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Article

Flood Vulnerability Assessments and Scenario Landscape Planning of Communities Around Industrial Estates in Ayutthaya

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Abstract: Thailand is vulnerable to severe flooding; for example, the 2011 flood affected 13 million people and caused significant socioeconomic damage. Because of a possible 100-year return period and other climate change effects, in 2012, industrial estates in Ayutthaya, such as the Rojana Ayutthaya Industrial Park, developed flood protection systems by raising the flood walls to around six meters above the mean sea level (MSL); however, the surrounding areas do not have comprehensive plans. This study analyzes the physical landscapes within a radius of two kilometers around Ayutthaya's industrial estate to assess flood vulnerability, after which we develop adaptation strategies based on community input for vulnerable areas. The topography and footprint maps are analyzed to identify the flood scenarios. To compare the urban and agricultural area differences, the highest 2011 water level of 5.30 meters above MSL was applied to identify two scenarios for moderate and extreme flood areas. Alternative mitigation solutions for both scenarios were discussed in a community focus group, which decided that the engineering resistance concept would best prevent moderate flooding because of the current flood protection levee improvements around the study areas. However, while the landscape resilience concept was seen by the communities as a more sustainable solution, it was considered difficult to implement due to land ownership issues. The moderate and severe flood mitigations are conceptually a resistance to resilience shift in flood control approaches, which could be adopted by other regions or countries that suffer similar problems.

Keywords: scenario analysis; flood management; vulnerability analysis; landscape planning; industrial estate

1. Introduction

Flooding is Thailand's most significant natural disaster event, making up almost 50% of the average annual natural hazards from 1980 to 2020 (World Bank Group, 2022). The manufacturing sector suffered roughly 70% of total damage and losses, estimated at around 1.4 trillion baht, mainly in six industrial estates in Pathum Thani and Ayutthaya (World Bank, 2012). Ayutthaya, a UNESCO World Heritage Site, is Thailand's most frequently flooded province. Agricultural communities in these areas have been largely replaced by manufacturing, which has resulted in significant migrant worker population increases, negative environmental impacts, and increased flood risks. Climate change also contributes to higher hazard frequencies, more significant damage, and widening flood areas.

This study focuses on the two-kilometer area around the Rojana Ayutthaya Industrial Park (RAIP), the largest industrial park in Ayutthaya. After the severe 2011 flood, the RAIP developed its own "triple flood protection system" to prevent future disasters, constructing a new dike 6.05 meters above the mean sea level (MSL). However, the areas surrounding the RAIP have no long-term flood intervention plans. Although there are some temporary disaster prevention strategies, such as using sandbags to block water, large areas remain vulnerable. Therefore, this study conducted a flood vulnerability assessment and analyzed the area's physical landscapes, after which we developed various flood adaptation scenarios and landscape planning strategies. Then, before finalizing the strategy for the vulnerable communities, we conduct community focus groups to discuss the possible landscape interventions.

2. Literature Review, Research Objectives, and Research Questions

2.1. Vulnerability Assessment Conceptual Framework

Vulnerability assessments are critical to disaster management and the development of effective adaptation strategies to combat the possible effects of environmental and climate change (Khan, 2012; O'Brien et al., 2006). Blaikie et al. (2004) define vulnerability as a pre-existing characteristic of a person, society, or situation that is unable to cope, resist, or recover from natural disaster effects. Rana and Routray, (2018) examine vulnerabilities across five dimensions: social, economic, physical infrastructure, institutions, and attitudes. However, physical damage (Cardona, 2013) and vulnerability cannot be determined without assessing the ability to adapt to or recover from disaster impacts (O'Keefe and Westgate, 1977). Four vulnerability assessment approaches have been suggested in previous studies (Anantsuksomsri and Tontisirin, 2018; Cardona, 2013): 1) the pressure and release (PAR) model, which is cost-effective and worthwhile at all levels (Blaikie et al., 2004). 2) the social-ecological perspective, which focuses on human-environmental relationships and the ability to change the environment and the effects of such changes on socioeconomic systems (Hewitt & Burton, 1971; Turner, 2010); 3) the holistic perspective, which seeks to determine the causes of dynamic vulnerability through a feedback loop based on disaster impact, sensitivity, and social response-ability (Birkmann and Fernando, 2008; Cardona, 2013); and 4) the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report Concepts, which define vulnerability as encompassing disaster impact, sensitivity, and adaptability, considers external environmental factors and analyzes long-term trends and effects (Brooks, 2003; Füssel, 2007; Füssel and Klein, 2006; Thornes, 2002).

Because the PAR model is a well-known tool for assessing disaster causes and understanding the risks and the impacts on vulnerable populations (Blaikie et al., 2004), we felt this model aligned well with this study. The model proposes three main vulnerability processes: root causes (Hansen, 1987), dynamic pressures (Cardona et al., 2012), and unsafe conditions (Cardona et al., 2012). Because flood risks are affected by preparedness, adaptation, and resource access (Cardona et al., 2012), we explore the physical and social vulnerabilities associated with flood disasters.

2.2. Physical and Social Disaster Vulnerability

Physical vulnerability refers to the environmental and physical factors that influence the resilience capacity of structures, such as homes, roads, and schools (Woodruff et al., 2018), with the associated possible mitigation measures being stronger construction, risk planning, and preparedness. Flooding increases physical vulnerability as it can significantly impact infrastructure and resident safety. Therefore, physical flood vulnerability factors, such as location, elevation, and community resilience, need to be assessed to ensure effective risk management and emergency preparedness (Papathoma-Köhle et al., 2011).

Vulnerable groups face greater risks and encounter greater recovery difficulties during disasters because of their poor prevention resources (Wongphyat & Tanaka, 2020). Using the PAR model, Nakasu et al. (2020) developed three indices, namely, exposure, susceptibility, and capacity; to investigate the social vulnerabilities in Ayutthaya's flooded industrial area and found that the exposure index tends to be high in industrial park locations; however, the capacity index in the Uthai District, where the RAIP is located, had the second-lowest score. Nakasu et al. (2022) also measured the subdistrict capacities two kilometers around the RAIP (Figure 1), finding that in the four subdistricts of Thanu, Khan Ham, Ban Chang, and Nong Nam Som, the capacity and protection in the urban Thanu and Khan Ham communities were superior to the farm-based Ban Change and Nong Nam Som communities. However, the urban and rural area needs are different because besides the physical flood damage, laborers and daily rate workers in urban communities usually suffer significant income loss. In contrast, local farmers used to occasional moderate floods have higher ecological resilience.

2.3. Resistance and Resilience

Because Ayutthaya is on a floodplain, annual flooding is expected. Under normal circumstances, most residents can cope with this natural phenomenon. Over time, however, increasing urbanization has extended the city periphery, which has made these annual floods more problematic. The 2011 flood was the worst since the beginning of flood records, during which the water level rose higher than that of Ayutthaya's western (the north railway) and eastern (Highway 32- Asian Road) regional levees. This disaster ignited considerable discussions on future mitigation if flood waters continue to rise above predicted levels, with many questioning whether it would be necessary to raise the levees continually.

This reflects the differences between engineering, landscape, and ecological resilience (Liao, 2012; Scheffer et al., 1993; Scheffer et al., 2001; Walker et al., 2004). Engineering and landscape resilience represent two distinct approaches to understanding and addressing system responses to disturbances. Engineering resilience is characterized by its focus on resistance and recovery, emphasizing the ability of a system or structure to maintain its primary function or return to its original state following a disruption, such as a natural disaster. This approach assumes a single equilibrium and predictability. Engineering resilience measures may include factors such as material strength, design redundancy, and the ability to absorb disturbances. However, when disturbances exceed thresholds, systems may shift to new equilibria, as exemplified by the 2011 record-breaking flood in Ayutthaya, which breached all protection levees and submerged the entire area. This event underscores the need for adaptable strategies, robust infrastructure, and financial risk mitigation, as Alhassani et al. (2024) highlighted, to create sustainable, inclusive, and resilient urban environments.

In contrast, landscape and ecological resilience emphasize tolerance, reorganization, and the capacity to adapt and transform amidst disturbances and uncertainty. These approaches recognize the existence of multiple equilibria and prioritize the maintenance of a system's basic structure, function, and identity while fostering long-term adaptability and transformation. Key elements of landscape resilience include stability, adaptive capacity, and transformation ability (Liao, 2012), which are critical for responding to changing environmental conditions.

While engineering resilience solutions are often praised for their quick and effective outcomes, they are frequently criticized for high costs and potential environmental harm. Conversely, landscape resilience measures are generally more affordable but face significant challenges, including limited land availability, competing priorities, extended timeframes for effectiveness, coordination complexity, and regulatory barriers. Despite these distinctions, the two concepts increasingly receive attention and are integrated within hybrid systems (Liao, 2012), blending the strengths of both approaches to achieve comprehensive resilience strategies. Recent research has indicated hybrid eco-engineering has become more popularized (Waryszak et al., 2021). A hybrid strategy combining both concepts proves more effective and has a high cost-benefit ratio. Managing flood risk is more than adopting a single system (Du et al., 2020).

2.4. Objectives and Research Questions

Much research focuses on Ayutthaya's World Heritage site and the associated industrial zones. Several government projects have attempted to protect these valuable economic areas but have allowed flooding in the agricultural areas with only minimum monetary compensation given to those affected. However, our study objectives were to use scenario analysis to assess the flood risks in the urban and agricultural areas in a two-kilometer radius surrounding the RAIP and designing flood mitigation measures for the local population, which has low coping capacities.

Scenario analysis is valuable for analyzing future impacts and exploring strategic alternatives (Liu and Wu, 2022). The resilience approach is more suitable than resistant management for examining extreme disaster events in river cities (Liao, 2012). Our specific research questions were as follows:

RO1: Are the local communities aware of possible flooding scenarios?

RO2: What are the current flood mitigation differences between urban and rural settings?

RO3: What landscape planning scenarios could benefit flood management and achieve the desired outcomes?

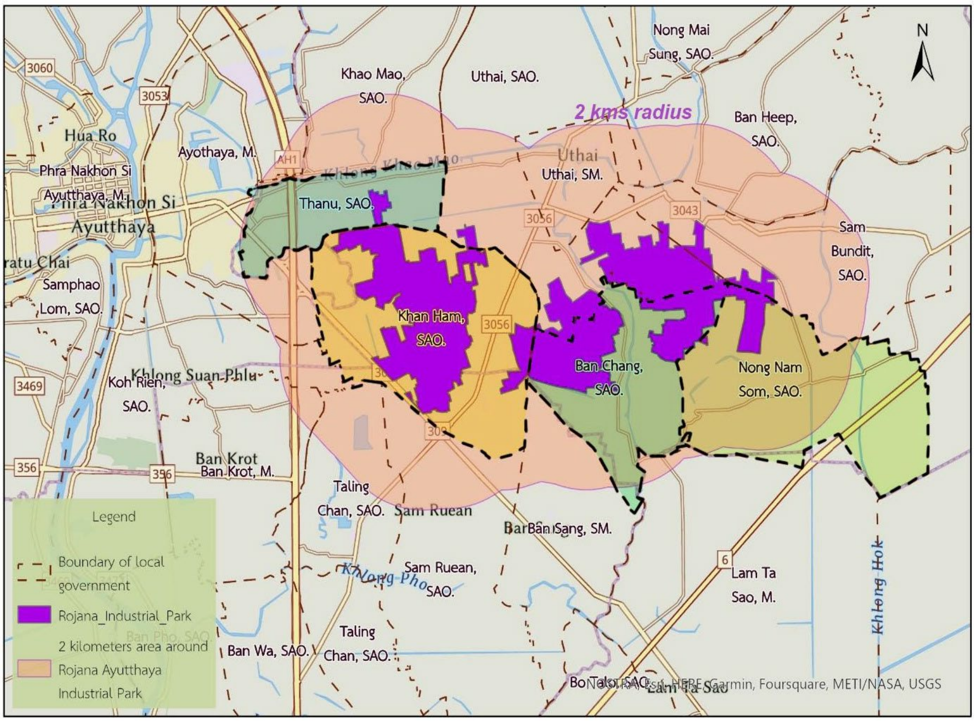

Figure 1. The two-kilometer area around the Rojana Ayutthaya Industrial Park (RAIP). Note. This area has four districts (Uthai, Phra Nakhon Si Ayutthaya, Bang-Pa-In, and Wangnoi) comprising 19 subdistricts. After examining the drainage systems, the four subdistricts; Thanu, Khan Ham, Bann Chang, and Nong Nam Som; adjacent to the RAIP, were selected for this study. Adapted from The two-kilometer area around the Rojana Ayutthaya Industrial Park, by ArcGIS (Version 10.8.2) [computer software], 2024. Copyright 2024 by ArcGIS.

3. Study Area

3.1. Topography and Environment in Phra Nakhon Si Ayutthaya Province

Phra Nakhon Si Ayutthaya Province, situated in the Lower Chao Phraya Basin, is a low plateau at the mouth of a river or delta characterized by river and seawater sediment accumulation. Over time, this sedimentation has become fertile clay soil ideal for rice cultivation (Palakawongse, 1984). Renowned as Thailand's breadbasket, this fertile land has played a crucial role in establishing regional urban communities. Due to geological processes, some areas along the river that were cut off from the original river have Oxbow lakes (Department of Mineral Resources, 2015).

3.2. Water Management Surrounding Ayutthaya Island

Surrounding Ayutthaya Island is a system of canals mainly developed from the natural waterways. On the north side is a Sra Bua Canal shortcut from the Lop Buri River (Siriphatthanakun, 2020). Because Ayutthaya has three rivers running through the province, flooding has occurred for generations. Traditional houses have been constructed on stilts to deal with seasonal floods (Panin, 2021), and several highways, which were built around 4.50 meters above the MSL, act as flood barriers. After the severe 2011 flood, the historical and highly economically valued areas increased the height of their flood wall protections and proposed to elevate the old dike systems around Ayutthaya Island from 5.30 meters to 5.80 meters above the MSL. This resistant system protects the UNESCO World Heritage Site and the residential and commercial buildings on the island. In 2012, RAIP also increased its flood protection dike from 4.60 meters to 6.05 meters above the MSL to deal with the 100-year flood return period and the possible climate change effects. However, these self-protection dikes have made the nearby populations more vulnerable.

3.3. Settlement

The RAIP is in the center of the 20,125 square kilometer Chao Phraya River basin. The lower part of the basin is a sediment area that was covered by the sea around 5000 years ago. This water-based settlement offers daily consumption, transportation, drainage channels, and agricultural irrigation services (Aruninta et al., 2020). The RAIP replaced parts of the original agricultural lands (Figure 2) while the surrounding areas remained agricultural. However, within two kilometers of the estate, urbanization has spread along the perimeter roads (Figure 2), with these many housing projects, especially the subdivision lots, now burdening the public and natural drainage systems and reducing their effectiveness.

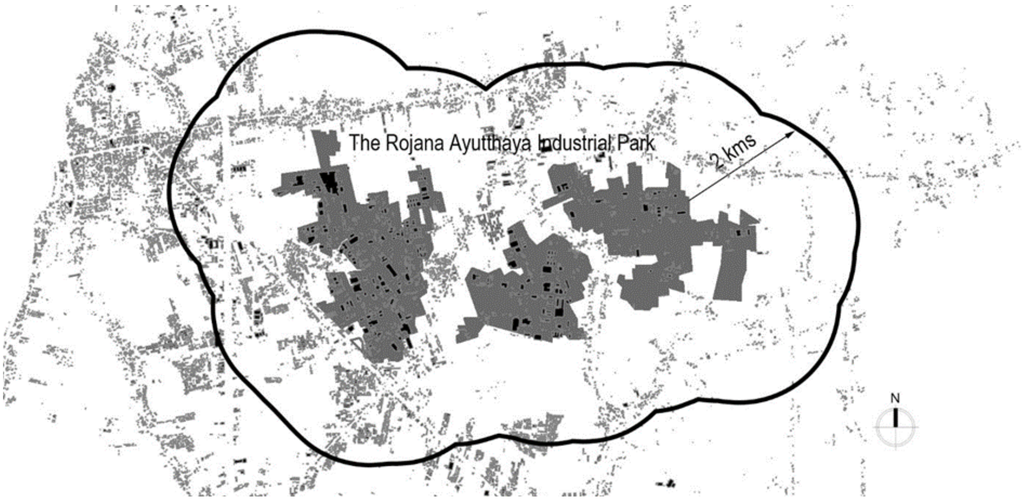

Figure 2. The Rojana Ayutthaya Industrial Park (gray Areas) and urbanization in the four subdistricts: Thanu, Khan Ham, Bann Chang, and Nong Nam Som.

4. Methodology

4.1. Vulnerability Assessment

Based on the PAR model, a site survey and interview were conducted to assess the physical vulnerabilities, the community's understanding of flood scenarios, and their capacity to cope with such events. Specifically, the questions focused on the community's experiences during the moderate 2022 flood and the severe 2011 flood, when the water levels exceeded five meters because of the Chao Praya and Pasak River overflows.

4.2. Spatial Analysis

Physical vulnerability and resilience are closely related concepts that describe a system's capacity to withstand and recover from adverse events or stresses (Woodruff et al., 2018). A spatial analysis was conducted to map the vulnerabilities within a radius of two kilometers around the industrial park to identify unsafe conditions, such as physical vulnerabilities and environmental factors, and understand the diverse needs in the flood-affected urban and agricultural areas. Topographical maps were analyzed to assess potential flood scenarios based on the moderate 2022 and severe 2011 floods. Aerial photos were also studied to understand the urban settings, forms, and patterns.

4.3. Mitigation and Scenario Development

Based on the vulnerability assessment and spatial analysis findings, we needed to consider the engineering and landscape resilience paradigms (Liao, 2012; Scheffer et al., 1993; Scheffer et al., 2001; Walker et al., 2004). The 2011 record-breaking flood in Ayutthaya exceeded the flood protection levee thresholds, which resulted in severe widespread flooding. Synthesis maps were then developed to assess place-based scenarios, design potential landscape planning policies, and identify the essential service and emergency evacuation locations. Landscape planning scenarios were also proposed to address area-based interventions that could respond to the differences between moderate-severe floods in the urban and agricultural areas.

4.4. Stakeholder Engagement

Stakeholders were engaged throughout the process to ensure that the landscape planning scenarios were informed by local knowledge, priorities, and concerns. The Community-Based Disaster Management group, which emerged from the concerned communities and developed the bottom-up mechanisms (Wongphyat and Tanaka, 2020), was consulted to assess the potential landscape planning strategies. Since sustainable planning necessitates civic engagement as part of the overall process (Likitswat, 2018; Ackerman et al., 2014; Joss, 2011), the proposed landscape interventions were shared with a community focus group for feedback before finalizing the resilience strategies for the vulnerable communities. Community leaders, authorities, and local disaster council representatives also reviewed the proposed scenarios and provided input to enhance the associated mitigation strategies (Figure 3).

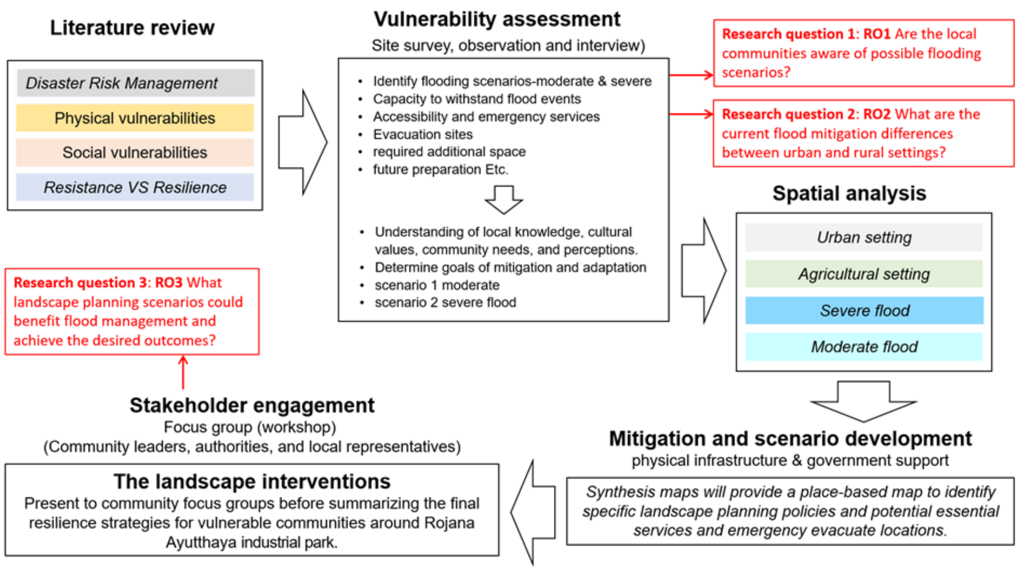

Figure 3. Research Flow Chart.

4.5. Data

4.5.1. Site Survey for Vulnerability Assessment

Questionnaires and interviews were conducted with community, business, and local government representatives from February to March 2024 in four subdistricts: Thanu, Khan Ham, Ban Chang, and Nong Nam Som. The key topics covered in the questionnaires and interviews were warning times, water levels, preparation, accessibility, emergency services, evacuation sites, flood relief operation centers (FROCs), required extra space, at-risk areas and utilities, and future preparations. Physical and environmental conditions were also discussed.

4.5.2. GIS Mapping for Spatial Analysis

Flood data and physical attributes in the study area in 2011, 2012, 2013, 2017, 2021, and 2022 were obtained from GISTDA (Geo-Informatics and Space Technology Development Agency). The flood data associated with the topography, roads, water bodies, building footprints, industrial park properties, municipal boundaries, and existing FROCs (public facilities) were mapped and analyzed using ArcGIS 10.8.2. A service radius of 2.5 kilometers was set to encompass the existing FROCs and potential new centers to ensure coverage in previously underserved areas. Aerial photos of the study area were drawn from Google Earth Pro .3.6.9796 (64-bit) to study the urban fabric and classify the areas as urban or agricultural.

4.6. Mitigation and Scenario Development

Based on the results, alternative mitigation and landscape planning scenarios for both moderate and severe floods were developed.

4.6.1. Stakeholder Engagement

A focus group (workshop) was conducted on March 8, 2024. At the Training for Trainers on Disaster Prevention and Response Preparedness focus group on March 8, 2024, in Ayutthaya City Hall, which comprised 30 representatives from all four subdistricts; Thanu, Khan Ham, Ban Chang, and Nong Nam Som; questions were asked and responded to the proposed landscape planning scenarios.

5. Results

5.1. Vulnerability Assessment

The site survey and interview results highlighted the flood preparation requirements in the four subdistricts, from which two scenarios were developed: 1) a total flood event similar to 2011 and 2) a partial flood event similar to those experienced in 2012 and 2022. In both scenarios, the site survey assessed water levels, warning systems, preparedness measures, emergency services, accessibility, evacuation sites, required areas beside dwellings, at-risk areas, at-risk utilities, and future preparedness needs (see Table 1).

In 2011, 2012, 2013, 2017, and 2022, there was poor preparation for potential flooding across all subdistricts. Despite the residents' awareness of the differences between moderate and severe floods, there was a prevailing belief that the flood risk was minimal because of the proximity of the villages to the industrial estate. Following the 2011 flood, only Khan Ham has utilized its resident broadcast warning system.

During emergencies, all subdistricts require essential provisions, such as food, communal kitchens, daily supplies, sanitation facilities, and medical care. However, it was found that the access to these emergency services during severe floods varied; for example, residents in urban areas, such as Khan Ham and Thanu, could access assistance via boats or large trucks capable of traversing shallow waters; however, the residents in the agricultural areas, such as Ban Chang and Nong Nam Som, relied solely on boats. When there were moderate flood events, the residents in all subdistricts used boats or trucks for transportation.

Since the flood events, the government has established evacuation sites and/or FROCs. In the severe flood, both urban and agricultural residents were evacuated to nearby centers; however, while urban residents were relocated to FROCs during moderate floods, most agricultural residents chose to stay home, and some decided to evacuate with their livestock and farm animals to major roads, which highlighted the need for additional space beside the FROCs.

Residents in the urban Khan Ham and Thanu subdistricts emphasized the need for thorough planning to mitigate chaos during flood events. They proposed raising and controlling watergates, dams, roads, and levees to prevent flooding and also felt that observation stations needed to be installed. Critically, residents noted the paucity of government-supplied boats, their poor quality, and limited one-season usability. The main at-risk areas are along the canals, waterways, and low-elevation residential clusters. These results were consistent with Nakasu et al. (2020, 2022) (see Table 1).

Table 1. Site survey information.

	Agriculture	Urban	Water level	Warning	Preparation	Emergency services	Accessibility
2011 (2554)							
Khan Ham		✓	> 2.00 m.	Broadcast	No major advance preparation	Food, daily supplies, sanitation, and toilet.	Boat, big truck for evacuation, Traveling to *FORCs* for services and supplies.
Thanu		✓	> 2.00 m.	Broadcast	No major advance preparation	Food, kitchen, daily supplies, sanitation, and toilet.	Boat, some took a day trip by truck to a department store (*Tesco-*

							Lotus) for supplies.
Ban Chang	✓		> 2.00 m.	Broadcast	No major advance preparation	Food, kitchen, daily supplies, sanitation. Medical supplies.	Boat
Nong Nam Som	✓		> 2.00 m.	Broadcast	No major advance preparation	Food, daily supplies, sanitation, and medical care.	Boat
2012–2013–2017–2022							
Khan Ham		✓	< the 2nd floor, No evacuation	Broadcast	No major advance preparation	Food, kitchen, daily supplies, sanitation, and toilet.	Boat and big truck for delivery of food and supplies
Thanu		✓	About knee height	No warning	No major advance preparation	Food, daily supplies, sanitation, and toilet.	Boat, some took a day trip by truck to a department store (*Tesco-Lotus*) for supplies.
Ban Chang	✓		Shin height	No warning	No major advance preparation	Food, daily supplies, sanitation, and toilet.	Boat and truck
Nong Nam Som	✓		Shin height	No warning	No major advance preparation	Food, daily supplies, sanitation, and toilet.	Boat and truck
2011 (2554)							
Khan Ham		✓	80% Automotive Industry Technical College, 20% remained at their own home OR temples nearby		Universal design for vulnerable groups, communal kitchen during long periods of flooding	Preventing chaos during evacuation. Raise dams, water gates, and levees, preparation of boats	Along the canals and waterway

Thanu		✓	Temples, shophouses, *Thanu's FROCs*, Outside Ayudhaya	Accommodation for vulnerable groups, universal design, communal Kitchen, parking, communication, and medical care	Planning evacuation routes, the river as a point of concern, Raise the house, levees, and watergates	Along the canals and waterway
Ban Chang	✓		Ban Change Schools, Ban Ghange Subdistrict FROCs, Thep-kun-chorn Temple	Farm animal area, sanitary, universal design for vulnerable groups	No indication	Majority of the area due to its lower elevation
Nong Nam Som	✓		Wat Khanon and Wat Nong Nam Som Temple, Wat Khanon and Ban Khu Khot Schools	Farm animal area, sanitation, universal design for vulnerable groups	No indication	Along the canals, waterways, residential clusters
2012−2013−2017−2022						
Khan Ham		✓	People remain in their properties	No indication	No indication	Along the canals and waterways
Thanu		✓	Some people move to Kra Sang Temple	No indication	No indication	Along the canals and waterways
Ban Chang	✓		No evacuation	Farm animals area. People remain at their properties	No indication	Majority of the area (low elevation)
Nong Nam Som	✓		No evacuation	Farm animal areas	No indication	Along the waterways, residential clusters

5.2. Spatial Analysis

5.2.1. Evacuation Sites or Flood Relief Operations Centers (FROC)

The evacuation sites are the same in both the severe and moderate flood scenarios. The FROCs in the Khan Ham subdistrict are the Automotive Industry Technical College and Khan Ham's Subdistrict Administration Office. The FROCs in the Thanu subdistrict are the Thanu Subdistrict Administration Office, Wat Sakae, the Wat Sakae School, Wat Krasang, and Wat Khao Din. The FROCs in the Ban Chang subdistrict are Ban Chang's Subdistrict Administration Office, Ban Chang's Subdistrict Health Promotion Hospital, the Ban Chang School, and Wat Thep Kunchon. The FROCs in the Nong Nam Som subdistrict are the Nong Nam Som's Subdistrict Administration Office, Wat Khanon, the Ban Khukhot School, Wat Nong Nam Som, and the Nong Nam Som Health Center (Figures 4 and 5).

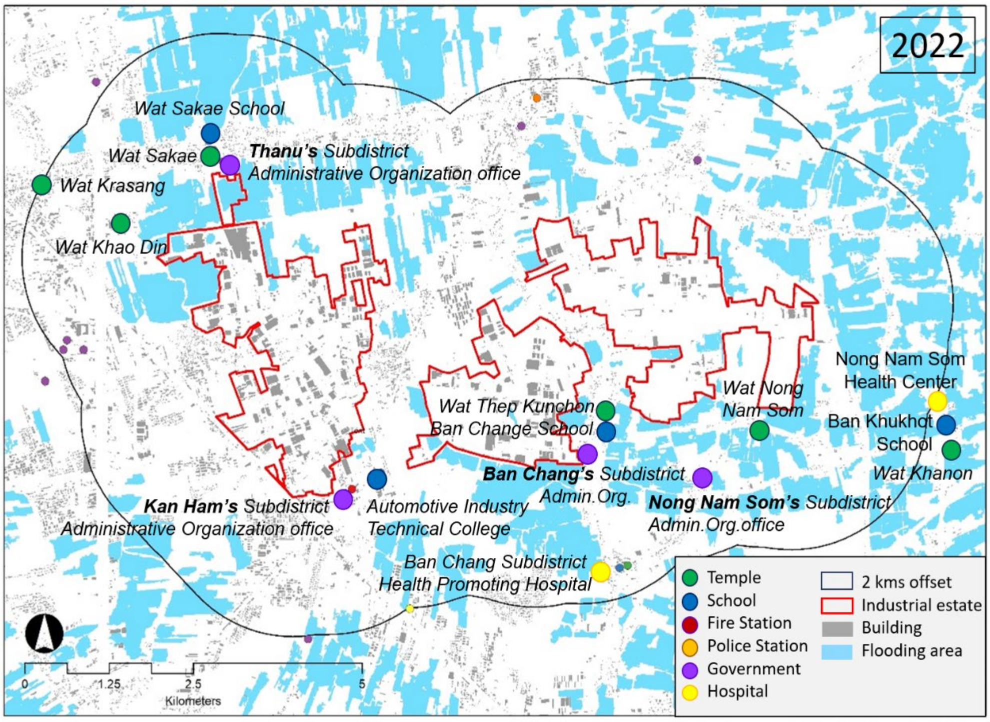

Figure 4. Flood areas in 2022, which indicate a moderate flood, and the current FROCs.

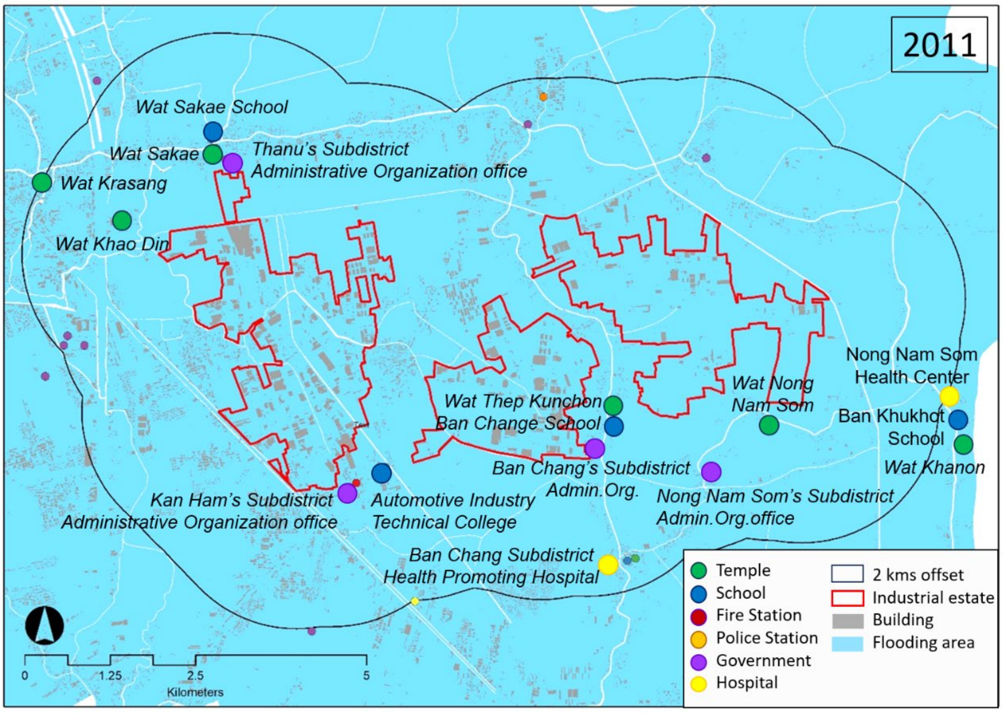

Figure 5. Flood Areas in 2011, which indicate a severe flood, and the current FROCs.

5.2.2. Urban and Agricultural Settings

The four subdistricts' aerial photo analyses and on-site surveys revealed distinct land use patterns. Kan Ham and Thanu (Figure 6) are both urban environments with many structures and paved areas. Because there are development clusters along both sides of the east-west Kow Mow Canal, neighborhoods in these areas are vulnerable to flooding. In contrast, Ban Chang and Nong Nam Som are predominantly agricultural, with vast green spaces and farmland, and the dwellings are sparse and are often clustered at intersections or along roadways (Figure 7).

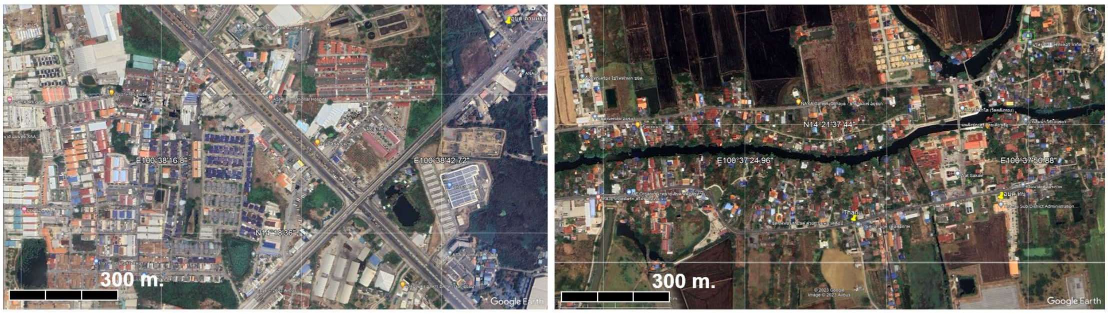

Figure 6. Kan Ham Subdistrict (**left**) and Thanu Subdistrict (**right**) show higher density settlements and more extensive footprint areas (Adapted from Map of Kan Ham and Thanu Subdistrict, by Google Earth, 2024. Copyright 2024 bt Google LLC.). Note. Most land use is residential; subdivision housing, townhouses, shophouses, commercial, warehouses, and industrial facilities. In Thanu, most land use is low-density residential (single houses), townhouses and apartments, some (but expanding) subdivision projects, and a few industrial facilities.

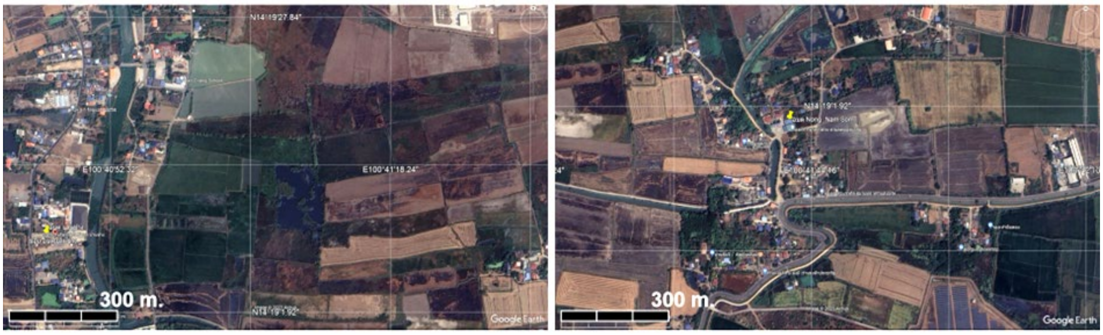

Figure 7. Ban Chang subdistrict (**left**) and Nong Nam Som subdistrict (**right**) (Adapted from Map of Ban Chang and Nong Nam Som subdistricts by Google Earth, 2024. Copyright 2024 by Google LLC.). Note. Mainly low-density settlements and more extensive areas of agriculture and farmland. Most land use comprises single-family houses clustered around access infrastructure and surrounded by green farmland fields.

5.2.3. Urban and Agricultural Flood Impacts during Flood Season

The typological differences between the urban and agricultural areas reflect the differences in the residents' lives and working conditions. In the severe flooding scenario, residents in both settings need to evacuate; however, in moderate flooding scenarios, defined by water levels below two meters and not surpassing the second-floor level, the agricultural and urban resident movements vary in the subdistricts. In the agricultural Bang Chang and Nong Nam Som subdistricts, the residents typically opt not to evacuate as the flooded areas primarily consist of green fields, which means that the residents can easily adapt by moving to higher floors and continuing their daily activities; however, there are some limitations on medical services and food supplies (Figure 8).

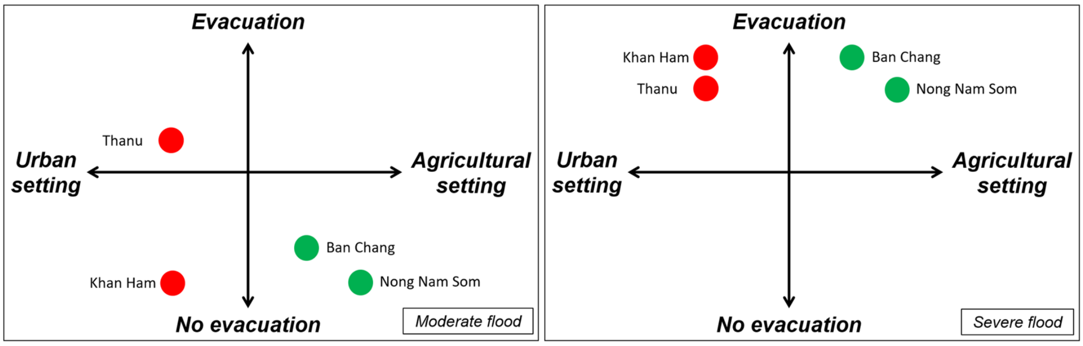

Figure 8. Urban and agricultural evacuation during the moderate and severe flooding scenarios. Note. In scenario 1 (**left**), moderate flooding condition (2022), only residents in the urban Thanu subdistrict need to evacuate as people in the agricultural areas remain in their properties. In scenario 2 (**right**), severe flood conditions (2011) (Figure 5), all residents evacuate.

5.2.4. Flood Scenarios

From 2011 to 2022, flooding in the study areas varied in severity, ranging from total flooding in 2011, which covered 88.87 sq. km. to less severe flooding in 2021, which only covered 7.37 sq. km. Data from the Geo-Informatics and Space Technology Development Agency, Public Organization (GISTDA) shows the flood area around the RAIP was 88.87 sq. km in 2011, 17.80 sq. km in 2012, 26.37 sq. km in 2013, 15.92 sq. km in 2017, 7.37 sq. km in 2021, and 21.47 sq. km in 2022 (Figure 9).

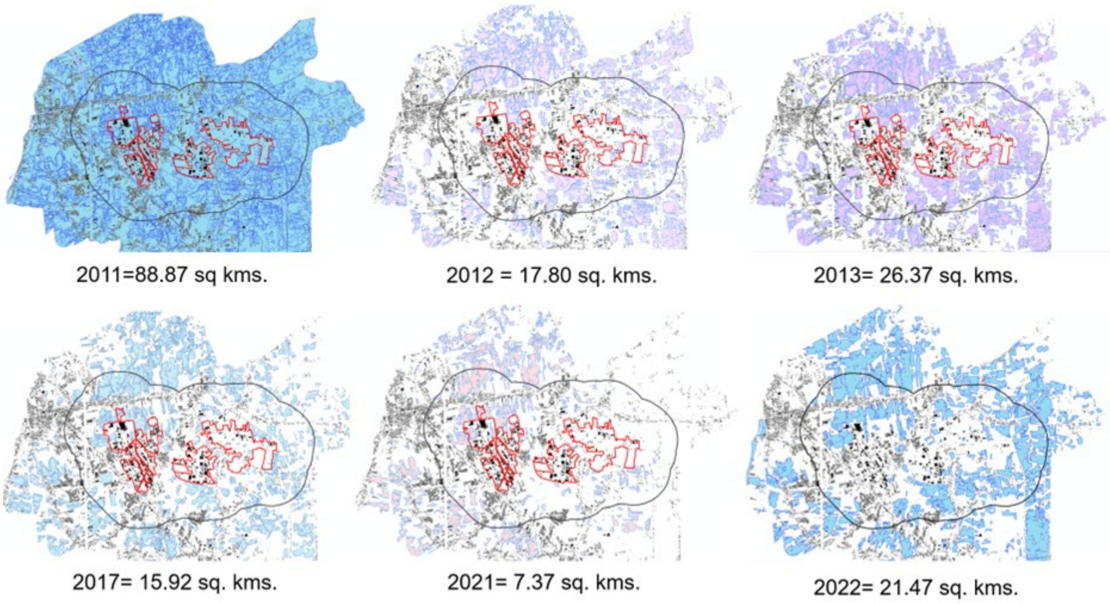

Figure 9. Flooded areas in 2011, 2012, 2013, 2017, 2021, and 2022.

Compared to all flood years, 2011 was the most severe as all areas were flooded, 2022 was moderate, and 2021 was the least severe (Figure 10).

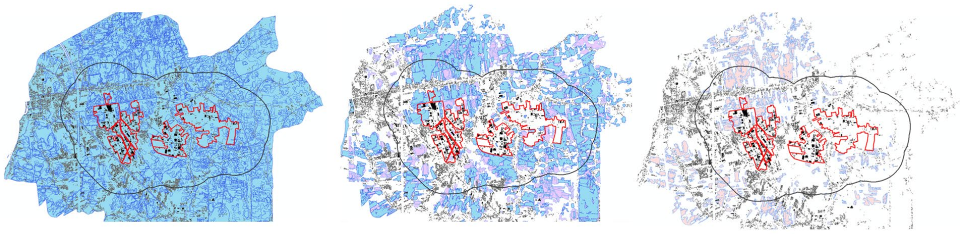

Figure 10. Flooded areas in 2011, 2022, and 2021.

This analysis assessed the social vulnerability in the four subdistricts; Thanu, Khan Ham, Bann Chang, and Nong Nam Som; using three main indices: exposure, susceptibility, and coping capacity (Nakasu et al., 2020). It was found that the exposure index was higher in the industrial park locations, and the capacity index was the second lowest in the Uthai District, where the RAIP is located. Nakasu et al. (2022) also found that the urban communities had higher capacities within the two kilometers surrounding the industrial park than the farm-based communities. However, because farm-based communities are used to dealing with occasional moderate floods, they possibly have higher ecological resilience.

Besides the physical damage, floods can cause significant income loss for laborers and daily wage workers, that is, after a flood, low-income earners generally struggle more to cope than business owners, who have greater recovery capacities. Industrial estate owners have invested in flood-resistant infrastructure, and local farmers are better prepared to deal with occasional moderate floods because of their higher ecological resilience. Therefore, as the urban and agricultural areas have diverse needs, we developed two main physical and environmental scenarios for moderate and severe flooding events.

5.3. Proposed Landscape Planning Scenarios

5.3.1. Scenario 1: Moderate Flooding

Since 2011, all subsequent floods in 2012, 2013, 2017, 2021, and 2022 have been moderate (Figures 9 and 10). This scenario focuses on critical local road accessibility to supply necessities and access evacuation routes. This would require raising the key roads high enough to travel by truck during moderate flood events. The government has established FROCs with a travel distance of 2.5 kilometers (the dashed lines). The routing and FROC locations are shown in Figure 11. The dashed lines indicate the proposed raised roadways and the FROCs, most of which are local public places that are converted temporarily or permanently during flood events, such as temples, schools, colleges, subdistrict administrative organization offices, hospitals, and health centers. The "last mile" between each residence and the evacuation routes is accessed by either foot or boat, depending on the FROC location (Figure 11).

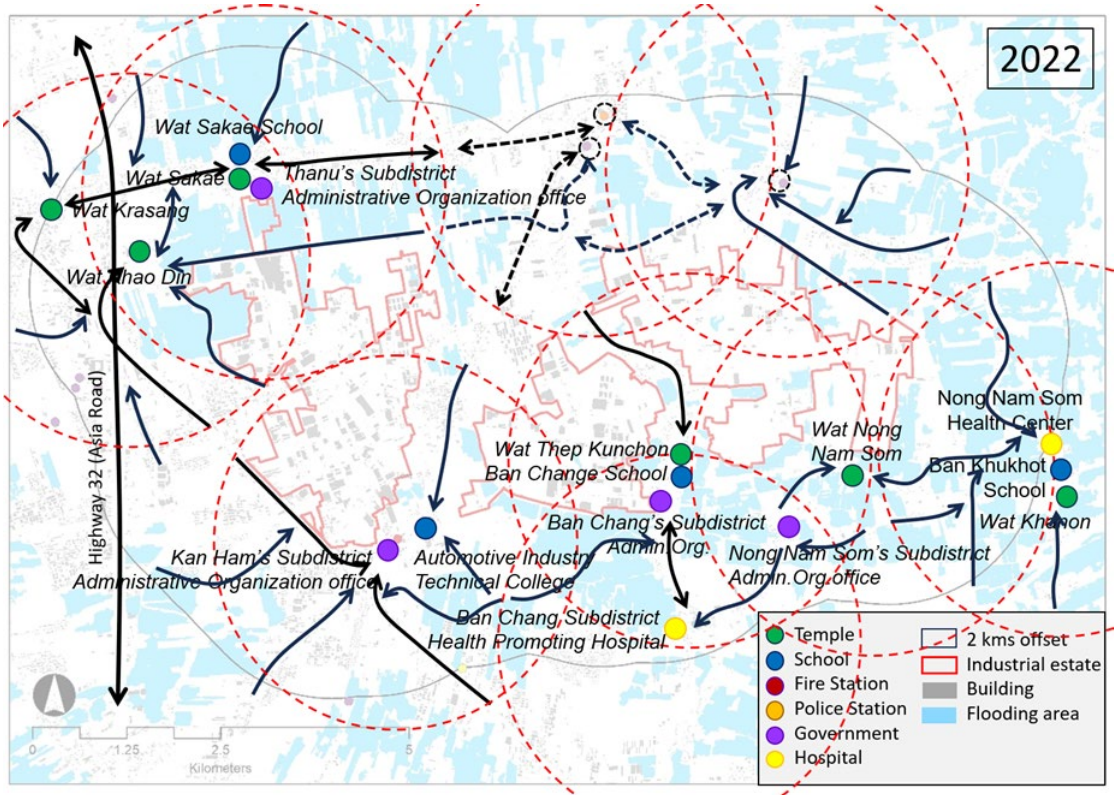

Figure 11. Scenario 1- Moderate Flooding. Note. (Figure 8 (left)) evacuation routes to all Flood Relief Operations Centers (FROCs) to be upgraded by being raised to at least the 2011 water level (Highway 32, Asian Road).

5.3.2. Scenario 2: Severe Flooding

As all areas are flooded in this scenario, both urban and agricultural residents must evacuate if the high water level is above the second floor. All current evacuation sites or FROCs on high ground above the flood level or slightly lower but protected by boundary levees can only be accessed by boat. Currently, there are 25 evacuation sites in 14 locations scattered primarily in the southern part of the study areas. Three locations (black dashed circle) in the northern part of the study area are proposed as possible future evacuation locations (Figure 12).

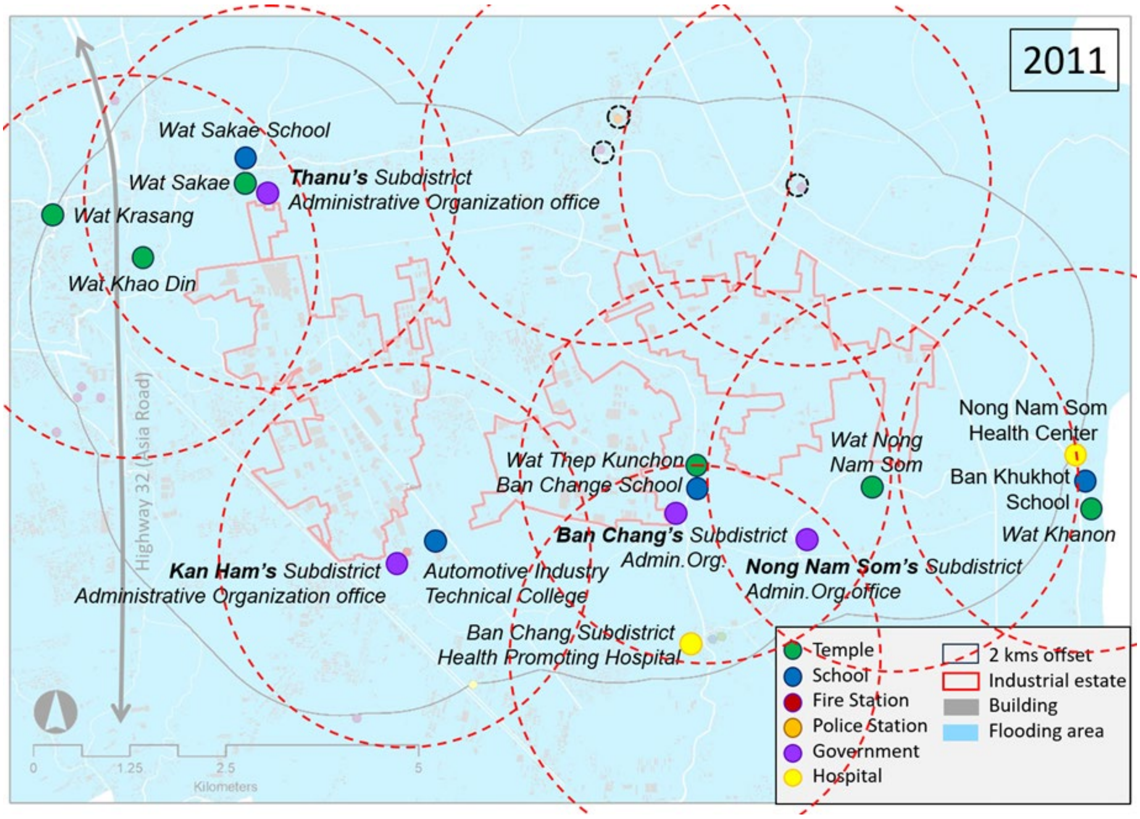

Figure 12. Scenario 2, Severe Flooding. Note. (Figure 8 (right)); all areas are flooded, including the evacuation routes and Highway 32 (Asian Road). Flood Relief Operations Centers (FROC) are only accessible by boat.

Given the potential recurrence of a flood as severe as the 2011 flood, a more resilient approach is needed. Rather than relying solely on elevated roads and designated FROCs, a more resilient proposal is to transform the housing clusters or villages into elevated safe zones. Inspired by an NGO "Friendship" project in Bangladesh (Friendship, 2019), this concept involves creating circular landfilled parcels to minimize erosion and provide space for dwelling units, livestock areas, gardens, and orchards. Central retention ponds would store water for the dry seasons, ensuring year-round self-sustainability for the community, including during flood events (Figures 13 and 14).

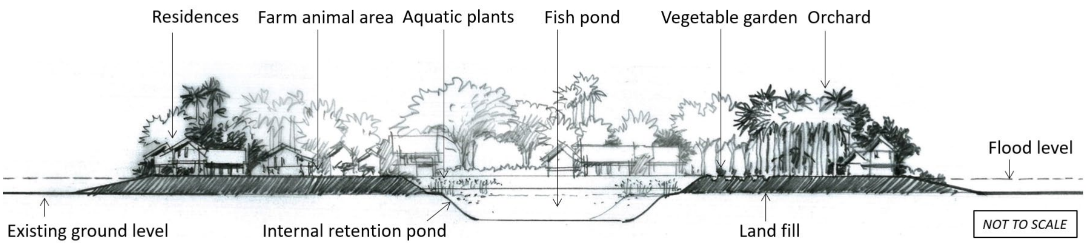

Figure 13. A typical section of the island model indicates the elements of self-reliance. Note. A retention pond for fish and water in the dry season, residential units, cattle and farm animals' areas, aquatic plants, vegetable garden, orchard, and other agricultural necessities.

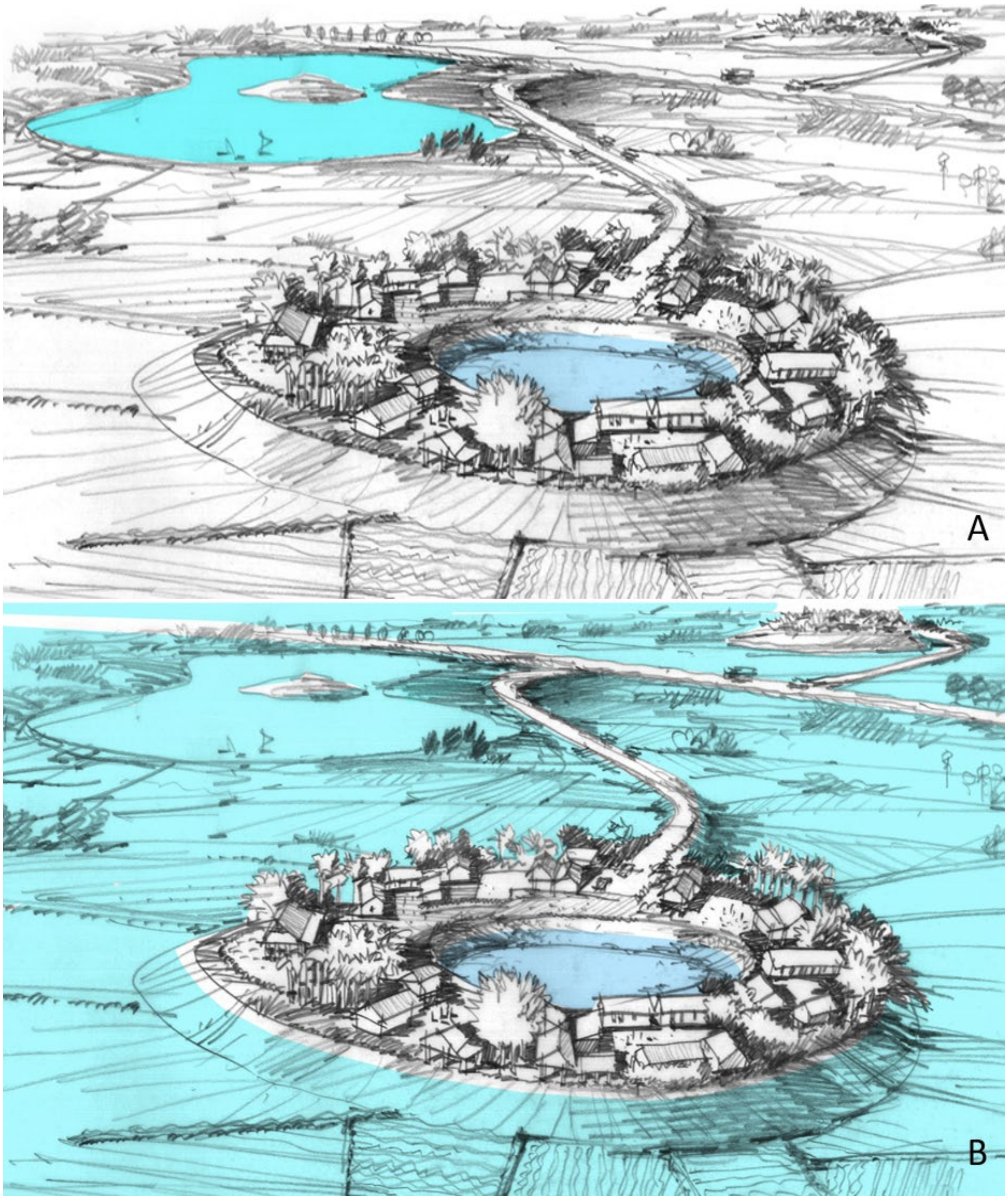

Figure 14. Normal condition vs. severe flood condition. Note. A) Lower land excavated to create a retention pond (far left in picture A). The earth from the excavation is used to create a landfilled island (the middle of the foreground and the far-right island in the distance). B) during a flood event, the island sustains itself. All raised- roadways provide access to the islands.

5.3.3. Focus Group

During the focus group, which comprised representatives from the Uthai District, questions regarding the proposed landscape planning scenarios were asked, and additional feedback was recorded (Figure 15).

Figure 15. Site Survey from February to March 2024 (**left**) and focus group workshop (**right**). Note. The "Training for Trainers on Disaster Prevention and Response Preparedness" focus group workshop, held on March 8, 2024, at Ayutthaya City Hall, included representatives from Uthai District. The workshop covered all subdistricts in the study area: Thanu, Khan Ham, Ban Chang, and Nong Nam Som (**right**).

Most people see floods as the primary severe disaster in the areas. Thanu and Khan Ham have recently been protected by raising the surrounding roadways. Generally, most people do not want to evacuate to the FROCs. Some built hardwood floor mezzanines after the first flood, and because the flood level did not exceed the second-floor level, they still had sufficient height to accommodate daily living. Annual floods last about 2−4 months. The focus group participants suggested that all roads be raised to protect them from floods in the next 20 years and that logistics and accessibility were the keys to successful mitigation.

5.3.4. Different Flooding Adaptations in the Urban and Agricultural Areas

When discussing the physical vulnerability differences between the urban and agricultural areas, the focus group suggested that only categorizing these areas as urban or agricultural would not suffice. Agricultural areas could be classified into within and outside the irrigated areas as irrigation impacts how the water is controlled. Since last year (2023), three of the four subdistricts; Thanu, Khan Ham, and Ban Chang; have experienced no flood impacts because they are within the flood prevention zones and irrigated areas. However, flood events affected all other areas beyond these irrigated zones, including Nong Nam Som. In 2024, there have been no problems unless the water crosses Highway 32 (Asian Road) and the railroad tracks (west of Ayutthaya), which occurred in 2011.

The industrial estates have implemented water barriers and evacuation plans. However, Ayutthaya's main challenge remains in the areas bordering the Chao Phraya and Pasak rivers, where protection is limited. Despite this, residents have drawn on their historical riverside lifestyles to mitigate the impact by constructing stilt homes. Due to these changes, except for potential overflows, the flood issues in Thanu, Khan Ham, Ban Chang, and Nong Nam Som should be minimal. However, flooding may occur in the Nong Nam Som subdistrict if water is released from the Raphiphat Canal Gate near the Rama XI Dam on the Pasak River.

Note: An "irrigated area" is an area of water resource development allocated for agricultural purposes. Therefore, agricultural areas are interpreted only as being within this area, as water is not assigned to the land outside (Royal Irrigation Department, Ministry of Agriculture and Cooperatives).

5.3.5. Evacuation to Flood Relief Operations Centres (FROC) and the Routes

Ayutthaya has seen minimal movement in evacuation plans for several reasons. First, Ayutthaya is a tight-knit riverside community accustomed to dealing with floods. Despite the inevitable impact, residents support each other and often stay with family if their homes are uninhabitable. Since the severe flood in 2011, many homes have been elevated, reducing the reliance on government relief centers. Second, while villagers prefer to stay put, they are willing to evacuate in crises such as the 2011 flood. Local authorities assist with access by building bridges and raising roads tailored to each area's needs. However, farmers prefer camping along roadsides over the FROCs because there are no areas available for farm animals at the FROCs.

5.3.6. Design Issues for the Proposed Landscape Planning in the Severe Flooding Scenario

The focus group suggested that while the design ideas were viable, the challenge lies in land ownership, as current lands have been passed down through generations. Implementing the design successfully would, therefore, require land readjustments. Finding suitable implementation sites also remains a concern.

6. Discussion

Generally, the Thanu, Khan Ham, Ban Chang, and Nong Nam Som subdistrict residents are well aware of the possible urban and agricultural flood scenarios. It was found that the urban communities within the two-kilometer radius of the industrial park have higher capacities to protect themselves from floods than the agricultural-based communities (Nakasu et al., 2022). Nevertheless, the farm-based communities can generally cope with occasional moderate floods because of their greater landscape and ecological resilience. As a result, the urban and agricultural flood requirements vary; however, the current flood mitigation strategies are uniform in both areas.

In summary, current flood prevention measures have significantly reduced flood risks. Three out of the four subdistricts, Thanu, Khan Nam, and Ban Chang, are now flood prevention zones or irrigated areas benefiting from improved flood prevention infrastructure. The 2011 flood prompted several proactive measures, and the industrial estates have taken independent steps to enhance their resilience. Although the areas adjacent to the Chao Phraya and Pasak rivers remain vulnerable, communities have adapted by building stilt houses and staying informed through the Royal Irrigation Department, Ministry of Agriculture and Cooperatives. If water is released from the Raphiphat Canal Gate near Rama 6 Dam on the Pasak River, the flood risks in the Nong Nam Som subdistrict demonstrate the ongoing need for reliance measures and coordinated responses.

The focus group results highlight the importance of considering different factors beyond the urban and agricultural areas. The subdivision of agricultural areas into irrigated and non-irrigated areas emphasizes the different water management practices that can affect flood vulnerability. Last year (2023), flood impacts were observed in non-irrigated areas; however, the irrigated areas; Thanu, Khan Ham, Ban Chang, and Nong Nam Som; remained unaffected. Additionally, the flood impacts in the urban areas were mainly related to drainage obstructions and water control operations.

The annual floods persist for approximately 2–4 months; however, more extreme conditions are expected in the future. This anticipation extends beyond the study area and is evident in other regions of central Thailand where waterfront communities are vulnerable (Khongouan & Khamwachirapithak, 2021). In the future, it was suggested that the levees or roads be raised because logistics and accessibility during floods are the keys to successfully mitigating the impacts in the expanding urban areas.

This study proposed two strategic forward-thinking infrastructure enhancement landscape planning scenarios to address both moderate and severe flood situations. For the moderate flood scenario, we emphasize engineering resilience as the primary strategy, with the key initiatives being the raising of the local roads connecting the neighborhoods to the FROCs to 5.80 meters above the MSL to ensure access for residents, particularly those in the urban areas. The plan also calls for the establishment of supplementary FROCs (Figure 11, outlined in black dashed lines) in the northern regions of the study area to reduce travel distances and increase response efficiency.

A comprehensive landscape resilience strategy is proposed for the severe flood scenario, which involves the construction of elevated platforms to house residences, livestock, farms, ponds, and essential amenities (Figures 13 and 14). This approach aims to create self-sustaining communities capable of enduring prolonged flooding events with minimal external support and travel requirements. By fostering sustainability and preserving daily routines, this holistic approach ensures survival during extreme events and enhances community resilience. However, despite overall support for the sustainable landscape resilience idea, the focus group raised concerns regarding land ownership.

To address these land ownership challenges, adjustments are suggested for the island model to accommodate individual families or close kin clusters, which reflects the Thai tradition of siblings often living together. The revised design designates areas for agriculture and livestock, separating them from the elevated stilt residences. This reconfiguration optimizes land use and balances cultural norms with practical rural living (Figures 16 and 17).

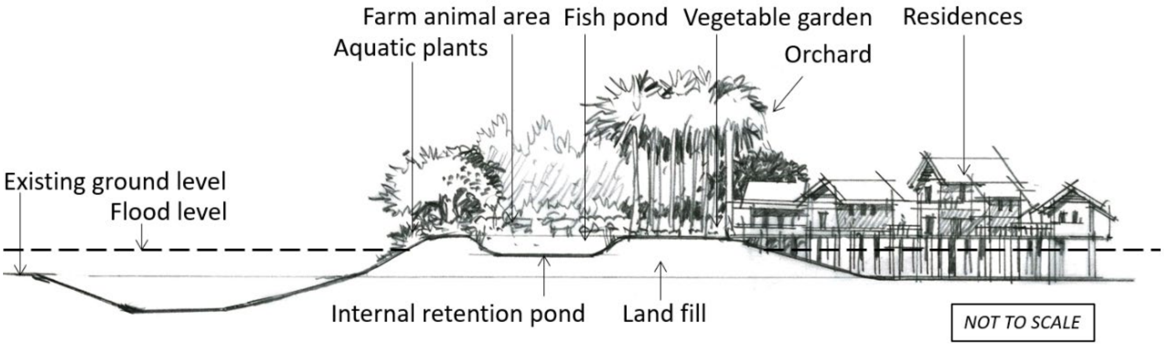

Figure 16. Smaller single-family island model. Note. A self-reliant residence compound is developed where the cattle and farm animal areas, aquatic plants, vegetable gardens, orchards, and other agricultural necessities are on land, while the residential units are on stilts.

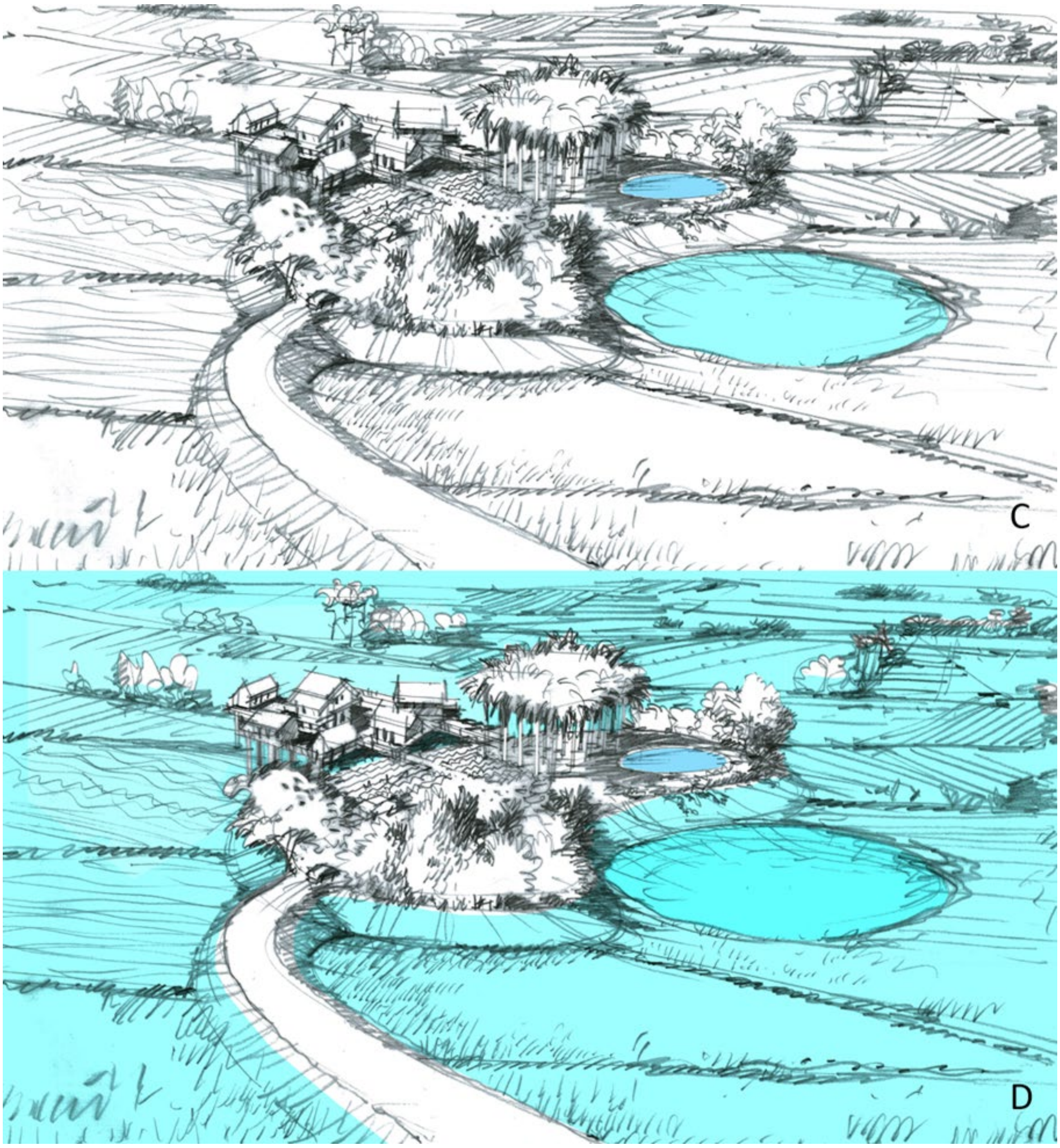

Figure 17. Normal vs. severe flood condition. Note. **C**) Lower land next to the island is excavated to create a retention pond. The earth from the excavation is used to create a landfilled island. **D**) during a flood event, the island sustains itself. Raised-up roadways provide access to the islands.

7. Conclusion

Over the past 13 years since 2011, the four subdistricts of Khan Ham, Thanu, Ban Chang, and Nong Nam Som have not experienced flooding as severe as that of 2011. Recent floods during the 2023-2024 flood seasons were less intense, with no recorded instances of riverbanks overflowing. However, the possibility of similarly severe or even more extreme floods in the future cannot be ruled out due to the impacts of climate change and uncertainties. This possibility underscores the urgency of implementing resilience-focused measures, as demonstrated in the results and mitigation strategies, while there is still time to act effectively.

Proposed landscape planning strategies for flood adaptations for every flood situation can provide higher resilience in vulnerable areas. Mitigation measures can contribute to long-term intervention plans for future flood events. This study suggests that future flood adaptation planning be conducted to complement the current flood control measures. Engineering resilience measures can focus on post-disturbance system recovery by maintaining primary and vital functions or structures and emphasizing infrastructure factors, such as levee strength and height. Landscape resilience, however, can extend beyond recovery to include adaptation, reorganization, and transformation in response to disturbances and changing conditions. While engineering resilience aims to restore the original state, landscape resilience aims to maintain basic structures while allowing for adaptation. The two proposed scenarios represent two ideas: engineering resistance for moderate floods and landscape resilience for severe floods.

However, challenges inherent in engineering and landscape resilience concepts are evident when compared. Engineering resilience solutions are often regarded as rapid and effective, particularly in managing floods. However, these approaches face criticism for their high costs and significant environmental impacts, deterring their adoption. Conversely, landscape resilience solutions are generally more cost-effective, but their implementation is challenging. These include limited land availability, competing land-use priorities (with landscape-based solutions often receiving lower priority), extended timeframes required for effectiveness, and the complexity of stakeholder coordination. Additionally, existing policies may inadequately support or prioritize landscape-based approaches, creating regulatory barriers.

These challenges highlight the importance of adopting a balanced, integrated approach that combines the strengths of large-scale engineering solutions with adaptive and sustainable measures like landscape resilience. Such a hybrid system can ensure strategic investments, mitigate environmental concerns, and enhance resilience against flooding (Waryszak et al., 2021; Du et al., 2020; Liao, 2012). In the context of this study, current measures, such as elevating roads and constructing flood barriers, function as control mechanisms during moderate flood events. These are complemented by the proposed self-reliant residential compounds designed to withstand future severe floods. This integrated strategy enables communities to maintain daily routines with minimal disruptions, enhancing long-term resilience. Together, the engineering and landscape approaches form a comprehensive flood management framework that prioritizes resilience and sustainability.

These approaches to flood scenarios could be adopted by other regions in Thailand as well as countries that experience similar problems. The breach of Ayutthaya's flood protection levees in 2011, which resulted in flooding across all areas, is a clear example of the potential transition from relying on engineering resistance alone to embracing and integrating landscape resilience in mitigating the impacts of severe weather and global climate change.

Authors' contributions

S.J.: Shusak Janpathompong: Conceptualization, Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Roles/Writing - original draft: and Writing—review & editing. R.B.: Ruttiya Bhula-Or: Investigation; Project administration; Resources. T.N.: Tadashi Nakasu: Investigation; Methodology; Project administration; Resources. P.C.: Paron Chatakul: Resources; Supervision. D.J.: Dalin Janpathompong: Conceptualization; Supervision. K.P.: Korrakot Positlimpahul: Data curation; Formal analysis; Investigation; Software; Visualization. MN: Mingkwan Nantavisai: Data curation; Funding acquisition. S.A.: Sutee Anantsuksomsri: Conceptualization; Data curation: Funding acquisition; Investigation; Methodology; Resources; Supervision; Validation; Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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Competing interests
The authors have no competing interests to declare.

Ethics and consent
The study was conducted in accordance with The Research Ethics Review Committee for Research Involving Human Subjects: The Second Allied Academic Group in Social Sciences, Humanities and Fine and Applied Arts at Chulalongkorn University, based on Declaration of Helsinki, the Belmont Report, CIOMS guidelines and the Principle of the international conference on harmonization – Good clinical practice (ICH-GCP) has approved the execution of the aforementioned research project. COA No. 078/66. Date of approval: March 22, 2023.

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