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Multiscale Flood Disaster Risk Assessment in the Lancang-Mekong River Basin: A Focus on Watershed and Community Levels

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Abstract: Floods are one of the most frequent and costly natural hazards worldwide, causing significant damage to infrastructure, agriculture, and livelihoods. The Lancang-Mekong River is a major river in Southeast Asia, but the basin is prone to flood disasters that may be exacerbated by climate change. Therefore, to better understand disaster risk and tailor disaster risk reduction measures, this study conducted multiscale flood disaster risk assessments at the watershed and community levels using indicator-based and hydrodynamic model-based methods. Both methods adopted open data with the supplement of local survey data. The results of the study showed that the flood risk is generally higher in the lower reach of the river due to high levels of both hazard and vulnerability. However, the community-scale risk assessment revealed that high flood-risk communities exist in low-risk zones, and vice versa, when the flood risk was assessed at the watershed scale. Such phenomena can lead to inadequate community preparedness for flooding or unnecessary allocation of resources for flood mitigation measures. These findings provide valuable insights for the development of disaster risk reduction strategies, policies, and plans based on an understanding of the risks. Furthermore, they offer a basis for prioritizing and targeting resources, particularly in areas with high population density or vulnerable communities.

Keywords: disaster risk reduction; flood disaster risk assessment; multiscale assessment; Lancang-Mekong River

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1. Introduction

Floods are among the most frequent and costly natural hazards in the world. They affect millions of people each year, causing significant damage to infrastructure, agriculture, and livelihoods and resulting in loss of life and displacement. Between 1998–2017, floods affected more than two billion people worldwide [1]. Meanwhile, climate change is expected to intensify and exacerbate flood disasters in many parts of the world [2,3]. Therefore, flood disaster is a serious threat to sustainable development and a major challenge for disaster risk reduction (DRR) efforts around the world.

Lancang-Mekong River is a major river in Southeast Asia and is crucial to socioeconomic and environmental well-being. However, climate change has led to the occurrence of increasingly unpredictable floods, which pose a significant threat to the social and economic development of the Lancang-Mekong River Basin. To minimize these impacts, it is necessary to identify and assess the flood disaster risks associated, including their causes and potential consequences. Therefore, the issue of flooding in the given basin is a topic of great interest to researchers. Several scholars have conducted research in various areas related to floods in the region, such as trends and variability [4], flood mapping [5], and the impact of floods on the lower Mekong region [6], as well as vulnerability to flooding [7]. However, there is a relatively limited amount of research specifically focused on flood disaster risk assessment in the region. This may indicate a gap in the literature, which could be addressed through further research to better understand the nature and extent of flood risk in the region.

According to the definition from the United Nations Office for Disaster Risk Reduction (UNDRR), disaster risk is defined as “The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity” [8]. In terms of flood disasters, flood disaster risk assessment calculates the probability of flood disasters under different intensities. Flood disaster risk assessment has been one of the research hotspots in geography, disaster science, hydrology and hydrodynamics, and other natural science disciplines. There has been significant development in the theory, models, and methods, and it has undergone a process from qualitative to semi-quantitative to quantitative [9]. Extensive research has shown that several methods were used to assess flood disasters, such as the indicator-based method [10,11], remote sensing and GIS [12], and hydrological modeling [13–16]. Machine learning-based methods are also used to assist flood risk assessments, such as coupling the maximum entropy and the FLUS model to predict future urban waterlogging-prone areas in research [17]. The methods mentioned above have already been developed to a relatively mature stage and have been widely applied in risk assessments in various locations. However, there is still room for exploration in technical methods, such as factor selection, accuracy, and precision. Additionally, some studies have recognized that as globalization progresses, countries become increasingly interdependent, making it more likely for the impact of disasters to extend beyond national borders and affect multiple countries [18]. The level of cooperation between countries can affect the effectiveness of the entire river basin risk management for international river basins [19]. However, there has been little study in existing risk assessment research that considers international cooperation factors in risk assessments.

Meanwhile, the Sendai Framework emphasizes that disaster risk assessment should be conducted at all levels, from the local to the national and regional levels, and should involve the participation of multiple stakeholders, including communities, civil society organizations, academia, and the private sector. Many studies have been conducted from different scales for flood disaster risk assessment, from the global scale [20–22], regional scale [23,24], national scale [25,26], and local scale [27]. While a growing body of literature examines disaster risk at a specific scale, such as local, regional, and global levels, there is a lack of studies that compare how the risk of disasters varies across different geographical scales. This gap in the literature is significant because it limits the understanding of the variations in risk levels across different scales.

Therefore, to better understand the flood disaster risks at different scales in the Lancang-Mekong river basin, this study developed a multilevel approach for assessing the flood disaster at the watershed and community. This study aims to identify and quantify spatial disparities from a multiscale perspective and help to take proactive measures to reduce their risk. The results of the study are expected to contribute to disaster risk reduction efforts in the Lancang-Mekong River Basin. The multilevel approach developed in this study will help decision-makers to identify areas of high flood disaster risk and develop targeted measures to reduce the risks.

2. Methods and Data

2.1. Lancang-Mekong River Basin

The Lancang-Mekong River is an important international river in the South-Central Peninsula (Figure 1). The river originates in the Tibetan Plateau of China and is known as the Lancang River in China. After leaving China’s Yunnan Province, the river flows through Myanmar, Laos, Thailand, Cambodia, and Vietnam, and finally flows into the South China Sea west of Ho Chi Minh City, Vietnam, and is called the Mekong River by the downstream countries. With a total length of 4880 km, the river is the world's third-longest international river and the longest in Southeast Asia.

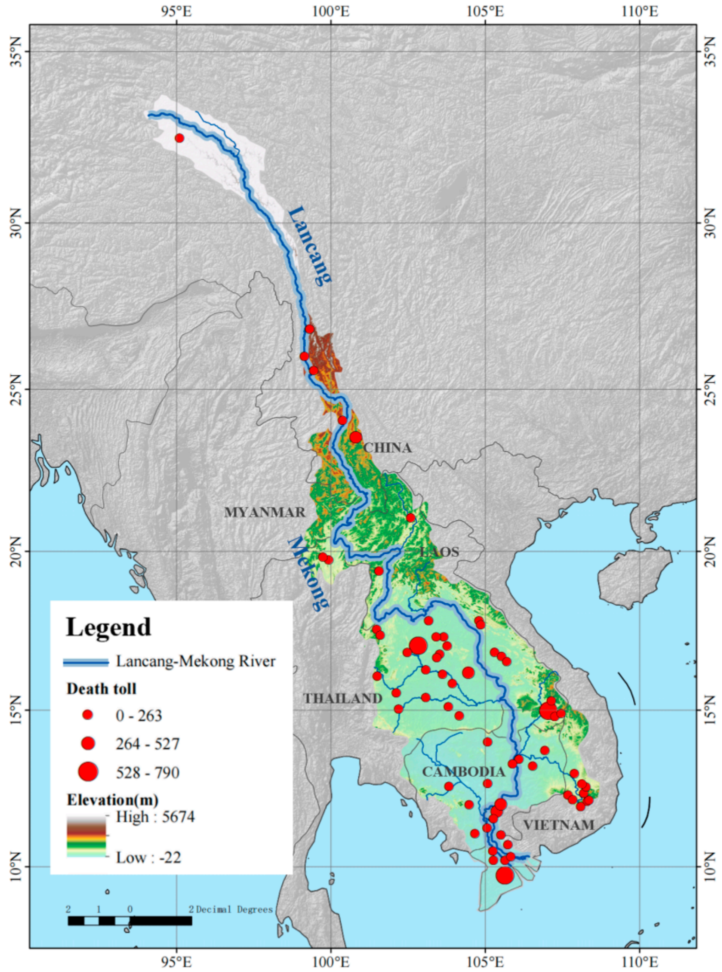

Figure 1. Spatial distribution of flood disaster events in Lancang-Mekong River basin (1985–2019) Data source: EM-DAT International Disaster database (https://www.emdat.be/ (accessed on 17 April 2020).

The Mekong River is one of the most promising areas for development in Asia and the world, as it is rich in agricultural, biological, forest, mineral, and water resources [28]. However, the Lancang-Mekong River faces numerous challenges, including climate change, water pollution, and unsustainable development practices. The river Basin is prone to floods due to natural conditions such as sizeable latitudinal span, topography, and precipitation variability. The upper reaches of the Lancang-Mekong River Basin in China are characterized by high mountain valley terrain, large drop-offs, and rapid currents. The middle and lower reaches have a tropical monsoon climate with abundant precipitation. They are controlled by both the southwest monsoon from the Indian Ocean and the northeast monsoon from the mainland, resulting in an uneven spatial and temporal distribution of precipitation in the basin. The Mekong River Commission (MRC), the average damage caused by floods in the Lower Mekong Basin (LMB) is about US$70 million per year [28]. According to EM-DAT [29], more than 200 floods have occurred in the Lancang-Mekong River basin since 1985, and the spatial distribution of flood disasters is shown in Figure 1.

Therefore, to better understand disaster risk in the Lancang-Mekong river, this study conducted multiscale flood disaster risk assessments at the watershed and community levels using indicator-based and hydrodynamic model-based methods. The overall roadmap of the multiscale risk assessment is presented in Figure 2.

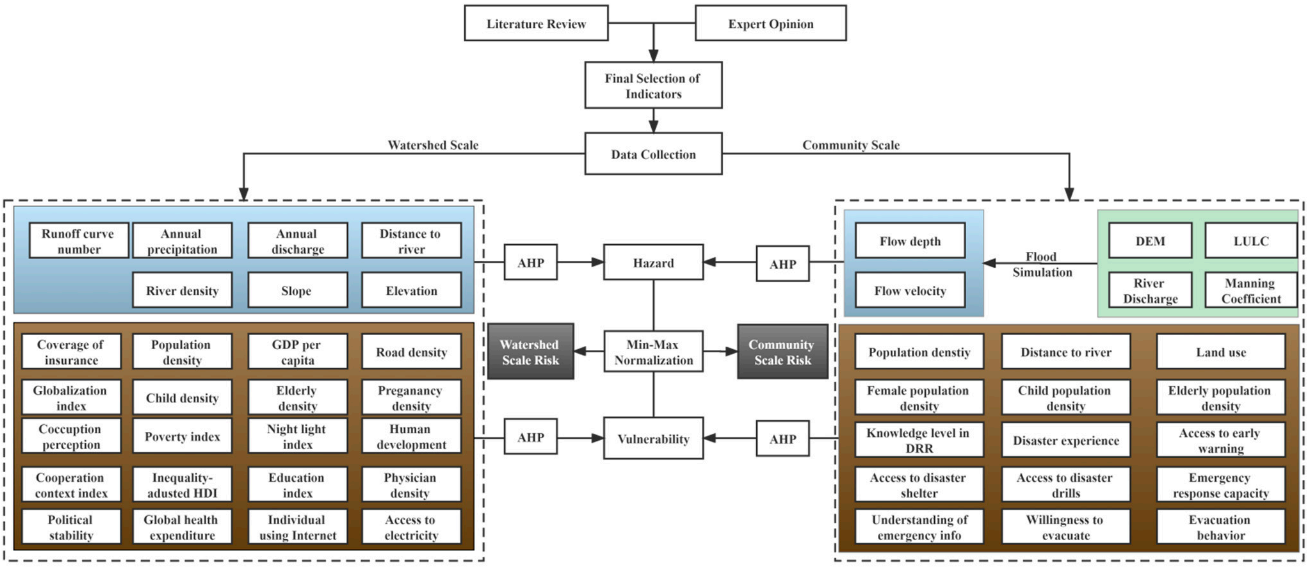

Figure 2. Roadmap of the multiscale risk assessment.

2.2. Indicator-Based Assessment

This study utilized the indicator-based approach to assess the flood disaster risk at the watershed scale. It is a method of assessing the potential risk of flood disaster in a particular area using a set of indicators. The Hyogo Framework for Action has also identified its importance as a key activity [9]. The indicators are selected based on their relevance to flood disaster risks in the study area, which can include a variety of factors, such as rainfall patterns, river flow rates, soil moisture, land use, population density, and infrastructure. However, there is no unified system and standard for indicator selection and a certain subjectivity in the risk assessment process.

This study selected the indicators of flood disaster risks for the Hazard and vulnerability, according to the well-accepted risk formula (Risk = Hazard × Vulnerability) [9]. After the indicator selection, this method will use mathematical and statistical methods to process and calculate the indicators to normalize the values of each indicator (usually set between 0 and 1). Followed by this, each indicator's weights would be assigned per the Delphi method, and then the risk values were calculated by overlaying the girded data. Finally, the risk values were graded into multiple levels (usually three, four, or five levels) by using the Natural Breaks. For example, Tang et al. (2005) selected multiple factors affecting the Hazard (terrain slope, number of days of heavy rainfall, river network buffer, standard area flood flow, flood history statistics, etc.) and vulnerability (population density, housing assets, percentage of arable land, industrial and agricultural output value per unit area, etc.) of flash floods. They completed a Red River basin's flash flood risk zoning map [11].

2.3. Hydrodynamic Model-Based Assessment

In this study, FLO-2D is used to estimate the impact range of flood disasters. By simulating the evolution of a major flood event, the flood dynamics parameters (water depth and flow velocity) during the flood event are obtained as important indicators for flood disaster hazard assessment. Flood inundation depth and flow velocity directly affect the degree of flood disaster. The larger the flood water depth and flow velocity, the larger the value of flood disaster risk.

Hydrodynamic modeling is one of the most commonly used small- and medium-scale flood hazard assessment methods. It is a numerical simulation of floods based on the natural characteristics of floods, considering the inundation area, inundation depth, flood ephemeris, and other factors. This method can calculate the possible inundation area, inundation depth, flow velocity, and other basic flood information of the river and the surrounding area under certain flood conditions so that it can visually reflect the flooding process.

FLO-2D is a two-dimensional (2D) flood simulation software developed by O'Brien to calculate the flow velocity, flow depth, and inundation extent of floods [30]. The Federal Emergency Management Agency (FEMA) has developed and certified it. This model was selected for the study due to its widespread use in flood risk assessment and management studies across different regions worldwide. Therefore, it has been tested and validated in many different scenarios, making it a reliable tool for predicting flood risk due to its efficient and stable numerical calculation capability [14–16]. Also, the FLO-2D model has several advantages over other similar models. For example, it allows for the use of high-resolution topographic data, which is essential for accurately modeling flood risk in complex terrain. It also allows for the simulation of both steady-state and unsteady flow conditions [30], which is important for simulating flood conditions in a river basin with complex hydrological processes at the local scale.

In general, FLO-2D is a volume-conserving model. It solves the Saint–Venant equations using an explicit central finite difference scheme, and thus, it can describe in more detail the flow wave propagation along the channel and floodplain [31]. The fluid flow is controlled by topography and flow resistance, and the 2D flood evolution is accomplished by numerical integration of the equations of motion and fluid volume conservation. The controlling equations include the continuity Equation (1) and the momentum Equation (2) [16].

$$\frac{\partial \mathrm{h}}{\partial t} + \frac{\partial hV}{\partial x} = i \tag{1}$$

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \tag{2}$$

2.4. Date Preparation

2.4.1. Hazard Data

1. Watershed scale

After reviewing relevant studies [32–35] and data availability, this study built the hazard assessment model for the watershed in three kinds: precipitation, river, and surface. Precipitation data were obtained from the National Oceanic and Atmosphere Administration of the US Department of Commerce (NOAA) [36], which were extracted to calculate the average annual precipitation. Regarding the river data, the annual discharge was driven from Global Runoff Database Center (GRDC) [37]. The distance to the river and river density was calculated in the ArcGIS based on the data from OpenStreetMap(OSM) [38]. Regarding the surface data, the slope and elevation were collected from the DEM data of the Shuttle Radar Topography Mission (SRTM) [39]; and the runoff curve number was from the GCN250 [40]. Details of the data are presented in Table 1.

Table 1. Hazard data for watershed scale.

Data Category	Assessment Criteria	Data Source	Time of Access
Precipitation	Average annual precipitation	NOAA	2018
River	Annual discharge	GRDC	2018
	Distance to river	OSM	2019
	River density		2019
Surface	Slope	SRTM	2018
	Elevation		
	Runoff curve number	GCN250	2020

2. Community Scale

For the community scale, this study selected six communities from China, Myanmar, Thailand, and Cambodia to conduct flood evolution simulation using the hydrodynamic model FLO-2D to project the hazard data. The inundation extent and depth of inundation are projected to complete the community-scale flood hazard assessment.

The heavy rainfall-type flood in early August 2020 was selected as the simulation object, and the data was from the MRC (Mekong River Commission) [41]. The flood evolution process was simulated in the research site. Table 2 presents their working conditions in detail.

Table 2. Working condition.

No	Country	Community	Hydrology Station	Flood		Discharge (m^3/s)	
				Start	End	Min	Max
1	China	Guan Lei	Jinghong	2020/8/6	2020/8/7	821	1361
2	Myanmar	Mong Yawng	Jinghong	2020/8/6	2020/8/7	821	1361
3	Myanmar	Mong Hpone	Chiang Sean	2020/8/8	2020/8/9	2450	3294
4	Thailand	Mae Ngeon	Chiang Sean	2020/8/8	2020/8/9	2450	3294
5	Thailand	Khong Chiam	Khong Chiam	2020/8/5	2020/8/6	8001	10,104
6	Cambodia	Stung Treng	Stung Treng	2020/8/6	2020/8/7	14,933	18,490

2.4.2. Vulnerability Data

1. Watershed scale

Based on the citations in relevant studies on a large scale [42,43], this study constructed the vulnerability index system on three dimensions: exposure, sensitivity, and adaptive capacity.

The exposure reflected how the elements at risk were distributed at flood disaster risk, including the population density data, GDP per capita, and road density. The more exposed to a disaster, the more vulnerable the elements at risk may be.

The sensitivity described how the elements at risk fare when exposed to flood disasters, which included data from two kinds: disadvantaged population density (Child population, Elderly population, and Pregnancy population), social development level (Multidimensional poverty index, Night light index, Human development index, Inequality-Adjusted HDI, and Education index).

The capacity specifies the ability of the whole society to adjust or cope with the impacts of disasters, which usually have a negative correlation with vulnerability. Effective flood disaster risk management in the international river cannot be separated from international cooperation within the basin countries [18,19]. Unlike many existing studies, this study specifically added some international political factors for vulnerability assessment by considering the Lancang-Mekong River basin as an international river in International cooperation. Therefore, this study extracted relevant data from three aspects: national implementation in DRR (Physician density, Global health expenditure, Individuals using the Internet, Access to electricity, and Coverage of social insurance programs), political environment (Corruption perception index and Political stability/no violence) and International cooperation (Globalization index and Cooperation context index).

Considering data availability and reliability, the population data, including density, child population, elderly population, and pregnancy population, were collected from the grided data of the World Pop (WP) [44]. Other data were extracted from the United Nations (UN) [45], World Bank (WB) [46], World Health Organization (WHO) [47], OpenStreetMap (OSM) [38], Transparency International (TI) [48], KOF Swiss Economic Institute and Cooperacy Organization [49]. Details of the data sources are displayed in Table 3.

Table 3. Vulnerability data for watershed scale.

Data Category	Assessment Criteria	Correlation with the Vulnerability	Data Source	Time of Access
Exposure	Population density	Positive	WP	2020
	GDP per capita	Positive	UN	2019
	Road density	Positive	OSM	2019
Sensitivity	Child population density	Positive	WP	2020
	Elderly population density	Positive	WP	2020
	Pregnancy population density	Positive	WP	2020
	Multidimensional poverty index	Negative	UN	2019
	Night light index	Negative	NOAA	2019
	Human development index	Positive	UN	2019
	Inequality-adjusted HDI	Positive	UN	2019
	Education index	Negative	UN	2019
Adaptive capacity	Physician density per 1000 pop	Negative	WB	2019
	Global health expenditure in GDP	Negative	WHO	2019
	Individuals using the internet	Negative	WB	2019
	Access to electricity	Negative	WB	2019
	Coverage of social insurance programs	Negative	WB	2019
	Corruption perception index	Negative	TI	2019
	Political stability/no violence	Negative	WB	2019
	Globalization index	Negative	KOF Swiss Economic Institute	2018
	Cooperation context index	Negative	Cooperacy Org.	2019

2. Community-scale

This study also constructed the vulnerability indicator system for the community scale on three dimensions: exposure, sensitivity, and adaptive capacity (Table 4). Regarding exposure, the data includes population density, distance to the river, and land use. The population density data were extracted from the World Pop (WP) [44]. The data of distance to the river was calculated in the ArcGIS from OpenStreetMap (OSM) [38], and that of land use was from Google Earth.

Table 4. Vulnerability data for community scale.

Data Category	Assessment Criteria	Correlation with the Vulnerability	Data Source	Time of Access
Exposure	Population density	Positive	WP	2020
	Distance to river	Negative	OSM	2018
	Land use	Positive	Google Earth	2020
Sensitivity	Female population density	Positive	WP	2020
	Child population density	Positive		2020
	Elderly population density	Positive		2020
	Knowledge level in DRR	Negative	Survey	2020
	Disaster experience	Negative		2020
Adaptive capacity	Access to early warnings	Negative	Survey	2020
	Access to disaster shelters	Negative		2020
	Access to disaster drills	Negative		2020
	Emergency response capacity	Negative		2020
	Capacity to understand emergency information	Negative		2020
	Willingness to evacuate	Negative		2020
	Evacuation behavior	Negative		2020

Considering that the community-scale vulnerability was more susceptible to local conditions [10], this study was set to use the first-hand field survey data at the community level regarding sensitivity and adaptive capacity. The survey data was from the UNEP-IEMP Sustainable Livelihoods Survey dataset, with over 800 samples in total in China, Myanmar, Thailand, and Cambodia. The field study used qualitative and quantitative methods to collect relevant information. The questionnaire and semi-structured interview methods were used to obtain information on public risk perception, disaster experience, and disaster knowledge level, as well as their willingness to evacuate and evacuation behavior in the face of disasters.

In terms of sensitivity, the data was from two dimensions: (1) the density of the disadvantaged population (female, child, and elderly) was from the World Pop, and (2) the individual differences in disasters (knowledge level in DRR and Disaster experience) was collected in the field survey. Also, for adaptive capacity, the data was from two dimensions, (1) the capacity of the community (the access to early warnings/disaster shelters and disaster drills and emergency response capacity); (2) the capacity of individuals (Capacity to understand emergency information, Willingness to evacuate and Evacuation behavior). Then, the survey data were processed by country, and the raster of each community was assigned according to the country in which they were located.

3. Results

3.1. Watershed Scale

The normalized results of the hazard assessment at the watershed scale are shown in Figure 3. Based on the natural breakpoint, the flood hazard values at the watershed raster scale were reclassified into four classes: very low (0~0.367), low (0.367~0.565), medium (0.565~0.702), and high (0.702~0.996). Among them, the area of very low hazard level was 81,875 km^2, the area of low hazard level was 219,325 km^2, the area of medium hazard level was 268,452 km^2, and the area of high hazard level was 207,700 km^2. Most areas of the river basin were above the medium hazard level, as the medium and high Hazard accounted for about 61.3% of the total area of the watershed. In contrast, the low Hazard accounted for 28.2% of the total area. The very low hazard area was the smallest in scope, accounting for only 10.5%.

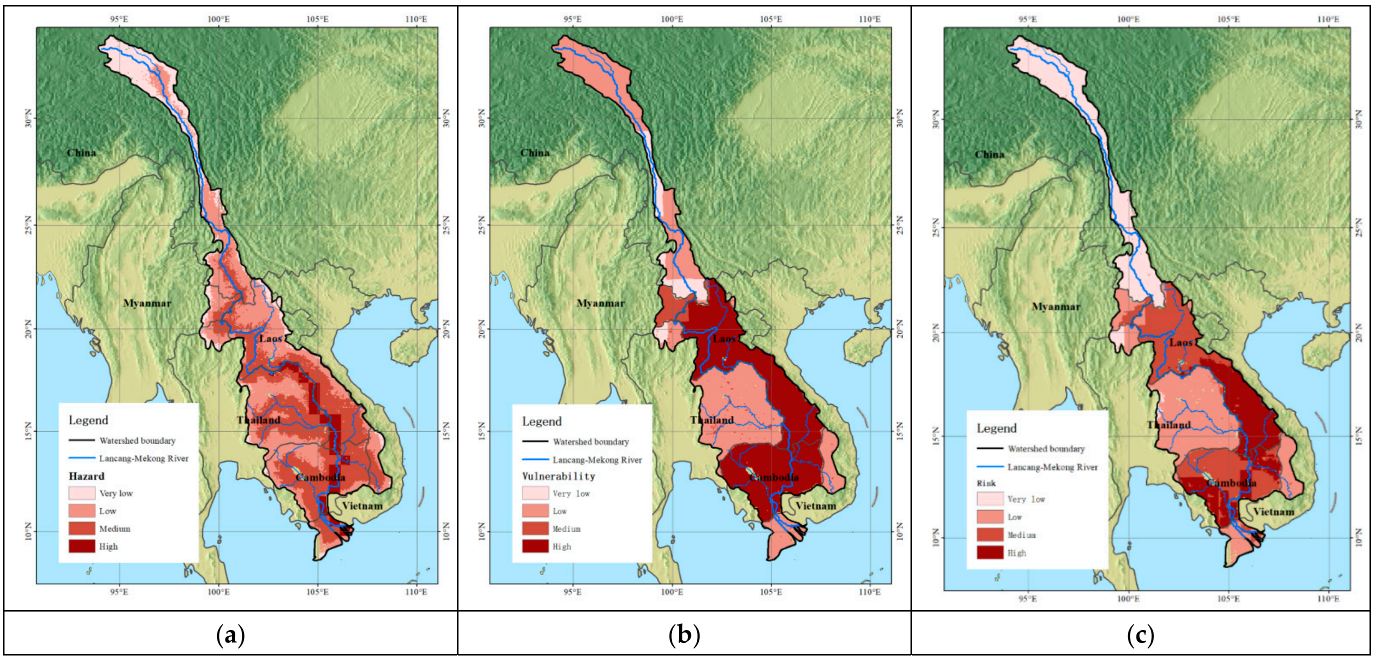

Figure 3. Assessment result at the watershed scale. (**a**) Hazard assessment result; (**b**) Vulnerability assessment result; (**c**) Risk assessment result.

Meanwhile, it can be found that the distribution of flood hazards in the basin has spatial characteristics. The flood hazard in the upstream area was lower than in the middle and downstream. High and medium levels of hazard were mainly distributed near the main streams and tributaries of the Lancang-Mekong River, especially in the middle and lower reaches of the river in Cambodia, Laos, and Vietnam.

The normalized vulnerability values for the entire river basin, with a mean value of 0.431, are displayed in Figure 3. The watershed vulnerability values were classified into four levels based on the natural breakpoint: very low (0~0.165), low (0.165~0.384), medium(0.384~0.537), and high (0.537~0.996). The size of each vulnerability level in the basin was unequally distributed, mainly in the low (45.3%) and high (44.7%) vulnerability areas. In contrast, very low and medium vulnerability areas were very small, accounting for only 10% of the total watershed area. Further, The distribution of vulnerability assessment results was somewhat related to national boundaries. Areas with high vulnerability concentrated in the left bank of the middle and lower Mekong (Laos, Cambodia, and Vietnam), accounting for more than half of the basin countries. Areas with low vulnerability were mainly located in the upper reaches of the Lancang River and the right bank of the Mekong River, concentrated in Yunnan Province, China, and Thailand. Therefore, although the proportion of high-vulnerability areas was nearly 44.7%, the high-vulnerability areas involved more countries and were more likely to cause greater impacts.

The risk value of each raster in the basin is first calculated by the risk formula ($R = H \times V$), and its values for the entire river basin ranged from 0~0.707 with an average value of 0.274. Then, the risk values were classified as very low, low, medium, and high based on the natural breakpoint method, and the risk assessment results are shown in Figure 3. From the analysis of watershed risk assessment results, most of the risk levels were around the low (31.7%) and medium (27.0%), while a few areas were distributed at a high level (19.7%). Regarding spatial distribution, the vast majority of low-risk areas were located in the upper reaches of the river basin in China. However, starting from the middle reaches to the lower reaches, the risk gradually increases. The risk was particularly high in the middle and lower reaches of the basin, in Laos and Cambodia.

3.2. Community Scale

The risk assessment results at the community level were also obtained by calculating the Hazard and vulnerability separately in this article, and its assessment process is displayed in Figure 4.

Based on the Flo-2D hydrodynamic model flood simulation described in Section 2.4.1, this paper multiplied the flow depth and flow velocity results to calculate the hazard results of six communities. The hazard results were then classified into four levels (very low, low, medium, and high) by the ArcGIS normalization and natural break method. According to the simulation results, all communities were inundated by the flood event in August 2020. Generally, the downstream communities were at higher hazard levels than the upstream communities, mainly because the downstream channel runoff was greater than the upstream channel in this flood simulation.

This study demonstrates the hazard assessment results at the community scale by taking Community 3 and Community 4 as examples. Community 3 and Community 4 were located adjacent to each other, respectively, in Myanmar and Thailand. This study has simulated the situations where both communities experienced the same flood event in August 2020, and the hazard assessment results are shown in Figure 4. Generally, in this flood event, the medium- to high-risk areas were mainly distributed near the main river channel and tributaries. Meanwhile, the result shows that Community 3 was at a much higher risk than Community 4. This assessment result was associated with the flood evolution process. Floods were easier to evolve due to the lower elevation near community 3. Conversely, floods evolved more difficult in Community 4 with lower flow depths and velocities, resulting in a lower hazard level.

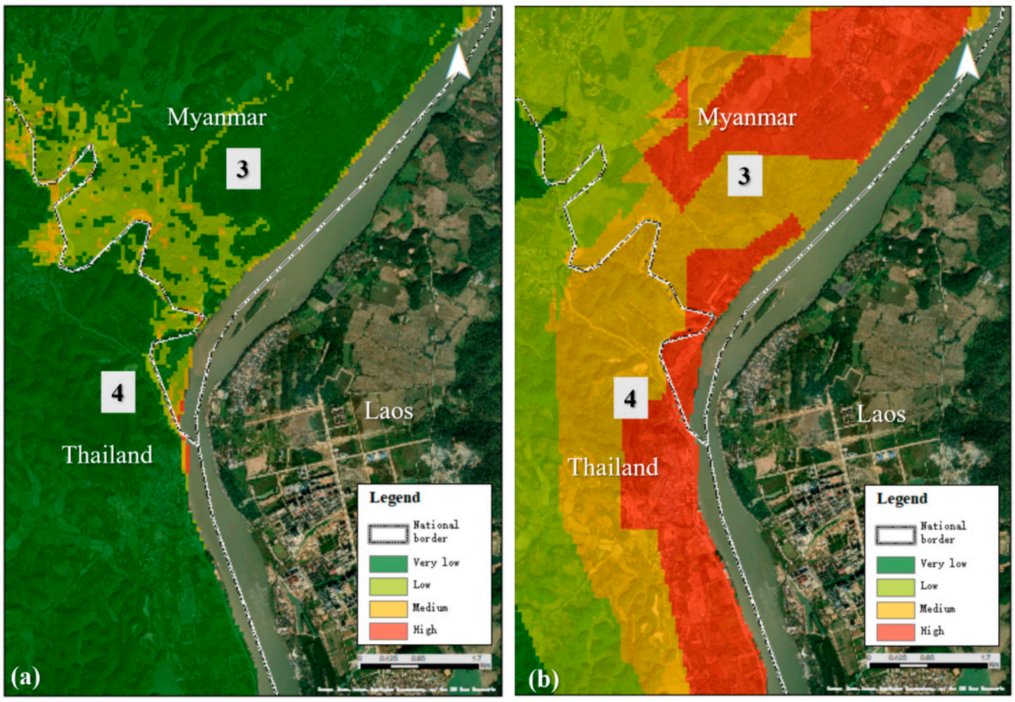

Figure 4. The assessment process for Communities 3 and 4 in Myanmar and Thailand. (**a**) Hazard assessment result; (**b**) vulnerability assessment result. (National border is based on the ESRI ArcGIS Online).

Regarding vulnerability, an indicator-based assessment method was also used at the community scale. Based on this, this study calculated the value for each community by overlaying the data of the three dimensions of vulnerability (Exposure, Sensitivity, and Adaptive capacity) as described in Section 2.4.2. The vulnerability assessment results were classified into four levels: very low, low, medium, and high.

In Figure 4, this study also demonstrates the vulnerability assessment results at the community scale by taking Community 3 and Community 4 as examples. It can be found that the vulnerability level was closely linked to the socioeconomic level and population distribution. The medium to high vulnerability level was mainly located around the residential areas along the Lancang-Mekong River.

The flood disaster risk assessment results were calculated by multiplying the normalized data of its hazard and vulnerability. The flood disaster risk at the community scale was reclassified into four classes: very low, low, medium, and high. The risk assessment results on the community scale were presented in a grid format (50 m $\times$ 50 m) in Figure 5. Generally, most areas were located at low risk in each community. It was found that the high-risk areas were mainly located in areas close to the river, especially those residential areas adjacent to the river. This was because many residential areas are located along the riverbank.

Community 1 and Community 2 were located in China and Myanmar in the upper reaches of the Lancang-Mekong River. Community 1 had a 1.3% of the total area at the medium- and high-risk levels and 8.8% at the low-risk area. Community 2 contained 1.4% of the medium- and high-risk areas and 6.3% of the low-risk areas. In comparison, in the same flood event, Community 1 had more risk areas (low, medium, and high) than community 2 because there was a more dense distribution of population and housing (higher vulnerability) near the riverbank in Community 1.

Regarding Community 3, there were 11.7% located in medium- and high-risk areas and 36.3% in low-risk areas. In contrast, Community 4 experienced lower levels, with only 0.4% at medium- and high-risk levels and 10.6% at low-risk levels. As previously discussed, this spatial variation was mainly attributed to the hazard assessment results.

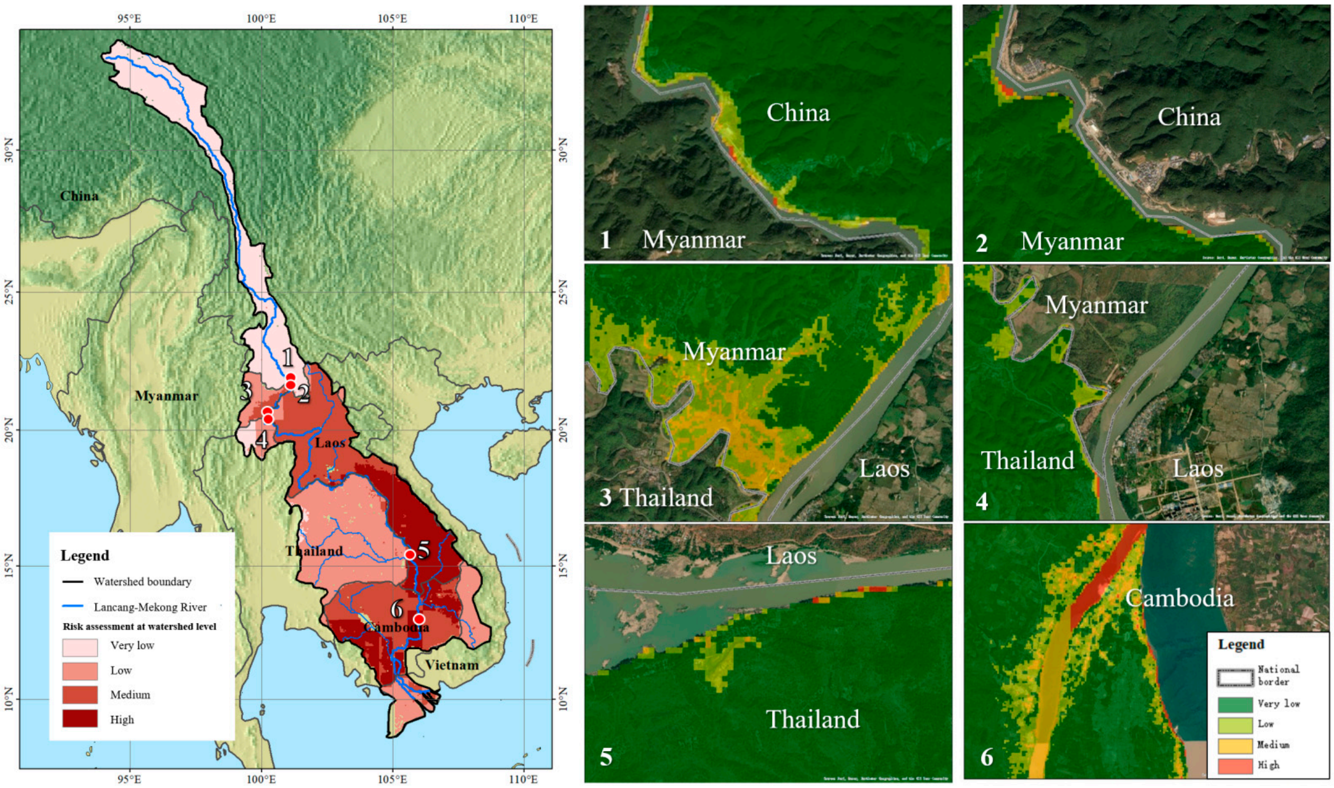

Figure 5. Risk assessment results at the community scale. (1) Guan Lei, China; (2) Mong Yawng, Myanmar; (3) Mong Hpone, Myanmar; (4) Mae Ngeon, Thailand; (5) Khong Chiam, Thailand; (6) Stung Treng, Cambodia. (National border is based on the ESRI ArcGIS Online).

Communities 5 and 6 were situated downstream of the Lancang-Mekong River. Community 5 had only 0.3% and 1.2% of the area in the medium- to high-risk and low-risk areas. Community 5 has a lower risk, although it is located downstream, due to the low flood risk due to the high DEM of the riverbank in Community 5, and thus this community has a relatively low flood risk. Conversely, the flood disaster risk in Community 6 was much higher. Many areas within the community were at risk, with 15.1% located at medium- to high-risk and 35.9% at low risk. It is because this community itself was located downstream, which normally with higher flood hazard. Meanwhile, there were still many populations and houses distributed near the riverbank (with high hazard levels), which increased the vulnerability of the flood disaster risk.

4. Discussion

4.1. Flood Disaster Risk at Watershed Scale

As displayed in Figure 3, flood disaster risk was found to be relatively high throughout the watershed, with the highest risk in the middle and lower reaches compared to the upper reaches. These findings align with the realities of the watershed, as depicted in Figure 1, where flood disasters were mainly concentrated in the middle and lower reaches from 1985 to 2019. The high risk in downstream areas was primarily due to the natural conditions, such as higher precipitation and well-developed water systems in the middle and lower reaches. These conditions led to higher hazard levels, particularly around the riverbank.

In addition, the middle and lower reaches of the basin had higher population density and greater economic development levels compared to the less populated upstream areas. The region also had well-known large cities such as Vientiane, Luang Prabang, Phnom Penh, Angkor Wat, and Ho Chi Minh, making it highly vulnerable to disasters. The combination of natural conditions and human factors in the middle and lower reaches led to a higher risk area that requires proper risk assessment and management to mitigate the impact of disasters.

The assessment results also indicate that while the countries in the middle and lower reaches of the watershed, including Thailand, Laos, Cambodia, and Vietnam, face a high level of hazard, only Laos and Cambodia were mainly concentrated in the high- and middle-risk areas. The disaster risk assessment process suggests that Thailand and Vietnam have a higher adaptive capacity to cope with disasters due to factors such as medical facilities, infrastructure, and government capacity. This finding is consistent with a survey study conducted in communities in Thailand, which showed that residents had a higher adaptive capacity to respond to flood emergencies than most of the countries in the watershed. For instance, almost 60% of the respondents had access to early warning information and understood how to act upon it. Additionally, more than 70% of respondents knew where the disaster shelters were located and how to reach them. Moreover, emergency drills were more accessible in Thailand than in most countries in the basin.

This result emphasizes the importance of reducing vulnerability, which is often more cost-effective than reducing hazards. Flood is a natural process, and its causes are primarily due to natural conditions such as meteorology, hydrology, and topography. While engineering measures can control the process of flood formation and movement, they are often expensive and difficult to implement. Therefore, reducing vulnerability through various measures is a relatively more cost-effective way to manage risk. For example, exposure can be reduced by avoiding building critical infrastructure and large cities in medium and high-risk areas during urban planning. Moreover, vulnerability can be reduced by implementing more disaster risk reduction (DRR) measures, such as disaster education and drills, to increase local adaptive capacity.

4.2. Flood Disaster Risk at Community Scale

The community-level risk assessment results presented in Figure 5 indicate that communities located downstream face greater risk when compared to those located upstream. This finding is consistent with the watershed-scale risk assessment, which suggests that higher river volumes in the middle and lower reaches of the river increase the likelihood of floods leading to inundated areas. Furthermore, it was observed that some communities might have limited access to disaster risk reduction (DRR) facilities, such as early warning systems and disaster shelters. This limited access poses significant challenges in responding effectively to floods and ultimately increases vulnerability. Consequently, medium- to high-risk areas are more prevalent in such communities.

Furthermore, the analysis reveals distinct spatial distribution characteristics of risk at the community scale. Specifically, medium- and high-risk areas are concentrated in residential areas closer to the river, which are more prone to flooding. If these areas have a high density of elements at risk, such as population and infrastructure, they can become high-risk areas.

Comparing the results of risk assessments at the watershed and community scales reveals significant multiscale risk anomalies. Some high-risk communities are located in low-risk areas at the watershed scale. For instance, Community 1 in Figure 3 appears to have a very low flood risk at the watershed scale. However, a community-scale assessment in Figure 5 reveals the existence of medium- to high-risk areas near the riverbanks due to high hazard levels and vulnerability factors such as population and infrastructure. Flood disaster risk at the watershed scale is typically assessed based on factors such as topography, land use, and hydrological data. However, these assessments may not fully capture local conditions or vulnerabilities, and there may be pockets of high flood risk within areas that are otherwise considered low-risk.

If a high-risk community exists within a low-risk zone, there is a risk that they may not be aware of the potential flood risk or may not have adequate measures in place to prepare for or respond to a flood event. This could result in significant damage to infrastructure and property, loss of life, and economic disruption. Therefore, this finding highlights the need for policymakers to conduct more detailed and localized assessments of flood risk in addition to watershed-scale risk assessments, particularly in areas with high population density or vulnerable communities. Otherwise, unforeseen disaster risks could result in human and economic losses.

Additionally, low-risk communities may be situated in high-risk areas at the watershed scale. For instance, Community 5 may be located at a high elevation near the river, making flood evolution challenging. While Figure 3 identified this community as high-risk at the watershed scale, a more detailed community-scale risk assessment in Figure 5 indicates that it is not at a high-risk level. When a low-risk community exists within a high-risk zone, it may allocate resources towards unnecessary flood mitigation measures that may not be cost-effective or necessary. In areas with low-risk assessments, such as Community 5, investing limited resources in urban planning and improving DRR effectiveness may not be necessary. Hence, a more refined risk assessment based on a watershed-scale assessment is required to better utilize limited resources in communities. For localized assessments of flood risk, additional measures such as flood protection infrastructure, early warning systems, or evacuation plans need to be considered.

5. Conclusions

Floods are among the most devastating disasters worldwide, with a broad range of impacts and a high tendency to have transboundary effects. This phenomenon is especially noticeable in the Lancang-Mekong river basin, where flood disaster risk management is particularly challenging.

This paper has conducted multiscale flood disaster risk assessments at the watershed and community levels in the Lancang-Mekong River Basin using indicator-based and hydrodynamic model-based methods. The results showed that the flood risk is generally higher in the river's lower reach due to high levels of both hazard and vulnerability at the watershed scale. However, there are also spatial disparities in flood risk across different scales. For example, there are high flood-risk communities located in the low flood-risk region. Distance to the river becomes one of the dominant factors in the flood risk at the community scale. This implies that different DRR measures should be adopted according to local contexts. This paper has contributed to a better understanding of flood disaster risks in a transboundary river basin and provided valuable insights for developing DRR strategies, policies, and plans based on an understanding of the risks.

Furthermore, this paper has highlighted some limitations and challenges for future research, such as data availability and quality, international cooperation factors, and stakeholder participation. This study's community-level assessment is limited to communities in China, Myanmar, Thailand, and Cambodia. Due to data limitations, Laos and Vietnam were not included, although the flood risks in these countries were also medium to high at the watershed scale and are of research significance. More comprehensive and effective flood disaster risk assessments can be conducted by addressing these issues to enhance resilience and sustainability in the Lancang-Mekong River Basin.

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