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Assessment of Multiple Water-Related Hazards under Changing Climate in an Urbanized Sub-Region of Yom River Basin, Thailand

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Abstract

Water-related hazards, such as river floods, flash floods and droughts, are becoming more frequent in the Upper Chao Phraya River Basin, Thailand, due to climate change and urbanization, causing significant societal, economic, and environmental damage. This study supports decision-making for nature-based solutions (NBS) to address mitigate these hazards. Using multi-criteria decision analysis, simulation modeling, and spatial analysis, the study identified precipitation and river discharges as key hazard drivers. Mapping hazard severity at various scales, the findings suggest that expanding green areas and water storage can enhance water management and reduce hazard impacts. This research offers critical insights for NBS adoption in water-related risk reduction.

Keywords

Adaptation, Hydrological Modelling, Multi Criteria Decision Analysis, Multiple Hazard Assessment, Natural Based Solution, Spatial analysis

1. Introduction

Thailand is among the top ten countries in the world in terms of absolute losses from natural disasters between 1998 and 2017. According to Wallemacq et al. (2018), Thailand is one of the countries that are most exposed to and affected by floods, flash floods, droughts, tropical storms, and forest fires. In 2011, the biggest historic flood in Thailand resulted in 9.1 percent of the land base flooded. Droughts between 1989 and 2019 are estimated to have led to a lack of water storage in farmlands and residential areas. Multiple water-related hazards pose significant threats to an expansive area. Additionally, nature-based solutions (NBS) are increasingly receiving attention in academic and policy discussions as effective approaches for addressing environmental challenges and enhancing resilience. Thereby, this study aims to reduce the impact of water-related hazards by providing decision-making support for proposed NBS as an alternative to traditional structural measures by leveraging natural processes and ecosystems, such as green spaces, wetlands, forests, vegetated lands, etc. The development of suitable methods and tools to support decision-making in dealing with the multiple hazard assessment (MHA) process is underway.

2. Literature Review

2.1. Studies of Water-Related Hazard Characteristics

Hydrological processes play an important role in the global water cycle and seasonal drivers (Trisurat et al., 2019; Clifton et al., 2018; Xu et al., 2016). Anthropogenic changes in natural and green surface areas, such as land misuse and urbanization, fuelled by climate change, tend to have a significant impact on high-and-low peak streamflow. Flooding is the event where water inundates land that is normally dry. Human activities such as land misuse and urbanization can increase the probability of flooding. Reduction in rainfall and soil moisture would further decrease streamflow and underground water storage, which then result in a hydrological drought (Environmental Technology, 2014; National Geographic Society, 2019; Sawatpru & Konyai, 2016; Dau et al., 2018; Rubinato et al., 2019).

2.2. Approaches to the Multiple Hazard Assessment

There is an abundance of approaches and methods that can be applied to assess multiple hazards. One of the interesting combinations is the hydrological and hydrodynamic models (HEC-HMS/RAS), the Multi-Criteria Decision Analysis (MCDA), and the spatial analysis, which are successively introduced below. The Hydrologic Modelling System (HEC-HMS) was developed by the U.S. Army Corps of Engineers. It is designed to simulate the hydrologic processes of watershed systems. It can be used for one-and-two-dimensional steady flow hydraulic calculation (Tate, 1999; Hydraulic Engineer Center, 2019; Scharffenberg, 2018; Hamlet et al., 2013). The MCDA integrated with the Analytic Hierarchy Process (AHP) method is powerful in analysing the key influence factors among different groups of factors in a given hazard. This method takes into account both natural and anthropogenic factors, while giving different weights to the factors (Skilodimou et al., 2019; Shadmehri Toosi et al., 2019; Seejata et al., 2018).

2.3. Nature-Based Solutions for Hazard Reduction

In flood and drought risk management, mitigation measures can be categorized into structural and non-structural solutions. Structural measures include, for instance, flood prevention infrastructure, early warning systems, etc. With an increased recognition of the role that ecosystems play in providing critical services to reduce and mitigate multiple types of flooding, NBS is recommended to be prioritized whenever possible (ADRC, 2019; Ilieva et al., 2018; Lafortezza et al., 2018; Faivre et al., 2017). The NBS is defined as "a strategically planned network of natural and semi-natural areas that deliver a wide range of ecosystem services." Examples of applicable NBS to water-related hazards include wetlands, riverine floodplains, natural detentions, etc. (European Environmental Agency 2015, UN Environment-DHI, UN Environment & IUCN, 2018; Debele et al., 2019; Swiss NGO DRR Platform, 2018). NBS can contribute to several benefits for water supply and wastewater management. Permeable pavements, changing impermeable surfaces into green spaces, tree planting, and storage areas for excess runoff are among the NBS possibilities (National Infrastructure Commission, 2017). Some of these measures also have tangible benefits for society by bringing nature back into the city and providing recreational green spaces.

Existing research on NBS has extensively examined their roles in managing water-related hazards and enhancing ecosystem services. For example, studies have highlighted the importance of reconnecting rivers to floodplains as a method to mitigate flood risks. Floodplains, by receiving overflow water from rivers, can slow water flow and reduce flood intensity, while also providing fertile land for agriculture and supporting fisheries, which contribute to biodiversity (Serra-Llobet et al., 2022; Thieme et al., 2023, Horváthová, 2019; Chen et al., 2015; Komori et al., 2012). Additionally, forests and naturally vegetated lands have been shown to mitigate extreme events by reducing the likelihood and severity of floods, landslides, and mudflows, thereby protecting infrastructure and residential areas (Khaspuria et al., 2024; Marengo et al., 2020; Depietri & McPhearson, 2017). The integration of alternative natural and green surface areas, along with natural and built storage areas like nature-integrated water storage, has been proposed as effective strategies for managing water-related hazards (Ferreira et al., 2021; Qi et al., 2020; Qi et al., 2021; UN Environment, 2016). This study builds on this body of work by proposing NBS that align with these established functions, offering a comprehensive approach to hazard reduction through enhanced water management with the focus on combining natural processes with engineered solutions that the system integrates natural processes with engineered infrastructure to manage water resources.

2.4. Relevant Studies on Water-Related Hazards in Thailand and Other Regions

Major hazards in Thailand, particularly in CPRB, are primarily water-related, including river floods, flash floods, and droughts (Putthividhya & Jomvoravong, 2016; Rangsiwanichpong et al., 2016; Sawatpru & Konyai, 2016; Poaponsakorn et al., 2015). Numerous scholars have studied these hazards. Chuenchooklin et al. (2015) demonstrated that hydrodynamic modeling (HEC-RAS) for planning retention ponds and diversion channels can significantly reduce flood depths in

Sukhothai Province, Thailand. Yang et al. (2023) indicated climate change and human activities are intensifying water scarcity and increasing flood and drought risks in the Upper Chao Phraya basin. By mid-century, per capita water resources could decline by 34.2%, with flood and drought risks rising significantly by the century's end. Sustainable land use practices may help mitigate these impacts. Jamrussri and Toda (2017) showed that non-structural flood countermeasures, such as reforestation and land use regulation, effectively mitigate peak discharge and control flood volume in the Chao Phraya River Basin. Petchprayoon et al., (2010) found that land use and land cover changes, especially urban growth and deforestation, significantly impact river discharge behavior in the Yom River Basin. Penny et al. (2023) uses MCDA-GIS analysis to evaluate the impact of NBS like wetlands and re/afforestation on flood hazard reduction in the Mun River Basin, Thailand. Results show that NBS effectively reduce flood hazards, especially when combined. The study addresses gaps in NBS research, with a focus on Southeast Asia. Zenkoji et al. (2019) analyzes rainfall trends and flood risks in Thailand's Mun and Chi River Basins. Using the Mann-Kendall test and generalized extreme value distribution, the study finds a significant increase in annual rainfall in the upper reaches. Inundation analysis with the Rainfall-Runoff-Inundation (RRI) model reveals that both the maximum inundation depth and inundation area have grown in recent years. Kanbua et al. (2009) investigated real-time warning systems for flash flood hazards in Phrae province, using an Artificial Neural Network (ANN) integrated with Automatic Weather Stations (AWS) to monitor and adjust the network system, demonstrating the effectiveness of this approach in providing advance notice of potential flash flooding. Dau et al. (2018) assessed drought severity in the Lower Nam Phong River Basin in Northeast Thailand using the Water Evaluation And Planning System (WEAP) model and SPI, identifying varying degrees of water scarcity and drought risk areas, which can inform water resource planning and drought management in Thailand.

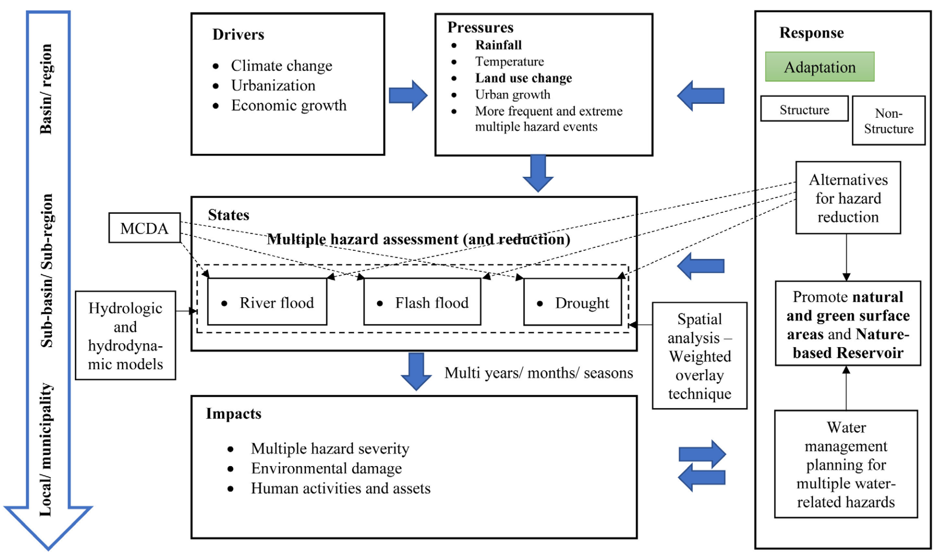
2.5. Summary

Hazards, particularly water-related hazards, stem from both natural and anthropogenic factors, exacerbated by climate change and urbanization. Among natural hazards, floods and droughts are particularly devastating and widespread. The water-related hazard studies with a strong emphasis on the role of NBS in mitigating these risks. It discusses the impact of anthropogenic changes and climate change on flood and drought hazards, highlighting the effectiveness of NBS, such as reforestation, wetlands, and floodplain restoration, in reducing these threats. Various methodologies, including hydrodynamic modeling (HEC-HMS/RAS), MCDA, AHP, and spatial analysis, are explored to assess and implement NBS. Research in Thailand's Chao Phraya River Basin and other regions demonstrates that NBS can significantly lower flood risks, particularly when combined with other measures. Studies in the Mun and Chi River Basins further show how increased rainfall and inundation risks can be managed through NBS, supporting sustainable water management. The review underscores the importance of integrating NBS into hazard mitigation strategies to enhance resilience in Thailand and comparable regions.

3. Methodology

3.1. Overall Approach and Methods

Figure 1 illustrates a conceptual framework highlighting both natural and anthropogenic factors influencing major water-related hazards (Gill & Malamud, 2017). While rainfall is a crucial natural factor, anthropogenic factors such as land use change, driven by urban expansion, climate change, and economic growth, play significant roles. The culmination of these factors intensifies the frequency and severity of multiple hazard events. This study's multiple hazard assessment integrates key variables, incorporating spatial and temporal variations to evaluate hazard states and their impacts on the environment, human activities, and assets (Liu, 2011; Shadmehri Toosi et al., 2019; Salami et al., 2017; Tiwari, 2019; Kalantari et al., 2018; Zhang et al., 2020). Adaptation strategies for mitigating water-related hazards and planning water management involve employing Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP) techniques to prioritize natural and anthropogenic factors affecting water-related hazards. Spatial analysis, along with hydrological and hydrodynamic models, helps determine hazard degrees and affected locations. Key influence factors were analyzed using simulation modeling, particularly through the application of HEC-HMS/RAS models. Trend analysis assessed historical variations in hydrological characteristics such as rainfall, water discharge, and temperature, predicting their future trends and probabilities of extreme hazard events (Champathong et al., 2013; Krinner et al., 2013). Additionally, potential Nature-Based Solutions (NBS) were tested to identify appropriate measures for reducing multiple hazards. Further operational details are provided in **Table 1**.



Source: Adapted from Liu et al., 2016; Salami et al., 2017; Shadmehri Toosi et al., 2019

Figure 1. Conceptual Framework.

Table 1. Operational framework.

Inputs	Processes	Analysis methods	Outputs
Results of local decision-makers' interviews and literature reviews	Task 1: To analyze the factors that influence the multiple hazard assessment using the MCDA approach	Document analysis, Local decision-makers' judgment and the AHP method	Influence factors to hazards with weighted scores
Digital Elevation Model (DEM), Soil map, Land use map, observed rainfall and discharge, water level, and Geometric data	Task 2: To develop the method for a river flood hazard assessment using HEC-HMS/RAS modeling with calibration and validation of modeling results	Computation of model simulation, Spatial analysis techniques	River flood hazard assess-ment
Rainfall data, Soil map, DEM, Geome-try data	Task 3: To develop the method for a flash flood hazard assessment using the MCDA approach and spatial analysis techniques	AHP method and Spatial analysis, with weighted overlay techniques	Flash flood haz-ard assessment
Rainfall data, Soil map, DEM, ground-water, Geometry data	Task 4: To develop the method for a drought hazard assessment using the MCDA approach and spatial analysis techniques	AHP method and Spatial analysis, with weighted overlay techniques	Drought hazard assessment
Results from Task 1 - 4	Task 5: To develop the method for assessing multiple hazards and potential reductions by integrating MCDA, Spatial analysis and model simulation techniques	AHP method and Spatial analysis, with weighted overlay technique, model simulation	Multiple water-related hazard assessment
Historical rainfall, discharge, and temperature data	Task 6: To analyze temporal and spatial trends of hydrological characteristic based on historical data at different scales	Trend analysis, Climatic indicators	Trend of historical hydrological characteristics, peak and low
Projected rainfall, discharge, and temperature data	Task 7: To analyze temporal and spatial trends of hydrological characteristics based on projection at different scales	Trend analysis, Climatic indicators	Trends of projected hydrological characteristics at peak and low levels

Continued

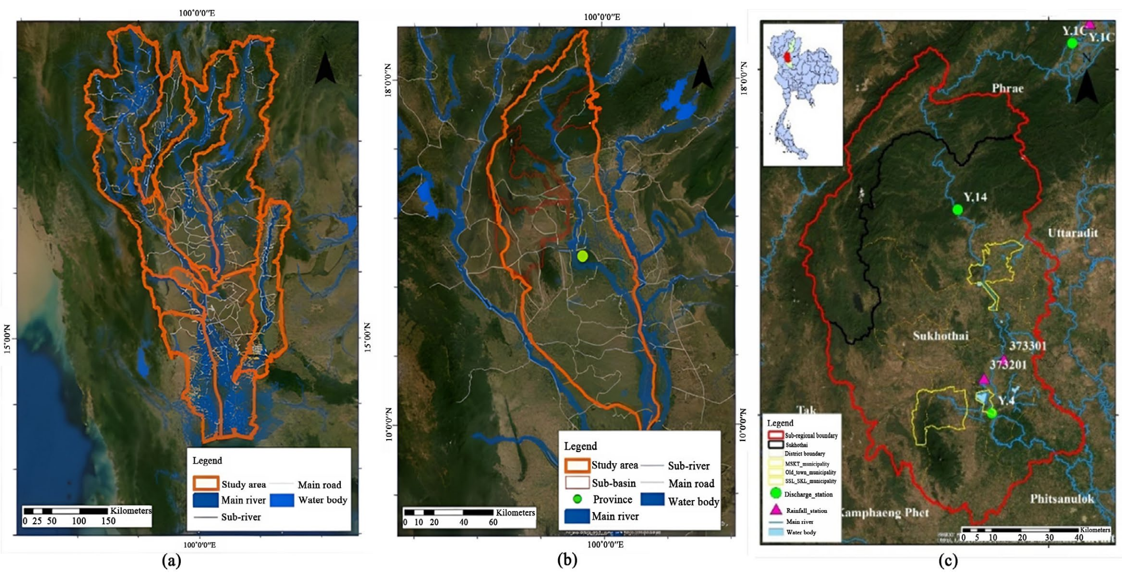
Natural and green surface areas, and natural storage volume	Task 8: To identify NBS alternatives for multiple hazards reduction	Document analysis, Computation of model simulation, Spatial analysis techniques	Hazard reduction potential under NBS scenarios
Results from Task 8	Task 9: To evaluate the identified alternatives for the multiple water-related hazard reductions	Simulation modeling, Spatial analysis techniques	Examples of hazard reduction measures

Source: Author's analysis (2020)

3.2. Study Area

3.2.1. Sub-regional/Basin Scale

The study area locates within the Greater Chao Phraya River Basin (G-CPRB) which covers seven main sub-basins. The study further focused on three municipal areas within Sukhothai province, including Mueang Sukhothai municipality, Old Town municipality, and Sri Satchanalai together with Sawankhalok municipalities (see Figure 2(a)-(c)). The middle Yom River Basin (YRB) is considered part of the Upper-CPRB (U-CPRB), which covers the provincial areas of lower Phrae, Sukhothai, and some parts of Phitsanulok, Phichit, and Kamphaeng Phet. It stretches from latitude 15˚50'N to 19˚25'N and from longitude 99˚16'E to 100˚40'E. This region is rich in natural wetlands, forests, and various soil types. These water resources play an important role in water supply and mitigation of water-related hazards.

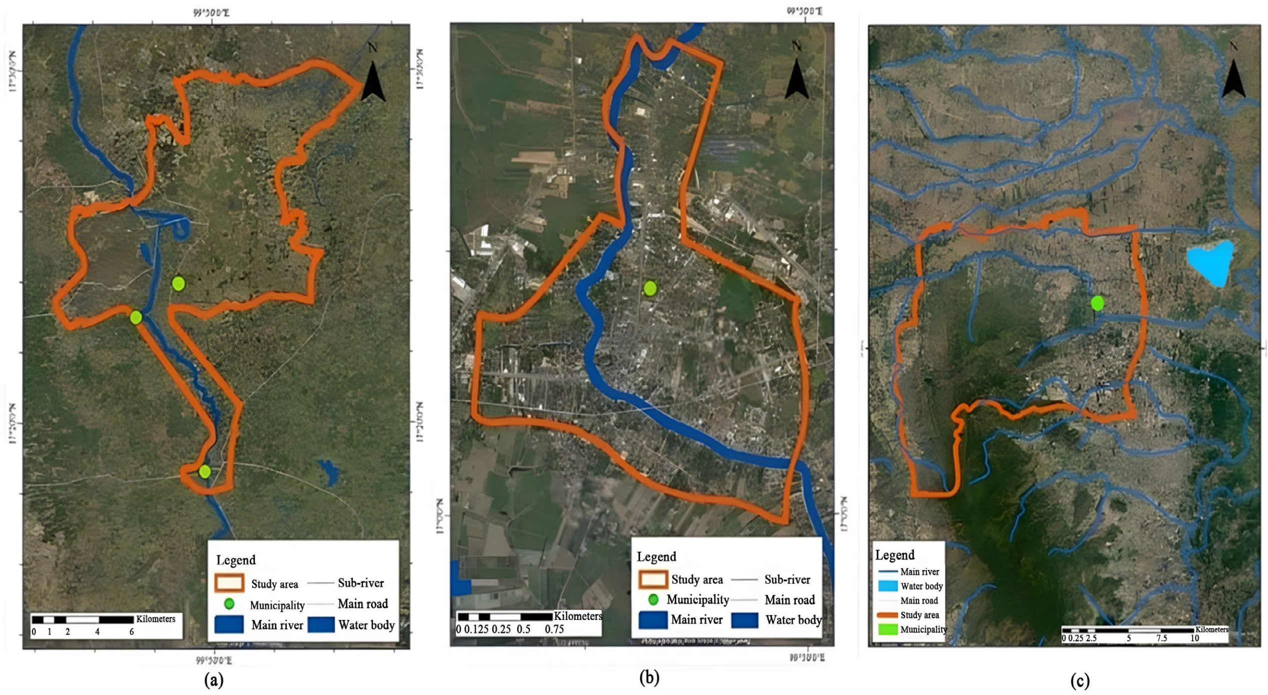


Source: Based on secondary data and shapefiles from Thailand GIS Resources in 2017, and created using the ArcGIS

Figure 2. (a) Boundary of the G-CPRB; (b) Boundary of the U-CPRB; (c) Boundary of the Sub-Regional and Local Studied Areas.

3.2.2. Municipality/Local Scale

At the local scale, three municipalities are covered in this study, including; (1) Si Satchanalai and Sawankhalok Municipalities (SSL and SKL), located in the upper part of Sukhothai province, which is an urban area on the highlands, shown in **Figure 3(a)**; (2) Mueang Sukhothai Municipality and its Vicinity (MSKT), the major hub of economic and community areas on the lowlands in the lower part of Sukhothai province, shown in **Figure 3(b)**; and (3) Old Town Municipality and its Vicinity (OLT), which is a hilly area where some famous tourist attractions are found, shown in **Figure 3(c)**. In general, the main economic activities in the studied area include farming, forestry, fishery and local commerce.



Source: Based on secondary data and shapefiles from Thailand GIS Resources in 2017, and created using the ArcGIS

Figure 3. Boundary of Si Satchanalai and Sawankhalok Municipalities; (b) Mueang Sukhothai Thani Municipality and Vicinity; (c) Boundary of Old Town Municipality and Vicinity.

3.3. Data Collection and Analysis

3.3.1. Data Collection

This study used both primary and secondary data. The primary data was collected through field observations and interviews with 23 local decision-makers from the organizations involved in natural hazard management and disaster preparedness activities. The secondary data covers historical datasets within the range of 2006 and 2018 on rainfall, river discharge, DEM, soil map, land use map, etc., mainly collected from official sources including Royal Irrigation Department (RID), Land Development Department (LDD) and Thai Meteorological Department (TMD) (see **Table 2**).

Table 2. Data Collection Items and Sources.

Data	Description	Sources	Data characteristics
Rainfall data	Daily unit	Thai Meteorological Department (TMD)	5 stations for Upper Yom River Basin such as 373201, 373301, 378201, 380201 and 386301 during 1988-2017
	Daily unit	Royal Irrigation Department (RID)	6 stations including Y.1C, Y.20, 73032, 73082, 73100 and 16092 during 1988-2017
	Daily unit	Coordinated Regional Climate Downscaling Experiment (CORDEX), Ramkhamhaeng University, Thailand	5 stations for Upper Yom River Basin such as 373201, 373301, 378201, 380201 and 386301 during 2018-2050
Runoff data	Daily and hourly unit	Royal Irrigation Department (RID)	From 2 gauging stations inside Yom River Basin include Y.1C and Y.14 during 2007 to 2011
Temperature	Daily unit	Thai Meteorological Department (TMD)	Degree Celcius
Digital Elevation Model (DEM)	SRTM	USGS	Resolution at 12.5 and 30 m. in 2017
River cross section of Yom River		Royal Irrigation Department (RID)	6 crossections including Y.3A, Y.4, Y.6, Y.14, Y.15 and Y.33 in 2017
Land use map	Resolution 30 m., 12.5 m.	Land Development Department (LDD)	During 2006-2018
Soil map	Resolution 90 m.	Land Development Department (LDD)	In 2017
Number of inhabitants	In Sukhothai province	Official Statistics Registration Systems	During 1995-2019
Households	In Sukhothai province	Official Statistics Registration Systems	During 1995-2019
Population density	In Sukhothai province	Official Statistics R egistration Systems	In 2019
Influence factors to the multiple hazards		Skilodimou et al. (2019); Palchaudhuri & Biswas (2016); Tri et al. (2019); Kazakis et al. (2015) and Stefanidis & Stathis (2013)	
Weighted score for influence factors		local decision maker's interview	23 local decision-makers to rank the major influence factors

3.3.2. Analytical Methods

This study used two main research approaches: simulation modeling for river flood hazard assessment and MCDA combined with spatial analysis for assessing flash floods, droughts, and potential mitigation solutions. Detailed descriptions of each assessment are provided below.

1) Baseline Analysis

Trend analysis was conducted using ETCCDI in RClimDex software to evaluate climatic indices and assess historical and projected rainfall trends across different spatial and temporal scales (see Table 3). Additionally, trend analysis was employed to examine urban growth, which has reshaped land use and population density, significantly increasing vulnerability to water-related hazards.

Table 3. Definition of extreme precipitation indices.

Index	Descriptive name	Definitions	Units
PRCPTOT (PRCP)	Annual precipitation total	Total annual precipitation in wet days (Rainfall volume ≥1 mm)	mm.
R20	Number of heavy precipitation days	Annual count of days when Rainfall volume ≥20 mm.	Days

2) River Flood Hazard Assessment

The HEC-HMS/RAS model was used to create inundation maps from runoff data, based on observed discharge from 2007 to 2017. Calibration was performed for 2007-2012 and validation for 2013-2017 using performance indicators such as coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), Volume Ratio (Vr), and Root Mean Square Value (RMSE). The results were classified into a flood hazard index (1 to 5) and mapped using GIS.

3) Flash Flood Assessment

The flash flood hazard assessment identified key factors such as rainfall intensity, slope, elevation, soil type, and land use with input from 23 local decision-makers. These factors were prioritized using the AHP method, assigning weighted scores through pairwise comparisons and normalization. The consistency of the weighted scores was verified using consistency ratios and random index indicators, as shown in equations (1)-(3).

$$\lambda \max = \sum_{i=1}^{n}\left[\sum_{j=1}^{n} aijwi\right] \quad (1)$$

Where, aij is judgment matrix data and wi is parameters weight

$$CR = CI/RI \quad (2)$$

Where, CR is Consistency Ratio, CI is Consistency Index, and RI is Random Inconsistency Index (as shown in Table 4)

Table 4. Random Index. (RI)

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

Source: Saaty (1977; 1980)

$$CI = \frac{\lambda \max - n}{n-1} \quad (3)$$

Where, λmax is Eigen Values, n is the Number of criteria or factors

Per the literature reviewed, the CR is ≤0.1, referring that the weighting coefficients are suitable, whereas if it is >0.1, the results of the weighted score and judgment are required to be reconsidered to ensure realistic results. Then, data layers for each factor were obtained from governmental agencies, converted to raster datasets, and reclassified using GIS software. Rainfall intensity was interpolated with IDW. Factors were rated on a scale of 1 to 5, and weighted scores were combined using a weighted overlay technique. The Raster Calculator tool generated a flash flood hazard map, reclassified into indices from 1 (very low) to 5 (very high) (Palchaudhuri & Biswas, 2016; Skilodimou et al., 2019; Tri et al., 2019).

4) Drought Hazard Assessment

The drought hazard assessment identified key factors such as rainfall, soil type, groundwater, land use, and water storage, prioritized using the AHP method with input from 23 local decision-makers. Consistency of the criteria was verified using consistency ratios and random index indicators, as shown in equation (1) - (3). GIS software was used to convert factors into raster data, with interpolation for rainfall, groundwater, and water storage. Factors were combined using a weighted overlay technique, producing a drought hazard map with indices ranging from very low to very high (Palchaudhuri & Biswas, 2016; Tingsanchali & Keokhumcheng, 2019).

5) Multiple Water-Related Hazard and Potential Reduction Assessment

The multiple hazard assessment (MHA) used quantitative methods based on individual hazard evaluations developed from Skilodimou et al. (2019). Equation (4) calculates the combined hazard levels from these assessments. GIS software, using the Overlay technique and Raster Calculator tool in Model Builder, was used to produce the multiple hazard assessment map.

$$MHA = RF + FF + DR \quad (4)$$

Where, RF is River flood hazard level, FF is Flash flood hazard level, DR is Drought hazard level

Overlaying individual hazard maps created the multiple hazard assessment map, showing spatial distribution with varying colors and values. Results are presented as three-digit numbers indicating hazard severity, with higher values representing greater hazards (see **Table 5**). For example, a value of 402 indicates high drought, no flash flood, and low river flood hazards in that area. This method enables the examination of hazard occurrences across different temporal and spatial scales.

Table 5. Classification of the hazard levels of Multiple Water-Related Hazards.

Value	River flood	Value	Flash flood	Value	Drought
1	Very low hazard	10	Very low hazard	100	Very low hazard
2	Low hazard	20	Low hazard	200	Low hazard
3	Medium hazard	30	Medium hazard	300	Medium hazard
4	High hazard	40	High hazard	400	High hazard
5	Very high hazard	50	Very high hazard	500	Very high hazard

Source: Adopted from Skilodimou et al. (2019)

4. Results and Discussions

4.1. Urbanization and Socio-Economic Trends

Urban growth over recent decades has significantly altered land use and population density in Sukhothai province, impacting the region's demographic exposure to water-related hazards. In 2019, the total population was 597,430 across 210,126 households, with a population density of 90.54 people per square kilometer. From 1995 to 2019, the population steadily decreased, while the average annual income of residents is 68,552 baht. The agricultural suitability of the province means 41% of the population works in farming, forestry, and fishery, 16% in local business, and 9% in production. Urban expansion, particularly from downtown Mueang Sukhothai Thani municipality and vicinity, has altered land use patterns, extending to Si Satchanalai district. The Central Business District (CBD) extends along the province's main roads, affecting land use in Mueang Sukhothai district. Residential and commercial areas have grown as urbanized areas expand, while natural surfaces, particularly water resources, and agricultural areas have gradually decreased. This shift has made urban areas more vulnerable to water-related hazards such as floods and droughts (DPT & Sukhothai Office, 2019).

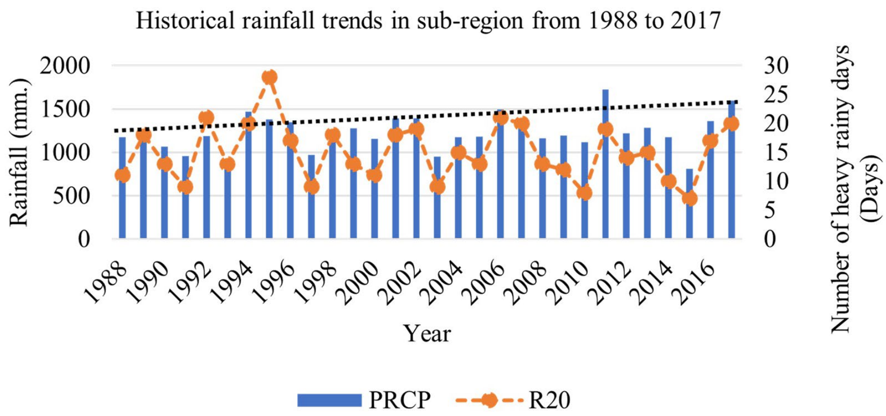
Between 2009 and 2018, industrial areas increased by 5.88%, water resources by 5.58%, government offices by 5.05%, commercial areas by 3.43%, and residential areas by 1.20%. Meanwhile, agricultural areas decreased by −0.33% annually. The consistent expansion of urban areas has converted farmland into residential, commercial, and administrative areas, altering the natural landscape and water flow patterns. Land use changes over the past decade (2006, 2011, and 2016) show shifts in five main categories: water body, agriculture, urban area, mixed activity, and forest.

These changes in land use and population distribution have heightened the demographic exposure to water-related hazards. The increasing concentration of people and economic activities in urban areas amplifies the impact of floods and droughts. Furthermore, these changes affect socio-economic conditions, leading to shifts in employment patterns, income distribution, and social equity. Vulnerable populations, particularly those in low-income households and those dependent on agriculture, face increased socio-economic challenges. Public health risks are also elevated due to the potential health hazards posed by floods and droughts, necessitating improved infrastructure and hazard mitigation strategies to protect the population and infrastructure.

4.2. Baseline Analysis and Factor Identification of Water-Related Hazards

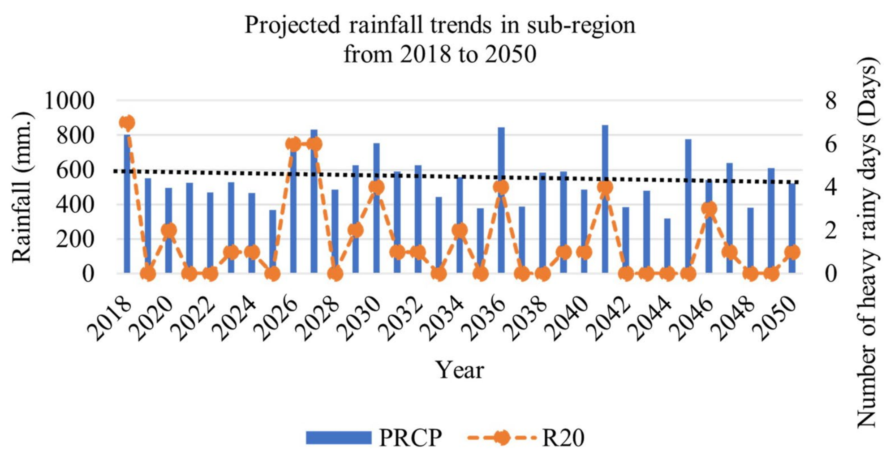
To understand the baseline trends of hydrological and climate characteristics over time in the sub-regional and focused areas, generally, rainfall in Thailand reaches its peak in May and then decreases until December to January which is the lowest volume (Hydro and Agro Informatics Institute, 2012). An analysis based on historical data showed that rainfall has steadily increased between 1988 and 2017.

In 2006, 2011 and 2016, extreme wet and dry conditions were observed alternately, which could have led to multiple water-related hazards. Rainfall will be limited in the next 30 years, leading to lower discharge rates. This implies that drought hazards are more likely to occur than floods (see Figure 4 - 5).



Source: Based on RU-CORE (2019) and TMD (2017)

Figure 4. Historical Rainfall Trends in Sub-Region from 1988 to 2017 Using PRCPTOT and R20 Indices.



Source: Based on RU-CORE (2019)

Figure 5. Projected Rainfall Trends in Sub-Region from 2018 to 2050 Using PRCPTOT and R20 Indices.

In the past, MSKT and OLT municipalities experienced high cumulative rainfall, while SSL and SKL observed lower rainfall levels. Given the influence of rainfall on discharge rates, historical sites within these areas faced threats from fluctuations in water volume during wet and dry seasons. However, projections from a climate model (RCP45 scenario) suggest that rainfall will increase in both the upper and lower parts compared to the middle sub-region, with discharge rates following historical trends across seasons. These changes significantly heighten the likelihood of water-related hazard events, amplifying the risk exposure of urban areas under study. This analysis underscores the baseline scenario of major hazards in the region, where precipitation emerges as the primary influencing factor for all water-related hazards. Certain factors, such as slope, elevation for flash floods, and groundwater and soil type for droughts, are more hazard-specific (see **Table 6**).

Table 6. Factors influencing water-related hazards in sub-region.

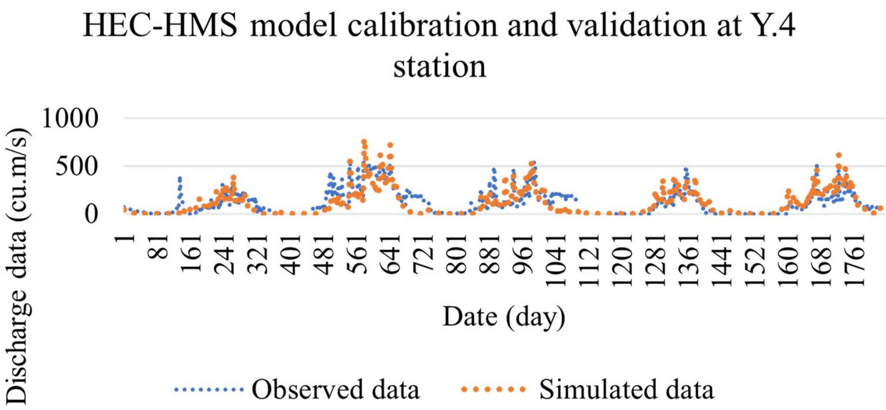
Hazards	Main factors	Sub factors	Weighted score	Rank
River flood	Natural	Precipitation	0.334	1
		Slope	0.118	4
		Elevation	0.104	5
		Soil type	0.082	6
	Anthropogenic	Natural and green surface areas	0.215	2
		Distance from river	0.148	3
Flash flood	Natural	Precipitation	0.438	1
		Slope	0.131	3
		Elevation	0.107	4
		Soil type	0.070	5
	Anthropogenic	Natural and green surface areas	0.253	2
Drought	Natural	Precipitation	0.418	1
		Soil type	0.091	4
		Existing groundwater	0.117	3
	Anthropogenic	Natural and green surface areas	0.245	2
		Distance from rivers	0.061	6
		Water storage	0.069	5

Source: Adopted from the interviews with 23 local decision-makers through the AHP analysis (2020)

4.3. Individual and Multiple Hazard Assessments

4.3.1. River Flood Hazard

Simulation models HEC-HMS and HEC-RAS were employed to mimic rainfall-to-runoff processes in the low Yom River basin (YRB) from 1988 to 2017, producing flood inundation maps at five-year intervals (2006, 2011, 2016). Calibration and validation ensured model reliability, confirming its suitability. Historical discharge at Y.4 station was analyzed using data from various years, revealing discrepancies between simulated and observed discharge, with better agreement in some years than others (Figure 6). Statistical analysis yielded acceptable Coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) values (0.50 - 0.75, **Table 7**). Despite generally satisfactory results, simulated discharge occasionally underestimated observed discharge. MSKT exhibited significant flood hazards in 2006, 2011, and 2016, primarily in its western region, while areas along the Sukhothai River were also prone to high to very high degrees of river hazard (**Figure 7(a)-(b)**).

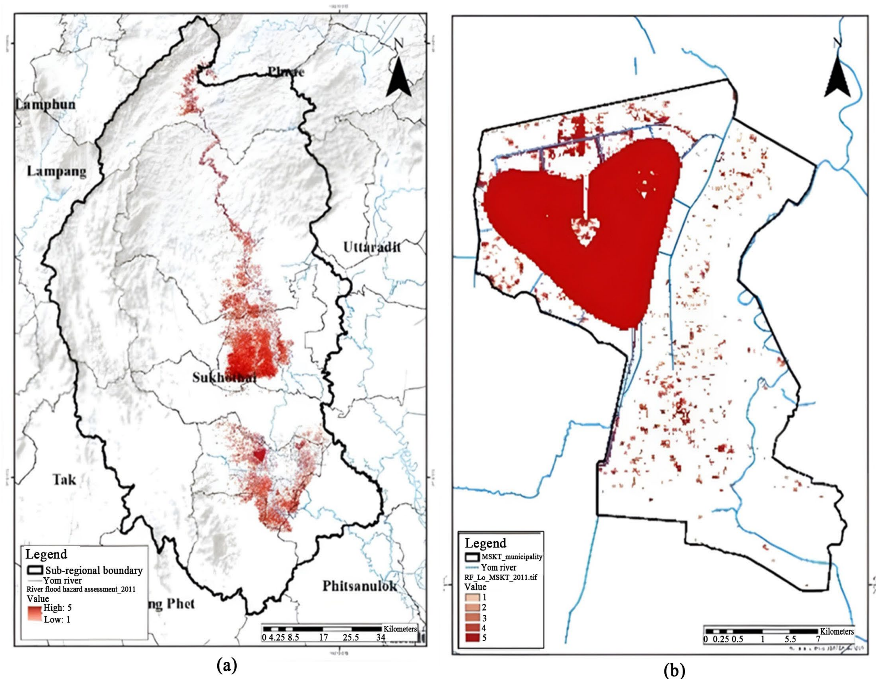


Source: Based on RID (2017) using HEC-HMS simulation

Figure 6. HEC-HMS model calibration and validation at Y.4 station.

Table 7. Statistical indicators of calibration and validation for HEC-HMS - Y.4 station.

Parameters	Y.4 station	
	Calibration	Validation
Coefficient of determination (R^2)	0.52	0.72
Nash-Sutcliffe efficiency (*NSE*)	0.50	0.71
Percent Bias (*PBIAS*)%	0.54	0.46
Volume ratio (V_r)	0.94	1.05
Root Mean Square Error (*RMSE*)	38.33	7.77



Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Based on RID (2017); LDD (2017) and USGS (2017) using HEC-RAS simulation and spatial analysis

Figure 7. (a) River flood hazard maps in 2016 at sub-regional scale; (b) river flood hazard maps in 2011 in MSKT.

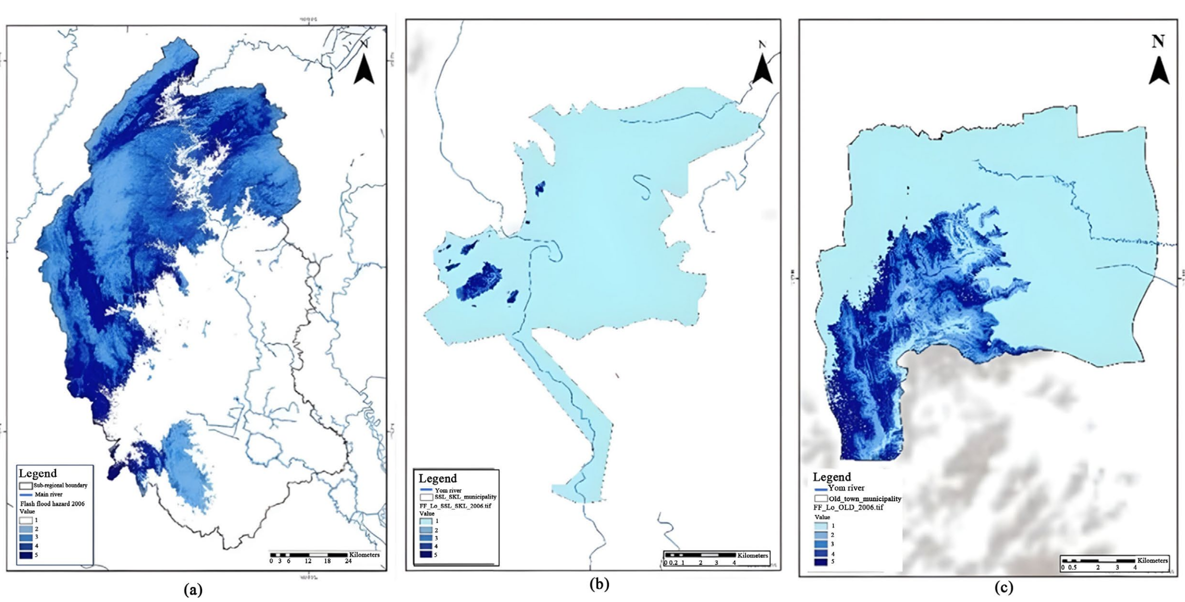
4.3.2. Flash Flood Hazard

The flash flood hazard assessment employed MCDA and GIS techniques, with predetermined influence factors and weights outlined in **Table 8**, adjusted per literature review. Peak rainfall data from seven stations covering the sub-regional area from May to September in 2006, 2011, and 2016 were considered, with precipitation identified as the most influential factor. Slope, elevation, soil type, and land use were also assessed. Slope and elevation were analyzed using GIS software, with higher ratios assigned to steeper slopes (>20 degrees) and elevations above 800 meters, respectively. Soil type, categorized into five classes based on water absorption abilities, and land use type, divided into vegetation, soil, and water body, were also considered. Sensitivity checking involved historical flash flood events recorded by local authorities and interviews with decision-makers and residents. The assessment revealed varying hazard levels across the region, with higher concentrations in mountainous areas. Flash flood hazards were generally low in municipalities, with MSKT experiencing no flash floods due to its lowland location. Overall, the study suggests that flash flood hazards primarily occur in highlands and hilly areas with steep slopes.

Table 8. Factors and their weights for the Flash Flood Hazard Assessment.

Hazards	Main factors	Sub factors	Weighted score	Class	Ratio
Flash flood	Natural	Precipitation (mm.)	0.438	>110	5
				90 - 110	4
				60 - 90	3
				30 - 60	2
				0 - 30	1
		Slope (Degree)	0.131	>20	5
				15 - 20	4
				10 - 15	3
				5 - 10	2
				0 - 5	1
		Elevation (m.)	0.107	>800	5
				600 - 800	4
				400 - 600	3
				200 - 400	2
				0 - 200	1
		Soil type	0.070	Clay loam	5
				Silk clay loam	4
				Sandy clay loam	3
				Loam	2
				Sandy loam	1
	Anthropogenic	Natural and green surface areas	0.253	Vegetation	5
				Soil	3
				Water body	1

Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Adopted from Skilodimou et al. (2019); Kazakis et al. (2015) and Stefanidis and Stathis (2013)



Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Based on TMD (2017); LDD (2017) and USGS (2017) using weighted overlay technique

Figure 8. (a) Flash Flood Hazard Maps in 2006 at Sub-Regional Scale; (b) Flash Flood Maps in 2006 in SSL and SKL; (c) Flash Flood Maps in 2006 in OLT.

4.3.3. Drought Hazard

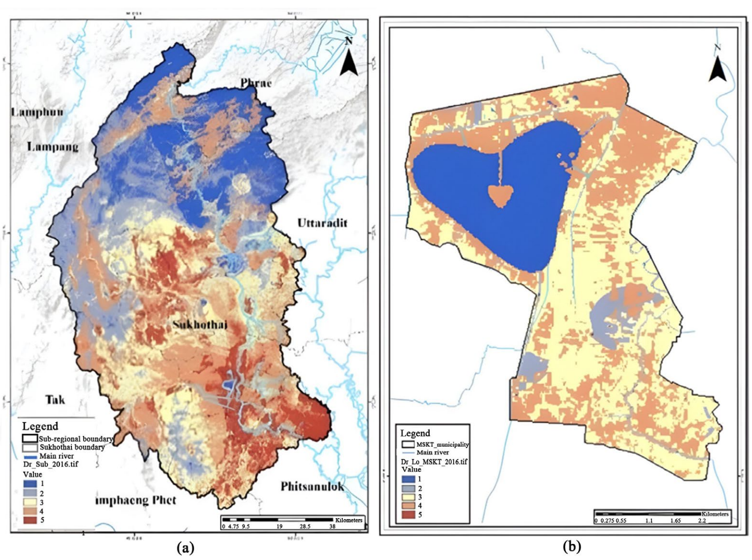
The drought hazard assessment utilized a methodology akin to the flash flood hazard assessment, with predetermined influencing factors and their respective weights outlined in **Table 9**. Notably, a very high hazard hotspot was pinpointed in the upper and western sub-region (**Figure 9(a)**). Examining rainfall data from seven selected stations spanning January to December in 2006, 2011, and 2016, precipitation emerged as the primary determinant of drought hazard. Low rainfall heightens the risk of drought, potentially exacerbating other contributing factors. Soil type, crucial for water absorption, was classified into five main categories based on their drought hazard mitigation abilities: Sandy loam, Loam, Sandy clay loam, Silt clay loam, and Clay loam, assigned values from 5 to 1 respectively. Sandy loam, with its superior water absorption capacity, garnered the highest rating.

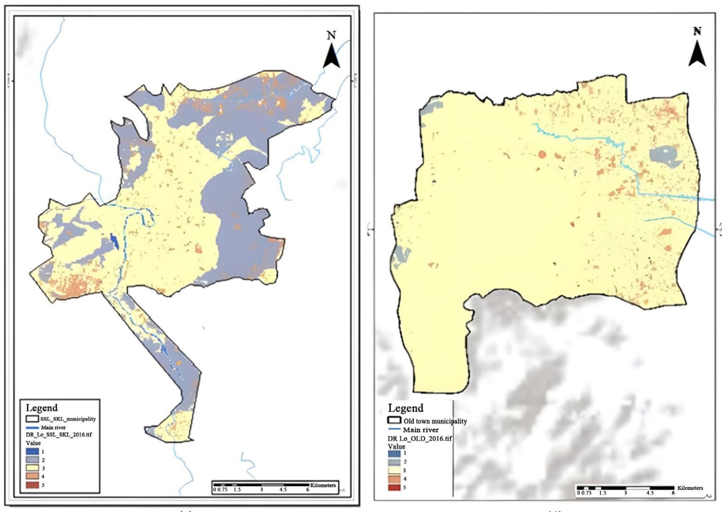
Existing groundwater availability significantly influences drought hazard. Low groundwater volume (<2 m^3/hr.) indicates high drought hazard and is given the highest weight. This study categorizes groundwater volume into five classes based on surface and subsurface water levels. Land use type, including natural and green surface areas, is another crucial factor classified into three classes: vegetation, soil, and water body, with values assigned accordingly. Proximity to river networks correlates inversely with drought occurrences, categorized into five distance classes. Water storage, classified into five classes based on the Natural Break (Jenks) method, also affects drought hazard. Municipalities, including MSKT, SSL, SKL, and OLT, generally face moderate to high drought hazards, except in 2011 due to heavy rainfall during a historical flood event (see **Figure 9(b)-(d)**).

Table 9. Factors and their weights for the Drought Hazard Assessment.

Hazards	Main factors	Sub factors	Weighted score	Class	Ratio
Drought	Natural	Precipitation (mm.)	0.418	≥2.0	1
				1.5 to 1.99	2
				1.0 to 1.49	3
				−0.99 to 0.99	4
				−1.0 to −1.49	5
				−1.5 to −1.99	6
				−2.0 and less	7
		Soil type	0.091	Sandy loam	5
				Loam	4
				Sandy clay loam	3
				Silk clay loam	2
				Clay loam	1
		Existing groundwater (m^3/hr.)	0.117	<2	5
				2 - 10	4
				10 - 15	3
				15 - 20	2
				>20	1
		Natural and green surface areas	0.245	Vegetation	1
				Soil	3
				Water body	5
	Anthropogenic	Distance from rivers (m.)	0.061	>1000	5
				600 - 1000	4
				400 - 600	3
				200 - 400	2
				0 - 200	1
		Water storage (MCM)	0.069	<4.822	5
				4.822 - 7.265	4
				7.265 - 9.144	3
				9.144 - 11.586	2
				> 11.586	1

Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Adopted from Palchaudhuri and Biswas (2016) and Tri et al. (2019)





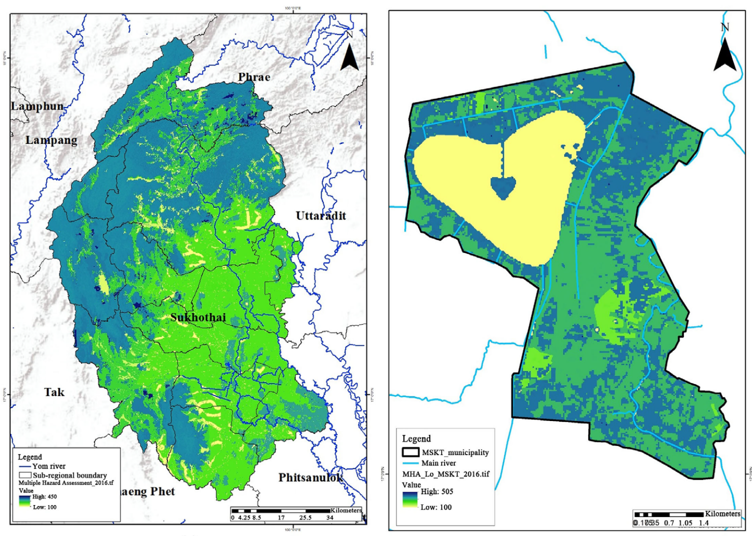
(c) (d)

Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Based on TMD (2017); LDD (2017) and USGS (2017) using weighted overlay technique

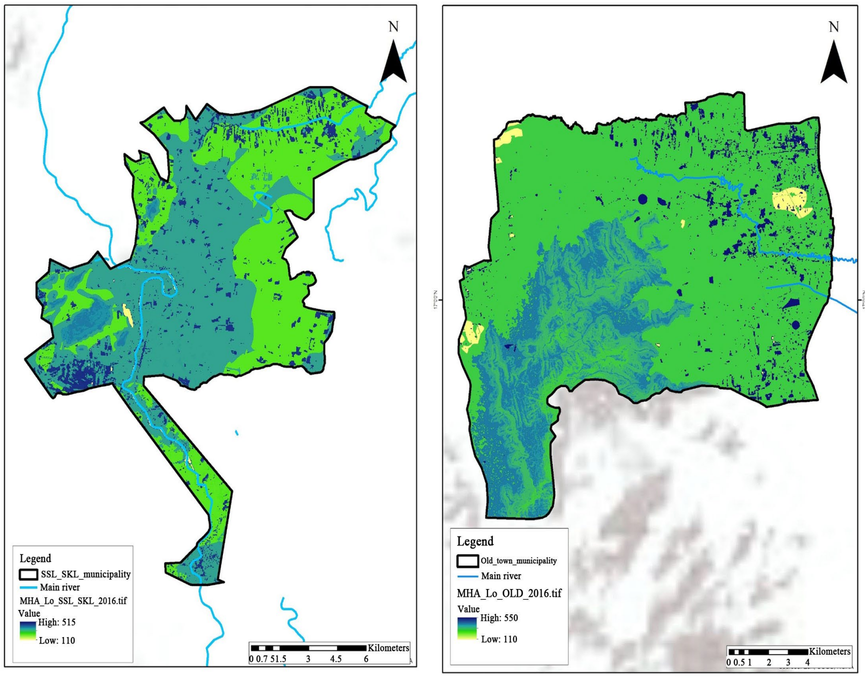
Figure 9. (a) Drought map in 2016 at sub-regional scale; (b) Drought map in 2016 in MSKT; (c) Drought map in 2016 in SSL and SKL; (d) Drought map in 2016 in OLT.

4.3.4. Multiple Hazard Assessment

Multiple hazards are predominantly concentrated in the upper and western regions of the sub-regional area, including river flood, flash flood, and drought hazards. In contrast, the middle and lower sub-regions face primarily high river flood hazards and moderate drought hazards (see **Figure 10(a)**). At the municipal level, major multiple hazards were observed in 2016. In MSKT (see **Figure 10(b)**), river flood hazards were high, while drought hazards ranged from moderate to high. SSL and SKL (see **Figure 10(c)**) experienced moderate to high drought hazards and very low flash flood hazards. Similarly, in OLT (see **Figure 10(d)**), drought hazards were moderate, and flash flood hazards were very low. Overall, areas with high degrees of river flood or flash flood hazards tend to exhibit moderate levels of drought hazards.



(a) (b)



(c) (d)

Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Based on RID (2017); TMD (2017) and LDD (2017) using weighted overlay technique

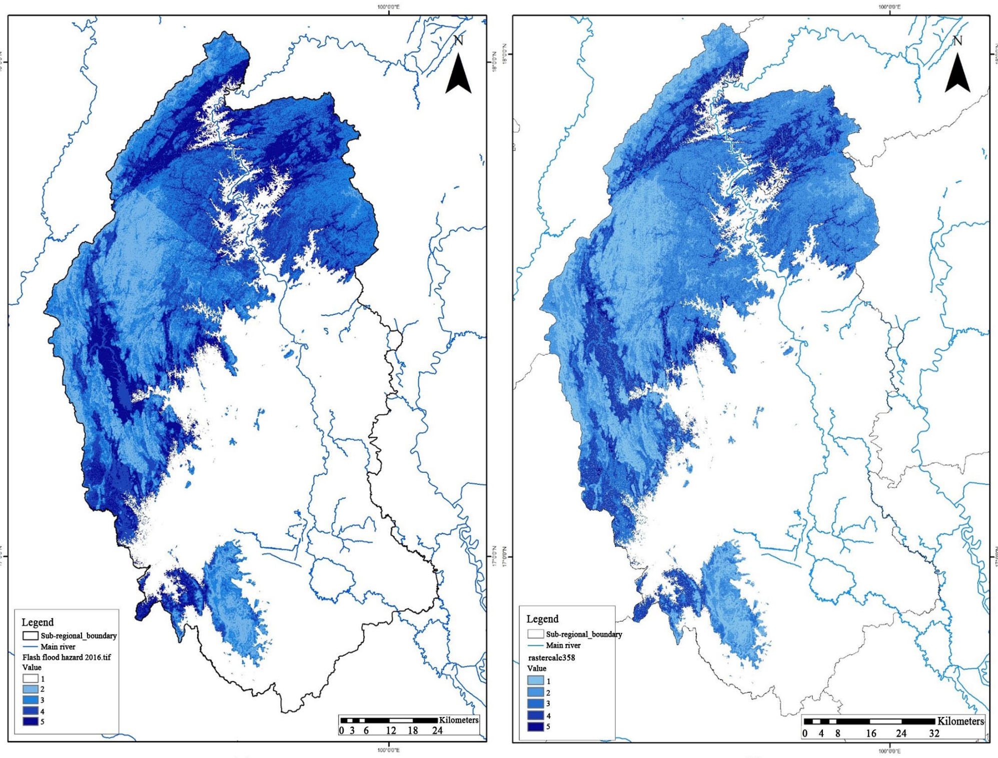
Figure 10. (a) Multiple hazard assessment map in 2016 at sub-regional scale; (b) Multiple hazard assessment maps in 2016 in MSKT; (c) Multiple hazard assessment maps in 2016 in SSL and SKL; (d) Multiple hazard assessment maps in 2016 in OLT.

4.4. Potential Nature-Based Solutions for Multiple Hazard Reduction

A Nature-based Solutions (NBS) study has examined how increasing natural and green surface area can potentially reduce the severity of multiple water-related hazards. As precipitation is the most influential factor, another NBS evaluated is a nature-integrated water storage which is designed to improve water management during wet and dry seasons.

4.4.1. Increase in Natural and Green Surface Areas

The study delved into the role of natural and green spaces in mitigating flash flood hazards, particularly in regions dominated by hills. Employing simulation modeling, a scenario analysis compared the base case with an alternative scenario, wherein 7% more green space was integrated into the study area. Sub-regional analysis revealed a notable decrease of 6.83% in the share of very-high-hazard surface area between the base and alternative cases (Figure 11), indicating the potential of increased vegetation to alleviate flash flood severity and reduce hazards. Moreover, the average degree of flash flooding hazards exhibited a drop from 2.19 in the base case to 1.65 in the alternative scenario, as evidenced by scoring results, underscoring the efficacy of vegetation expansion in hazard reduction.



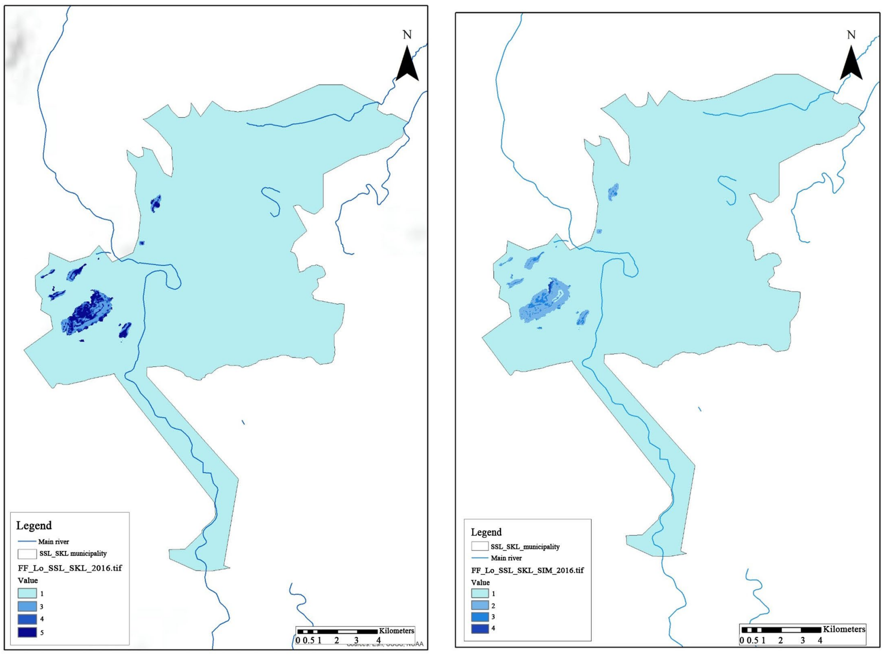
(a) (b)

Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Based on TMD (2017); LDD (2017) and USGS (2017) using weighted overlay technique

Figure 11. Base case (a) and alternative case (b) with increasing natural and green surface area by 7 percent in the sub-region in 2016.

At the municipal scale, there are minor variations in the shares of surface areas across different hazard degrees between the baseline and alternative scenarios. Specifically, in SSL and SKL, the share of very-high-hazard surface area relative to the total studied area would decrease by 0.96 percent, while the high-hazard area would decrease by 0.56 percent. Conversely, the low-hazard area would increase by 1.9 percent. Regarding the average degree of flash flood hazards, the scoring result decreases marginally from 1.07 in the base case to 1.03 in the alternative scenario (**Figure 12**).

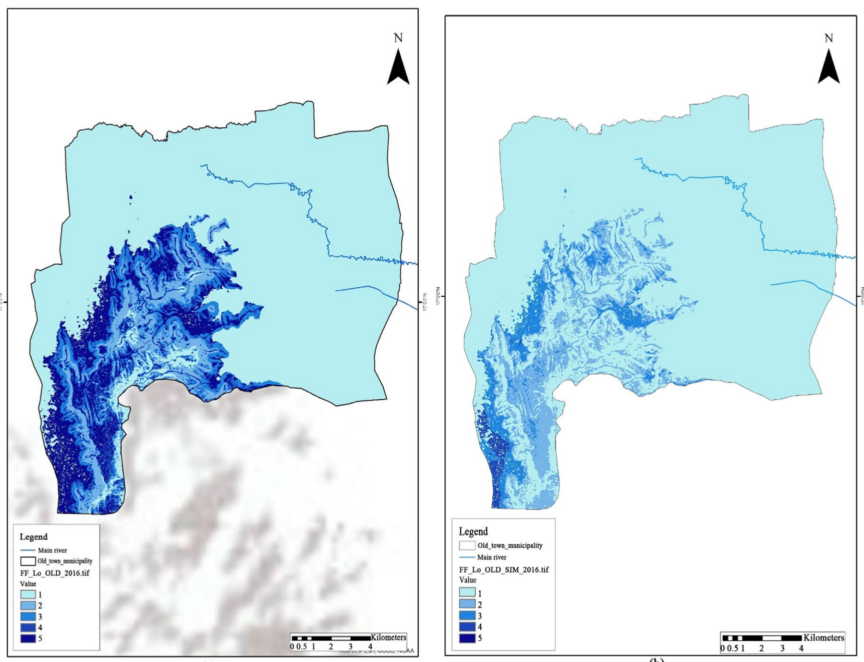
In OLT, flash flood hazards are generally low, except in areas with highlands and steep slopes. The share of very-high-hazard surface area relative to the total studied area would decrease by 9.3 percent, while the high-hazard area would increase by 4.07 percent (**Figure 13**). Increasing natural and green surface areas by 7 percent tends to reduce the severity of flash flood hazards by 20.69 percent at the sub-regional scale and, respectively, by 1.97 percent and 15.91 percent in SSL/SKL and OLT. However, the impact would be relatively limited in urbanized areas where flash flood hazard is generally low. This difference in flash flood hazard reduction is reasonable, given that the hilly areas with a higher degree of flash flood hazards are located in the northwest of the studied sub-region, which does not encompass SSL/SKL and OLT.



(a) (b)

Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Based on TMD (2017); LDD (2017) and USGS (2017) using weighted overlay technique

Figure 12. Base case (a) and alternative case (b) with increasing natural and green surface area by 7 percent of a local area investigating in SSL and SKL in 2016.



(a) (b)

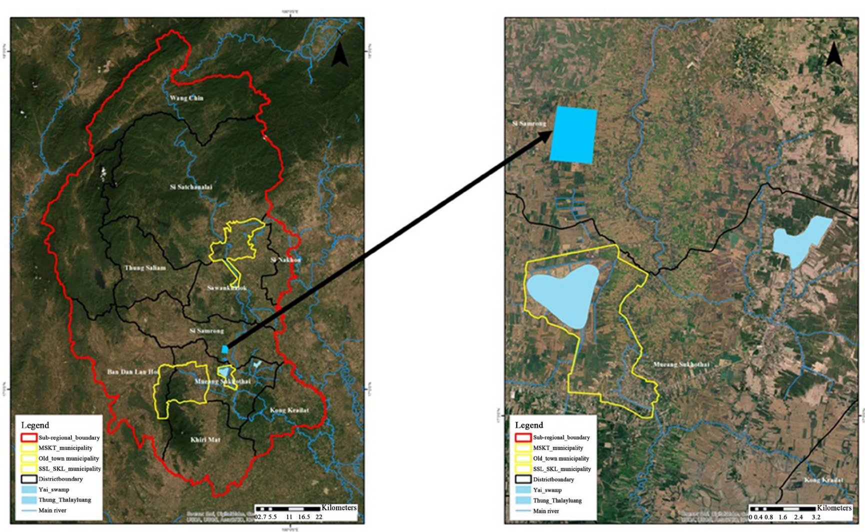
Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Authors' analysis (2019), based on TMD (2017); LDD (2017) and USGS (2017) using weighted overlay technique

Figure 13. Base case (a) and alternative case (b) with increasing natural and green surface area by 7 percent of a local area investigating in OLT in 2016.

The study on the integration of natural and green spaces in hilly regions to mitigate flash flood hazards highlights significant benefits, including a 6.83% reduction in very-high-hazard areas and a decrease in the average hazard degree from 2.19 to 1.65. A comprehensive cost-benefit analysis reveals that the benefits of reduced flood damage, enhanced property values, and improved environmental and social conditions outweigh the costs of implementation, maintenance, and opportunity. However, potential negative effects such as displacement, maintenance challenges, high initial costs, and economic trade-offs need to be addressed through careful planning and community engagement to ensure the success and sustainability of the project.

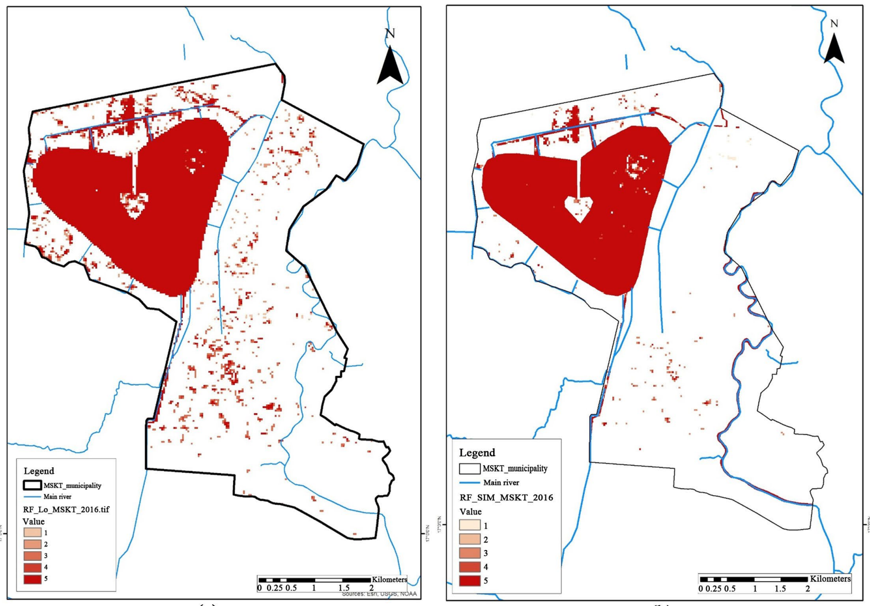
4.4.2. Nature-Integrated Water Storage

A nature-integrated water storage can effectively reduce flood risk and address water consumption issues in MSKT. The storage, designed with a 5-square-kilometer area, 15-meter depth, and 75 million cubic meters capacity, is situated in the upper MSKT to safeguard the city center from river floods. Additionally, restoring natural wetlands in Si Samrong district supports flood prevention and ensures water supply during dry seasons. The nature-integrated water storage offers balanced water control year-round, benefiting MSKT and its vicinity. To simulate the effects of the storage, the hydrological model that incorporated various operation scenarios, such as controlled water release during peak rainfall and water retention during dry periods. The model assumed optimal operation protocols, including maintaining water levels to prevent overflow and ensuring sufficient water storage for dry periods to maximize flood mitigation and water conservation. Simulation modeling indicates a significant decrease of 26.86 percent in high-hazard areas and a notable 31.75 percent increase in low-hazard areas, suggesting a shift from very high to moderate hazard levels, particularly benefiting MSKT municipality and surroundings.



Source: Based on TMD (2017); LDD (2017) and USGS (2017)

Figure 14. The location of nature-integrated water storage at sub-region scale.



(a) (b)

Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high; Source: Based on TMD (2017); LDD (2017) and USGS (2017) using HEC-RAS and spatial analysis

Figure 15. Base case (a) and alternative case (b) with the nature-integrated water storage in MSKT in 2016 for a river flood hazard assessment

Given the cost-benefit analysis and potential negative consequences, the nature-integrated water storage construction project involves an initial cost of 1 billion baht with a construction period of 720 days (This estimate is based on the 2008 building cost of a

nature-integrated water storage, Thung Talayluang; with land acquisition in SKT in 2019, the construction rise from 2008 to 2019 is predicted to be 10%.). Assuming operational costs at 1% of the initial cost annually and a project duration of 30 years with a 5% discount rate, the project currently shows negative economic viability. By increasing the annual benefits to 90,000,000 THB through enhanced agricultural productivity, water sales, flood prevention, and tourism development, the present value of benefits could sufficiently surpass the total costs, making the project economically viable. However, potential negative effects such as environmental impact, displacement of communities, and maintenance challenges must be carefully considered and mitigated.

4.5. Discussions

Urban growth in Sukhothai province has notably increased the region's vulnerability to water-related hazards, such as floods and droughts. The transition from agricultural to urban areas, particularly around the CBD in Si Satchanalai, has led to significant alterations in land use and water flow patterns. This urban expansion has heightened exposure to these hazards, resulting in socio-economic impacts, including shifts in employment, income distribution, and social equity. These changes particularly affect low-income and agricultural-dependent populations, underscoring the need for improved infrastructure and targeted hazard mitigation strategies.

The key variables influence the severity of multiple hazards, including precipitation, natural and green surface areas, nature-integrated water storage, and discharge rates. The variability of these factors across time and space is crucial, as irregular rainfall can disrupt discharge rates, leading to extreme events and exacerbating hazard severity. The findings indicate that river floods are common in lowlands along the Yom River, while flash floods are more frequent in steep-sloped areas during wet seasons. Drought hazards, conversely, are prevalent across the sub-region during dry periods. Implementing nature-integrated water storage systems designed to capture 50% of rainfall in critical areas could optimize discharge rates, thereby mitigating hazard severity and reducing the proportion of high-risk areas.

When comparing these findings with studies from the Mekong River Basin—an area characterized by diverse climates, urbanization trends, and water management practices—the broad applicability of NBS becomes evident (Yang et al., 2023; Dang et al., 2021; Cerè et al., 2017; Limsakul and Singhruck, 2016; Cohen et al., 2012). The Mekong Basin's varied climatic conditions and rapid urbanization underscore the effectiveness of NBS in managing flood risks and stormwater. This study, focusing on the Mun River Basin in Thailand, addresses a gap in NBS research within Southeast Asia by utilizing MCDA-GIS analysis for flood hazard reduction (Penny et al., 2023; Seddon et al., 2020).

Strategies such as wetlands, reforestation, and crop diversification have been shown to significantly reduce flood hazards, particularly when combined with NBS approaches. Although the nature-integrated water storage project initially appears economically unfeasible due to high construction costs and projected operational expenses, enhancing annual benefits through improved agricultural productivity, water sales, flood prevention, and tourism could make the project viable. It is crucial to carefully consider potential negative impacts, such as environmental degradation and community displacement, to ensure a balanced approach. This socio-economic analysis provides a robust foundation for policymaker recommendations, balancing economic and environmental factors to guide effective decision-making.

To enhance the broader applicability of our findings, we propose a framework for adapting these methods to other regions. For instance, similar nature-integrated water storage systems could be implemented, such as those in Mae Suai, Chiang Rai (Busaman et al., 2021), and Dok Krai, Rayong (Soytong et al., 2023), as well as internationally in regions like the Loess Plateau in China (Chen et al., 2022; Yu et al., 2020) and the Tama River Basin in Japan (Muto & Yokokawa, 2022). This framework involves integrating localized data on precipitation, discharge, and land use, and considering site-specific factors such as terrain and socio-economic conditions. A targeted cost-benefit analysis should be conducted to evaluate both the economic viability and potential negative impacts of NBS, including community displacement and land use changes. By tailoring the framework to regional contexts and incorporating socio-economic impacts, we can enhance resilience and effectively mitigate hazards across various regions.

5. Conclusions and Recommendations

Key factors influencing multiple hazard occurrence and reduction were identified and hierarchized by local decision-makers. River floods are predominantly found in lowlands along the Yom River, while flash floods are more frequent in steep-sloped areas during the wet season, and drought hazards are widespread across the sub-region during dry periods. The implementation of nature-integrated water storage, capturing 50% of rainfall in key sub-regions, is shown to effectively mitigate the severity of these hazards by optimizing discharge rates and reducing high-risk areas. This approach not only aligns with prior research on discharge reduction but also demonstrates the broader applicability of NBS managing flood risks across diverse regional contexts, such as the Mekong River Basin. Additionally, the study addresses a gap in NBS research, highlighting the effectiveness of strategies like wetlands, reforestation, and crop diversification in reducing flood hazards, particularly when combined in integrated approaches. Increasing natural and green surface areas, as well as having nature-integrated water storage, tend to be helpful in reducing multiple hazards. Both measures can moderate the severity of multiple water-related hazards. They can also reduce affected surface areas at sub-regional and local scales.

The study faced some limitations, including location-specific key factors and the exclusion of some potential variables due to data inaccessibility. Reliance on historical data limits predictive power, and the evaluation of NBS for hazard reduction is only demonstrated at a sub-regional scale, lacking local detail. Future research should explore additional factors, including a more comprehensive socio-economic analysis that considers the impacts of demographic changes, income distribution, and land use shifts on vulnerability to hazards. Testing NBS measures at various scales, incorporating projected data for improved predictive accuracy, and integrating socio-economic variables will enhance the relevance and effectiveness of hazard mitigation strategies. Additionally, the methods developed in this study should be subject to further testing for broader applicability across different regions and hazard types, with particular attention to socio-economic disparities that may influence hazard exposure and resilience.

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significant inputs during this study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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