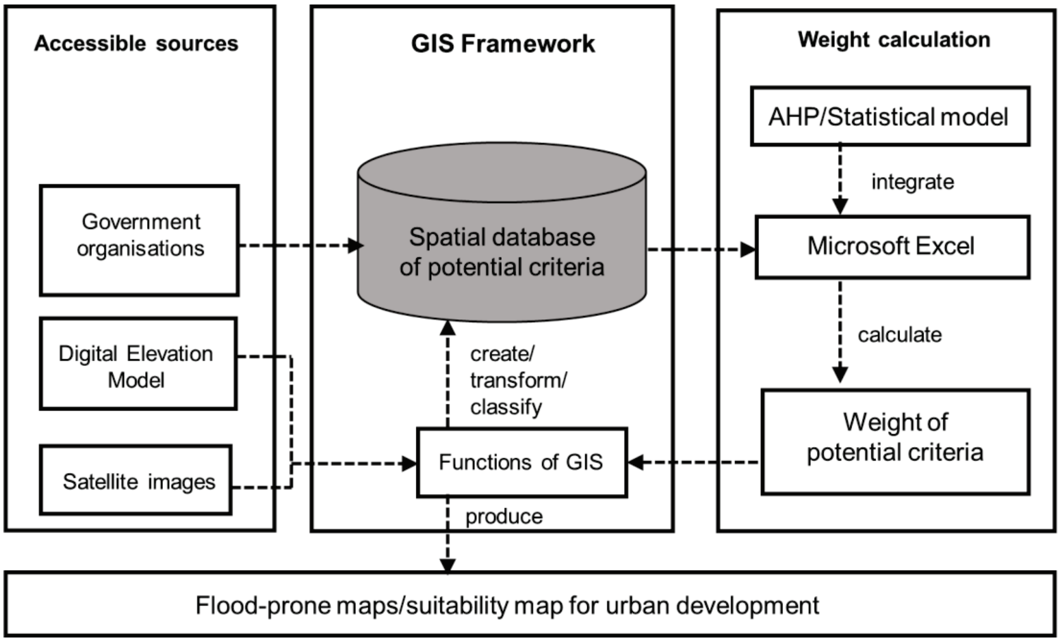

Figure 80 Conceptual process to develop the suitable policy through maps in the data-scarce environment

8.3 Direction of future study

Although this dissertation has clarified the patterns of the built-up area expansion in the provincial cities on the floodplains in the data-scarce environment by focussing on Nong Khai City, the unexplored answers remain. That is why it is necessary to fulfil the understanding of the built-up area expansion in the provincial cities on the floodplains in the data-scarce environment. The direction of future study is divided into two scales.

8.3.1 Direction of future study in macro scale

1) To support the findings of *Nirat NongKhai* in Chapter 2 and construct the knowledge of settlement and land use in premodern time, other historical evidence such as legend, travel notes, and paintings should be collected, archived, and analysed to extend the current knowledge.

2) To support the urban planning based on the patterns of the population change, the impacts of the shrinking city and stagnant city in Chapter 3 on the economy and society should be studied and clarified.

3) The patterns of other small provincial cities in the northeast and other regions should be studied to develop the knowledge of the urbanisation in the small cities of Thailand.

4) The driving factors of the built-up land expansion in Chapter 4 were analysed based on the spatial data without considering the factors associated with human decision which is also complex and relates to various factors. In the future, to fulfil the understanding of the driving

factors of the built-up land expansion, the factor of the human decision on the built-up land expansion such as residential areas should be studied. The understanding of the human decision will support the policy of constraint and incentive in Chapter 7.

5) In Chapter 5, the performances of the models to produce the flood susceptibility maps were assessed only for the model in the group of the statistical modelling method. The performances of the flood susceptibility maps from other groups of models such as the artificial intelligence and machine learning model method and the multi-criteria decision-making modelling method should be compared.

6) In Chapter 6, the weight values to assess the suitable areas for urban development were evaluated by academic experts. In the future, the locals and stakeholders should be integrated as the experts. The weight values from different experts should be compared, and the influence on the final mapping should be analysed.

7) According to Chapter 7, the incentive and constraint to support the implementation of zoning should be studied in terms of the framework of law, financial conditions, and practical possibilities.

8) Although the boundary of flood-prone areas and the suitable areas for urban development were developed from the statistical-based model and can calculate the weight value from Microsoft Excel, the equation of each method is still complicated. To support the application of this method in the local governments, the extensions of Microsoft Excel should be developed based on the simple interface and flexible based on the accessible data and local contexts.

8.3.2 Direction of future study in Nong Khai City

1) Although this study predicts the expansion of the built-up lands in Nong Khai City, the prediction is based on the same trend as the previous expansion. To respond to the BRI's development, the effect of the economy development on the built-up land expansion due to the BRI's development and relevant projects should be evaluated to decrease the sprawl of the built-up lands in unsuitable areas.

2) As stated in Chapters 6 and 7 that the very highly suitable areas for urban development around the train station should be developed to support the urban growth. In the future, the feasibility study on the Transit-Oriented Development (TOD) should be focused to plan and design the areas surrounding the train station to gain the maximum benefits from the HSR development.

3) The style of architecture in the flood-prone areas of Nong Khai City should be collected and categorised. Then, the capacity to cope with floods of each architecture should be studied to

develop and reduce the vulnerability of the architecture in the flooding season. To reduce the vulnerability of the architecture and communities in the future, the effect of climate change on the flooding at the local scale should be clarified, then, the effects of severe flooding on the architecture due to climate change should be considered. The effects of climate change on the base flood elevation affect the suitable level of the ground floor, and the effect of climate change on the severity of flood is related to the structure, including the endurance of architecture during long-period flooding. In addition, to support the development and adaptation of architecture to cope with floods, the daily lives and behaviours of the locals in Nong Khai should be studied to design and manage a suitable architectural space that harmonises with the local lives.

Appendix 1: List of conditioning factors and literature review relating the flood susceptibility and flood risk analysis between 2017-2021

Table 1A

15 most conditioning factors

	Conditioning factors														
No. article*	Slope	Elevation	Land use	Rainfall	Soil type	TWI	Distance from rivers	Geology and lithology	Drainage or Stream Density	Curvature	Distance to streams	Geomorphology / Terrain/Landform	SPI	Flow Accumulation	Aspect
1	1	-	1	1	1	1	1	1	-	1	-	-	1	-	1
2	1	1	-	1	1	1	1	1	-	1	-	-	1	-	-
3	1	-	1	-	1	-	-	-	1	-	-	-	-	-	-
4	1	1	-	1	-	-	-	-	1	-	-	-	-	-	-
5	1	-	1	1	-	-	1	1	1	-	1	-	-	1	-
6	1	-	1	-	1	1	-	1	-	-	-	1	-	-	-
7	1	1	-	-	1	1	1	1	-	1	-	-	1	-	1
8	1	1	1	1	1	-	-	-	1	-	-	-	-	-	-
9	1	1	1	1	1	1	-	-	1	-	-	1	-	-	-
10	1	1	1	1	-	1	1	1	-	1	1	-	-	1	-
11	1	-	1	-	1	-	1	1	1	1	-	-	-	-	1
12	1	1	-	1	-	-	1	-	-	-	-	1	-	-	-
13	1	1	1	1	-	1	-	-	-	1	1	-	1	-	-
14	1	1	1	1	-	1	-	1	-	1	1	1	1	1	-
15	1	-	1	-	1	1	1	1	-	1	-	-	1	-	1
16	1	1	1	-	1	1	-	1	-	1	1	-	1	-	1
17	1	1	1	1	1	-	-	1	-	-	-	-	-	-	-
18	1	1	-	1	1	-	1	-	1	-	-	-	-	-	-
19	1	1	-	1	-	-	1	-	1	-	-	1	-	-	-
20	1	1	1	1	-	1	1	-	-	-	-	-	-	-	-
21	1	1	1	1	-	1	1	1	1	1	1	-	-	-	1
22	-	1	1	1	1	1	1	-	-	-	-	-	1	-	-
23	1	1	1	1	-	1	-	-	1	-	-	-	-	-	-
24	1	1	1	1	-	1	-	-	1	1	-	-	-	-	-
25	1	1	1	1	1	-	-	-	1	-	-	-	-	-	-
26	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-
27	1	-	1	-	-	-	-	1	-	-	-	-	-	1	-
28	1	1	1	1	1	-	-	-	1	1	1	-	-	1	-
29	1	1	-	-	1	1	-	-	-	1	-	-	-	-	1
30	1	1	-	1	1	1	1	1	1	-	-	1	-	1	-
31	1	1	1	1	-	-	1	-	1	1	-	1	-	1	-
32	-	1	1	-	1	-	1	1	1	-	-	1	-	-	-
33	1	1	1	1	1	-	-	-	-	-	1	1	-	-	-

No. article*	Conditioning factors														
	Slope	Elevation	Land use	Rainfall	Soil type	TWI	Distance from rivers	Geology and lithology	Drainage or Stream Density	Curvature	Distance to streams	Geomorphology / Terrain/Landform	SPI	Flow Accumulation	Aspect
34	1	1	1	1	1	-	1	1	1	-	-	-	-	-	-
35	1	1	1	1	1	1	-	1	-	1	-	-	1	-	-
36	1	1	1	1	1	1	-	1	1	1	1	-	-	-	1
37	1	1	1	1	1	1	1	1	-	1	-	-	-	-	-
38	1	1	1	1	-	1	1	-	1	1	-	-	-	1	-
Sum	36	31	30	28	23	21	19	19	19	18	9	9	9	8	8
Ranking	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Table 1B

Conditioning factors in the ranking of 16-30

	Conditioning factors														
No. article*	Sediment Transport Index	NDVI	Altitude	Drainage Density	Groundwater depth	River flow direction	Distance from roads	Impervious surface	Road density	Population density	Proximity to stream confluence	Runoff Coefficient/ Surface runoff	Distance to villages	Distance to stormwater drainage networks	Distance to embarkment breach locations
1	1	1	1	-	-	-	1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
4	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	1	-	-	-	-	-	-	-	-	1	-	-	-
7	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-
13	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
14	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
15	1	-	1	-	-	-	1	-	-	-	-	-	-	-	-
16	-	1	-	1	-	-	-	-	-	-	-	-	-	-	-
17	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-	1	-	-	-	1
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
22	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-
24	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26	-	-	-	-	1	-	-	-	-	-	-	-	-	1	-
27	-	-	-	-	1	-	-	-	-	-	-	1	-	-	-
28	-	1	-	-	1	-	-	-	-	-	-	-	-	-	-
29	1	-	-	1	-	-	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
31	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

No. article*	Conditioning factors														
	Sediment Transport Index	NDVI	Altitude	Drainage Density	Groundwater depth	River flow direction	Distance from roads	Impervious surface	Road density	Population density	Proximity to stream confluence	Runoff Coefficient/ Surface runoff	Distance to villages	Distance to stormwater drainage networks	Distance to embarkment breach locations
33	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-
34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
37	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sum	5	5	4	4	3	3	2	2	2	2	2	2	1	1	1
Ranking	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30

Table 1C

Frequent conditioning factors in the ranking of 31-49

No. article*	Conditioning factors																		
	Rainstorm frequency	Mean Sea level	Draining Capability	Height above nearest drainages	Topographic Ruggedness Index	Content of clay	Green Infrastructure Farmland	Soil Texture	Slope length factor	Retarding Basin	Stream Transport Index	Flood depth	Flood duration	Distance from fault	Elongation ratio	Stream order	Household frequency	Terrain Roughness Index	Hydrogeology
1	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-
2	-	-	-	-	-	-	1	-	1	1	-	-	-	-	-	-	-	-	-
3	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-
24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
27	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
31	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

No. article*	Conditioning factors																		
	Rainstorm frequency	Mean Sea level	Draining Capability	Height above nearest drainages	Topographic Ruggedness Index	Content of clay	Green Infrastructure Farmland	Soil Texture	Slope length factor	Retarding Basin	Stream Transport Index	Flood depth	Flood duration	Distance from fault	Elongation ratio	Stream order	Household frequency	Terrain Roughness Index	Hydrogeology
35	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
36	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
37	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ranking	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49

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