Spatial Analysis for Bridge and Road Site Selection: A Multi-Criteria Decision Framework for North and Northeast Thailand

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Abstract
This study is part of a master plan by Thailand's Department of Rural Roads to design new bridge and road construction projects across 37 provinces in the North and Northeast regions. Potential sites were evaluated based on physical accessibility and environmental factors, considering eight criteria including slope, road density, distance from existing bridges, accessibility to educational institutions, workplaces, tourist sites, hospitals, agricultural areas, and villages. Using multi-criteria decision-making (MCDA) and the Analytical Hierarchy Process (AHP) within a GIS framework, we assessed origin-destination trips to identify optimal sites for new bridges and roads. Initially, 1,534 potential bridge locations were identified and evaluated using AHP to determine the relative importance of each factor. The GIS-based MCDA process enabled effective spatial data analysis, refining the sites based on environmental constraints and proximity to existing structures. Ultimately, 185 suitable locations for bridge construction were selected, including 98 sites in Northern Thailand and 87 in the Northeast. The study demonstrates the effectiveness of combining AHP and MCDA within a GIS framework for infrastructure planning. It underscores the importance of integrating multiple criteria to achieve sustainable and efficient development. The findings offer a robust framework for policymakers to identify and prioritize infrastructure investments that address both current and future needs.

Keywords: Analytical Hierarchical Analysis, Bridge and Road Site Selection Analysis, Geographic Information System, Multi-Criteria Decision Analysis

1. Introduction

Bridge and road networks have a significant impact on local accessibility and transportation. The Northern and Northeastern regions of Thailand have historically had limited road connectivity. The existing transportation systems are unable to handle the increasing traffic volume due to congestion. To address this issue, the Rural Roads Department is developing a master plan to construct bridges and road networks in these regions. This master plan will guide the construction of additional bridges and the linking of existing road networks to provide the maximum coverage possible in the region. To optimize the expansion of the local transportation system, the department is investigating viable locations for bridge construction and connecting routes.

The Geographic Information System (GIS) is a crucial tool for the spatial management of related elements and is used in a variety of spatial planning applications. This allows us to view the entire picture and provide proper planning and decision-making solutions. Multi-Criteria Decision Analysis (MCDA) is frequently used in combination with GIS in a variety of contexts [1][2][3][4][5][6][7][8][9][10] and [11].

In 1977, Saaty introduced a multi-criteria decision analysis method based on the Analytic Hierarchy Process (AHP), which allows decision-makers to find the most appropriate solution and helps them better understand their decision-making problems [12].

There has been limited research on the selection of bridge and road sites up until now. Previous studies, such as the work by [13], have demonstrated the usefulness of GIS in identifying appropriate locations for bridge construction. They used GIS and the Fuzzy Analytic Hierarchy Process (FAHP) to rank potential river bridge construction sites based on criteria that took into account travel, economic, and physical factors. The length and height of the bridge were also considered. The study included two simulated scenarios: one with existing bridges and one without.

The dual AHP method is a powerful multi-criteria decision-making tool which enhances robustness by applying AHP in two distinct phases. This approach is particularly beneficial in infrastructure planning. For example, [13] integrated GIS with the Fuzzy Analytic Hierarchy Process (FAHP) to rank potential sites for river bridge construction, considering various travel, economic, and physical factors, and simulating scenarios with and without existing bridges. Similarly, [14] utilized a two-phase decision-making process with the Grey Analytic Hierarchy Process (G-AHP) for planning Park-and-Ride (P&R) systems in urban areas. This method involved initially ranking criteria within specific categories and then determining their overall importance, compared against other multi-criteria methods like FAHP and BWM. The dual AHP approach, by first assessing accessibility within categories and then integrating these results to prioritize areas for development, allows for a more detailed evaluation and balanced decision-making. This methodology provides a comprehensive framework for complex infrastructure decisions, ensuring that specific factors and overall priorities are both adequately considered, as demonstrated in the cited studies.

The Department of Rural Roads in Thailand used data from various infrastructure factors, such as river networks, road networks, and existing bridges, to analyze the demand for bridge crossings. These travel demand factors included the need to travel between different areas and localities, community needs, and environmental considerations such as watersheds, class 1A reserved forest areas, national park areas, and wetlands. The analysis was performed using multi-criteria decision analysis techniques such as Origin-Destination Matrix and Potential Surface Analysis. The goal of this study was to use GIS and dual AHP to identify potential locations for a new bridge and road construction in 37 provinces in Thailand's North and Northeast regions.

2. Study Area

The study area for this research encompassed 37 provinces in Thailand, including 17 provinces in the northern region and 20 provinces in the northeastern region. The northern provinces are Chiang Rai, Chiang Mai, Nan, Phayao, Phrae, Mae Hong Son, Lampang, Lamphun, Uttaradit, Tak, Phitsanulok, Sukhothai, Phetchabun, Phichit, Kamphaeng Phet, Nakhon Sawan, and Uthai Thani. The northeastern provinces are Kalasin, Khon Kaen, Chaiyaphum, Buriram, Maha Sarakham, Mukdahan, Yasothon, Roi Et, Loei, Sisaket, Sakon Nakhon, Surin, Nong Khai, Nong Bua Lamphu, Amnat Charoen, Udon Thani, Ubon Ratchathani, and Bueng Kan (Figure 1). The total study area covers 340,337.20 square kilometers, with coordinates extending from 97.25°E to 105.61°E and 14.14°N to 20.45°N.

3. Methodology

3.1 Determination of Potential Areas for New Bridges and Connecting Roads Construction

In this stage of the study, we used GIS-based multi-criteria decision analysis approaches supported by AHP models to investigate the potential locations for new bridges and connected roads. AHP simplifies complex problems by breaking them down into their constituent parts and aggregating and combining these components at multiple levels to create a multi-level analytical structural model based on the relationship between the elements and their subordinate connections. Professionals or researchers can determine the relative importance of each factor by comparing these criteria using a matched comparison method. This study included physical variables, accessibility to activity factors, and environmental factors. Figure 2 illustrates the overall process, which starts with evaluating potential locations for new bridges and then connects the two nearest sites across a river with a new bridge. The bridges are then linked to the nearest existing road. The research methodologies are as follows:

3.1.1 The criteria selection

To analyze potential locations for new bridges and connecting roads, we systematically collected and categorized spatial data and associated information into three distinct categories:

- Physical Factors: This category includes the density of existing bridge positions, road density, area slope, and the presence of rivers. These factors were utilized to evaluate the potential suitability of the area, considering elements such as main rivers with year-round water flow and the locations of existing bridges.

- Accessibility to activity factors: These factors, such as accessibility to educational/institutional/ government offices, tourist attractions, hospitals, and agricultural land, were used to assess the potential accessibility of the area of interest.
- Environmental Factors: This category encompasses national park areas, wildlife sanctuaries, wetlands, watershed areas classified as 1A, and regions prone to natural disasters. These factors were used to identify areas that may require special considerations due to legal constraints and environmental preservation needs.

Table 1 provides a detailed overview of the variables, sub-factors, symbols, and units of measurement utilized in this study. Following the collection of relevant factor data, correlation statistics were examined and used as a guideline for selecting the most pertinent variables. This systematic approach ensures a comprehensive and nuanced evaluation of each potential site, balancing developmental needs with environmental and accessibility considerations.

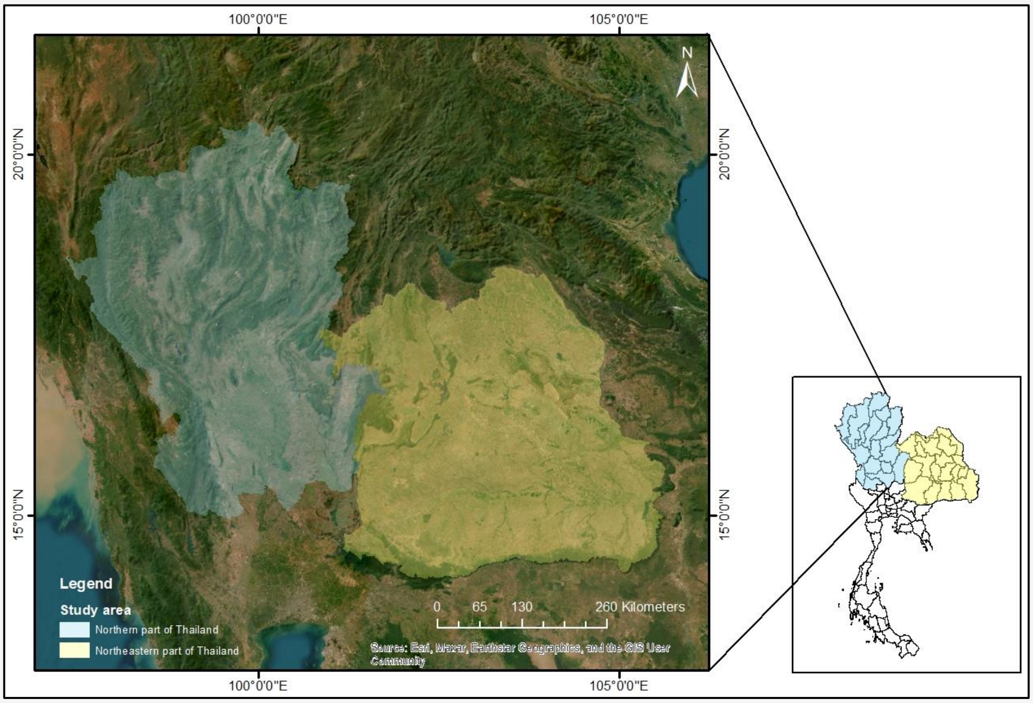

Figure 1: The northern and northeastern parts of Thailand

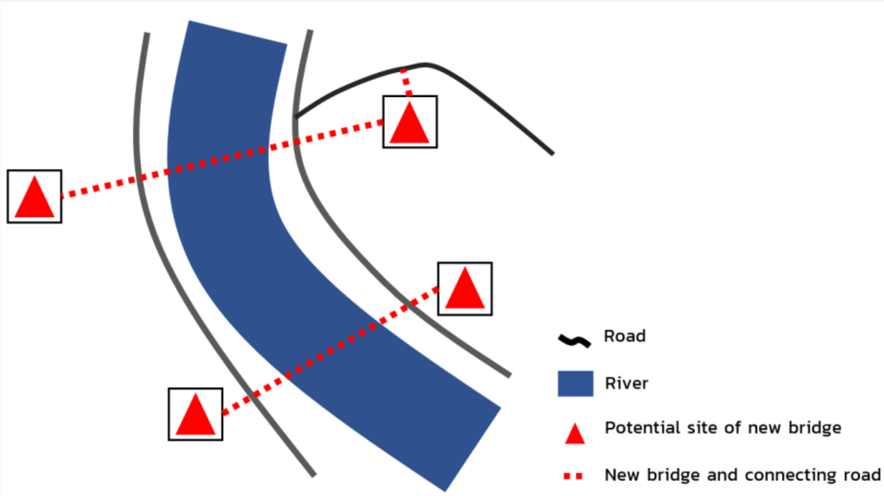

Figure 2: The concept of identifying potential areas for new bridges and connecting roads

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Table 1: Factors used in this study

Factor	Item	Sub-factor	Symbol	Unit
Physical factors	1	Slope	A1	%
	2	Location of the existing bridge	A2	m
	3	Road density	A3	m/10,000 m^2
	4	River*	A4	m
	5	Distance from villages and municipalities	A5	
Accessibility to Activities factors (distance)	6	Educational/government offices	B1	m
	7	Tourist attraction	B2	
	8	Hospital	B3	
	9	Agriculture land	B4	
Environmental factors**	10	National Park	D1	m^2
	11	Wildlife sanctuary area	D2	
	12	Wetland	D3	
	13	Watershed - Class 1A	D4	
	14	Disaster area	D5	

3.1.2 Preliminary process of analyzing the potential area and suitable bridge location

In this study, we examined potential areas and optimal bridge locations using eight key factors: slope, road density, distance from existing bridges, accessibility to schools and workplaces, accessibility to attractions, accessibility to hospitals, accessibility to agricultural land, and distance from villages. These factors played a crucial role in the decision-making process for identifying suitable bridge positions, as depicted in Figure 3. For the analysis, we employed a raster data model with a spatial resolution of 100 meters by 100 meters, integrated with a MCDA method and the AHP. We used centroid analysis to pinpoint clusters of potential sites, representing the positions of the nodes. These representative locations were then scrutinized to determine the most suitable spots for new bridges. This systematic approach ensured a thorough evaluation, balancing various physical, accessibility, and environmental considerations. The detailed process for evaluating the potential for new bridges and selecting connecting road sites using MCDA and AHP is as follows:

(1) The travel types were divided into four main categories: School and working place, Hospital, Agricultural land, and Tourist attraction. Each travel type had distinct factors selected for evaluation.

(2) The study considered several common factors across all travel type groups, including slope (%), distance from the existing bridge, road density, and distance from village and municipality. Additionally, each travel type group had specific factors: the "School and government office" category included accessibility to schools and government offices, the "Hospital" category included accessibility to hospitals, the "Agricultural land" category included accessibility to agricultural land, and the "Tourist attraction" category included accessibility to tourist attractions.

(3) Scores for each factor were divided into five levels, ranging from 1 to 5, with the class range determined by the standard deviation value of each factor. A score of 1 indicates a low potential for new bridges and access roads, while a score of 5 indicates a high potential.

(4) Eight experts in bridge and road construction identified the factors, utilizing the AHP technique. Each group of factors included distinct sub-criteria tailored to various travel types. Initially, weight scores were determined using AHP and then multiplied by the suitability scores for each factor. The resulting scores for each factor group were then re-evaluated using the AHP method to prioritize areas with high potential for new bridge and road connections.

(5) The selection of areas suitable for new bridge and road connections was based on their proximity to the nearest river, using a 940-meter buffer zone from the river's center. This buffer distance reflects the average distance from villages to the closest river. This method facilitates the identification of optimal locations for the construction of new bridges and connecting roads around the designated river.

(6) The potential areas for constructing new bridges and connecting roads are analyzed according to the planned travel situation, using the weight values for each factor determined by the experts. The equation 1 used to analyze the potential areas for constructing new bridges and connecting roads is as follows:

$$Y = X_1W_1 + X_2W_2 + \dots + X_nW_n \quad \text{Equation 1}$$

Where:
- X = refers to the variables used in the analysis.
- Y = refers to the potential site for the construction of new bridges and connecting roads.
- W = refers to the weight value obtained from the hierarchical decision-making method. A result is a group of potential areas according to different travel scenarios.

(7) 2.2 km buffer from the center of the river is created by selecting potential bridge and road development areas. The buffer distance was determined by averaging the distances between all villages and the current bridge.

(8) The bridge and associated road locations are analyzed using origin-destination network analysis methodologies to create a line connecting the main potential areas between the rivers. If the prospective areas between the rivers are more significant, additional routes will connect the two locations. The connecting line results represent the locations of new bridges and connecting roads determined by this investigation. However, in this study, the connecting lines were chosen to be at least 940 meters apart, and 940 meters away from the position of the existing bridge (where 940 meters was the mean distance of the bridge in the study region).

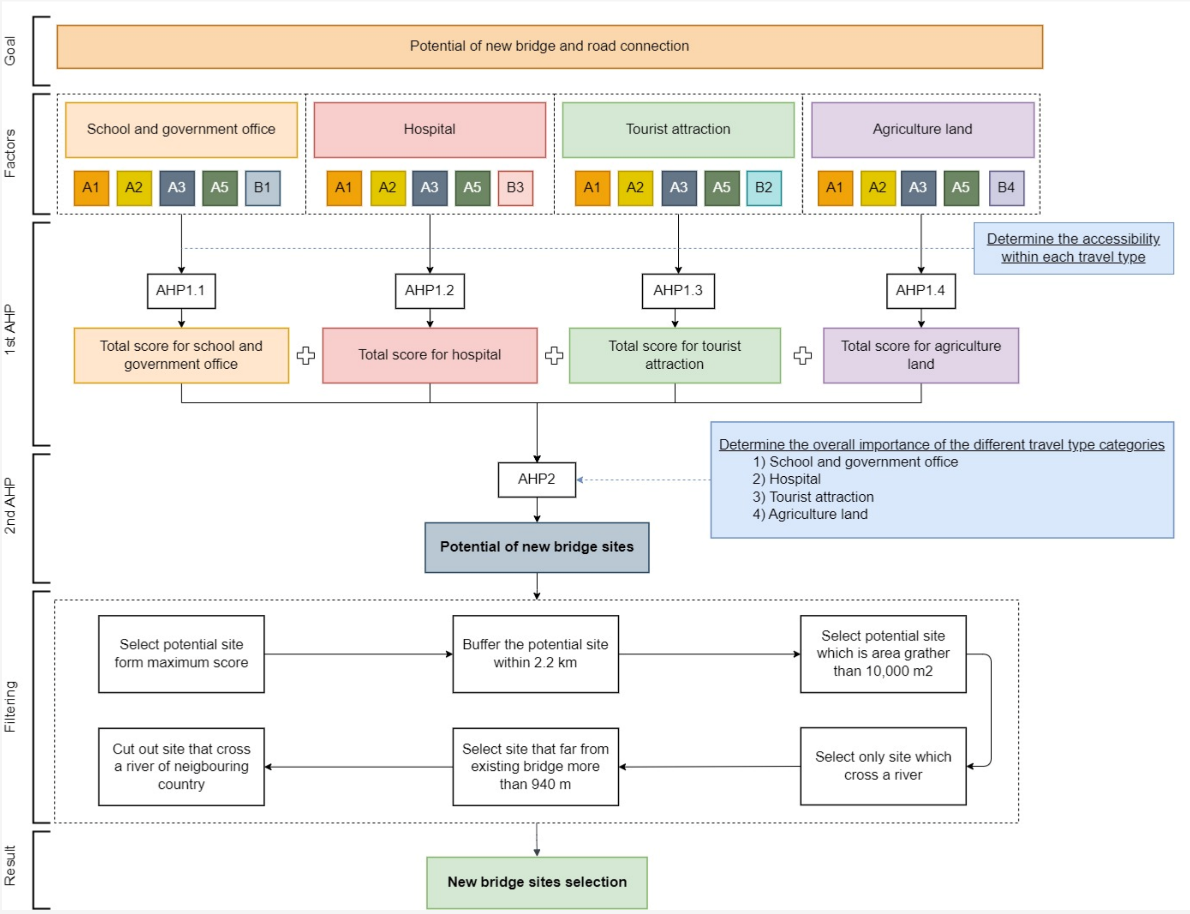

Figure 3: Bridge location analysis framework using GIS

4. Results

4.1 The Results of the Selection of Variables Used in the Study

The correlation matrix in Table 2 reveals varying levels of correlation among the eight factors. While B1 (accessibility to educational/government offices) and B3 (accessibility to hospitals) exhibit a notably high correlation with a coefficient of 0.95, indicating a strong relationship due to their geographical distribution within the same community areas, other factors show low to moderate correlations. This suggests that most factors do not share the same degree of proximity or locational attributes, leading to diverse accessibility patterns. Therefore, it is important to interpret the correlation matrix in Table 2 by considering each pair of factors individually, recognizing that only B1 and B3 demonstrate a strong correlation.

4.2 Results of Data Analysis for Each Factor

The study examined the effects of each element mentioned. The following details were categorized into three groups of factors:

4.2.1 Physical factor

Slope: The slope factor helps determine the characteristics of areas with varying slope intensities. We calculated the slope percentage using the ASTER GDEM product, which offers a spatial resolution of 90 meters and encompasses the project area across 37 provinces. According to Figure 4, the northernmost part of the area primarily features steep slopes, while the lower northern and northeastern regions exhibit relatively gentle slopes. The slope percentages across the entire project area range from 0 to 136.225. Areas with higher slopes are generally less suitable for constructing new bridges and connecting roads due to potential stability and accessibility issues.

Table 2: Statistics correlation matrix

Factors	A1	A2	B1	B2	B3	A5	B4	A3
A1	1.00							
A2	0.41	1.00						
B1	-0.32	-0.05	1.00					
B2	-0.47	-0.07	0.61	1.00				
B3	-0.33	-0.06	0.95	0.64	1.00			
A5	0.38	0.46	-0.04	-0.08	-0.04	1.00		
B4	0.31	0.34	0.05	0.04	0.05	0.60	1.00	
A3	0.42	0.63	-0.02	-0.10	-0.03	0.65	0.54	1.00

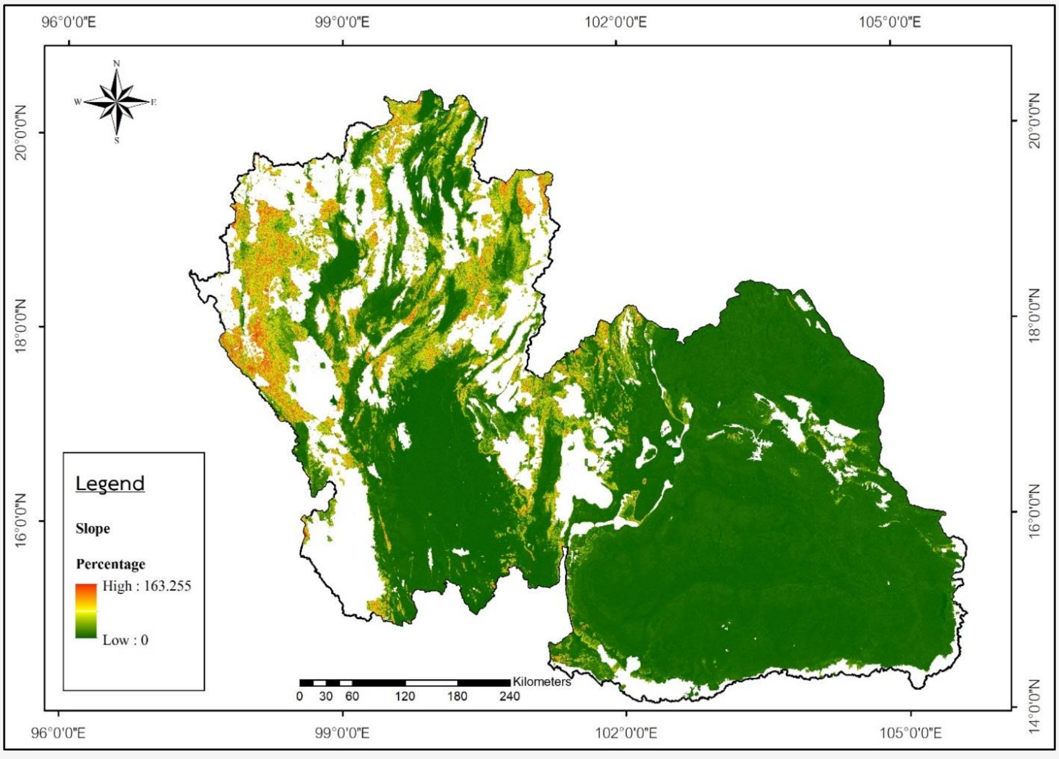

Figure 4: The slope characteristics of the area

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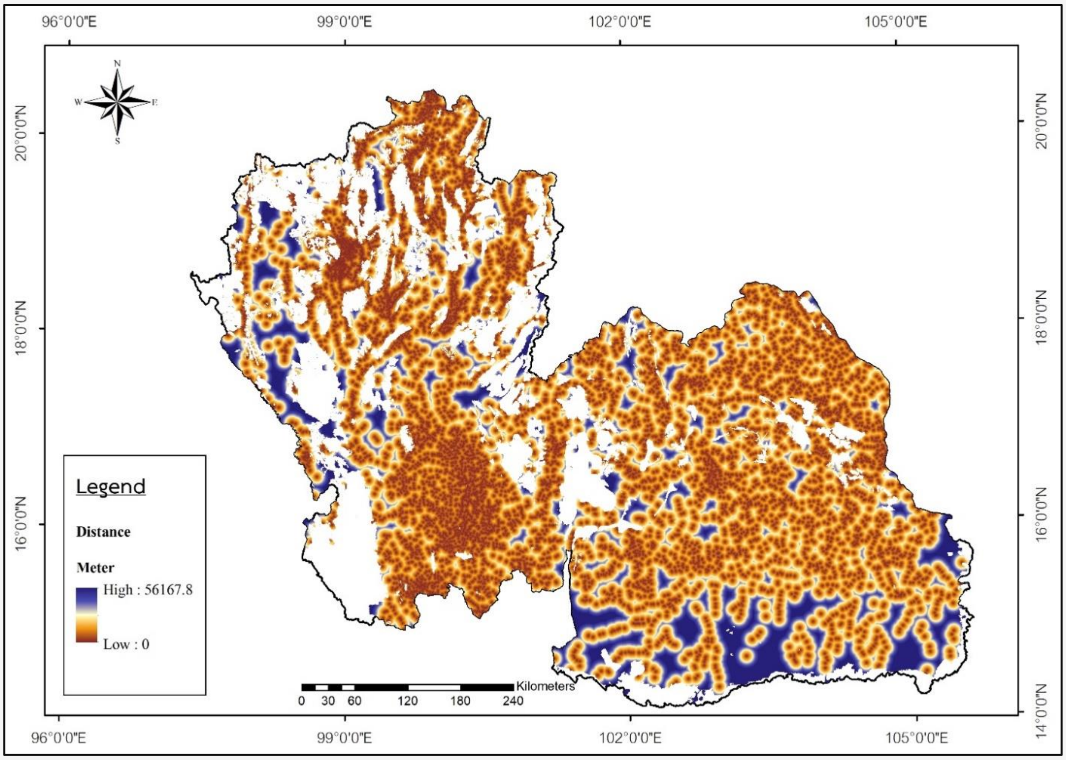

Figure 5: Distribution of the existing bridge locations

Distance Factor from the Existing Bridge: This factor identifies potential areas for new bridges by analyzing their distance from 4,386 existing bridges. As depicted in Figure 5, the density of existing bridge sites is higher in the northeastern region compared to the northern region. Areas significantly distant from current bridge locations up to 56,167.8 meters, are considered more suitable for new bridge construction, as they indicate a gap in the current network that new bridges could address. This spatial analysis helps in identifying strategic locations for new infrastructure to improve connectivity.

Road Density Factor: The road density factor *(road length (meters) per 10,000 square meters)* represents the characteristics of an area's existing road network. This metric is calculated as road length per 10,000 square meters. According to Figure 6, the density of road is significantly higher in the Northeastern region compared to the northern section of the North, where the terrain is more mountainous and has a steep slope. Areas with less density are more likely to be targeted for building new bridges and connecting roads, as these regions would benefit the most from improved accessibility and connectivity.

Distance from River (Square Meter): While the distance from river was not directly associated with other factors in this study, it played a crucial role in selecting potential bridge and connectivity sites. We focused on rivers with year-round flow and those with existing bridges. A 1-kilometer buffer zone was created around the river's centerline, as illustrated in Figure 7. This buffer zone was instrumental in identifying potential regions for new bridge construction, ensuring that new bridges would effectively enhance connectivity across the river, complementing existing infrastructure.

4.3 Facility Access

Educational and Government Office: Access to educational institutions and government offices was a key consideration, reflecting each area's ability to engage in activities such as schooling and business operations. We calculated the distance from schools and government offices using data from 24,390 locations, which included 18,162 educational institutions and 5,628 government office positions, as shown in Figure 8. This distance analysis assessed the accessibility of these facilities. Regions closer to schools and government buildings have a better potential for developing new bridges and connecting roads compared to areas that are more distant, as improved access would significantly benefit these communities.

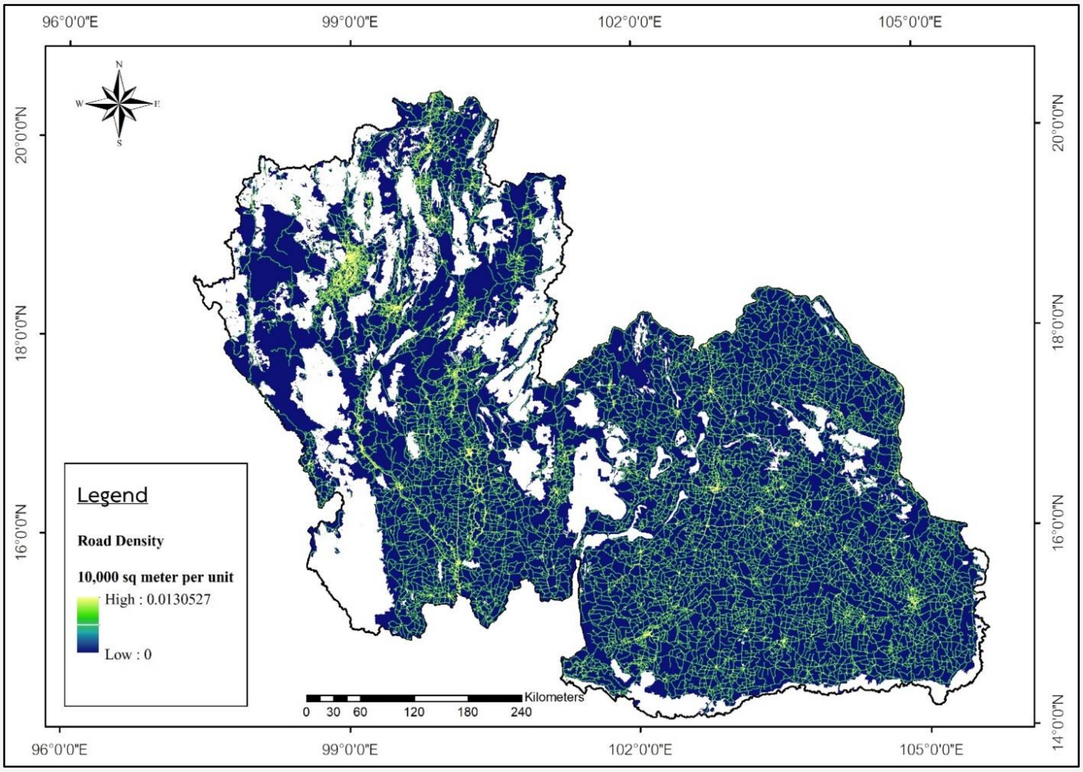

Figure 6: Road density

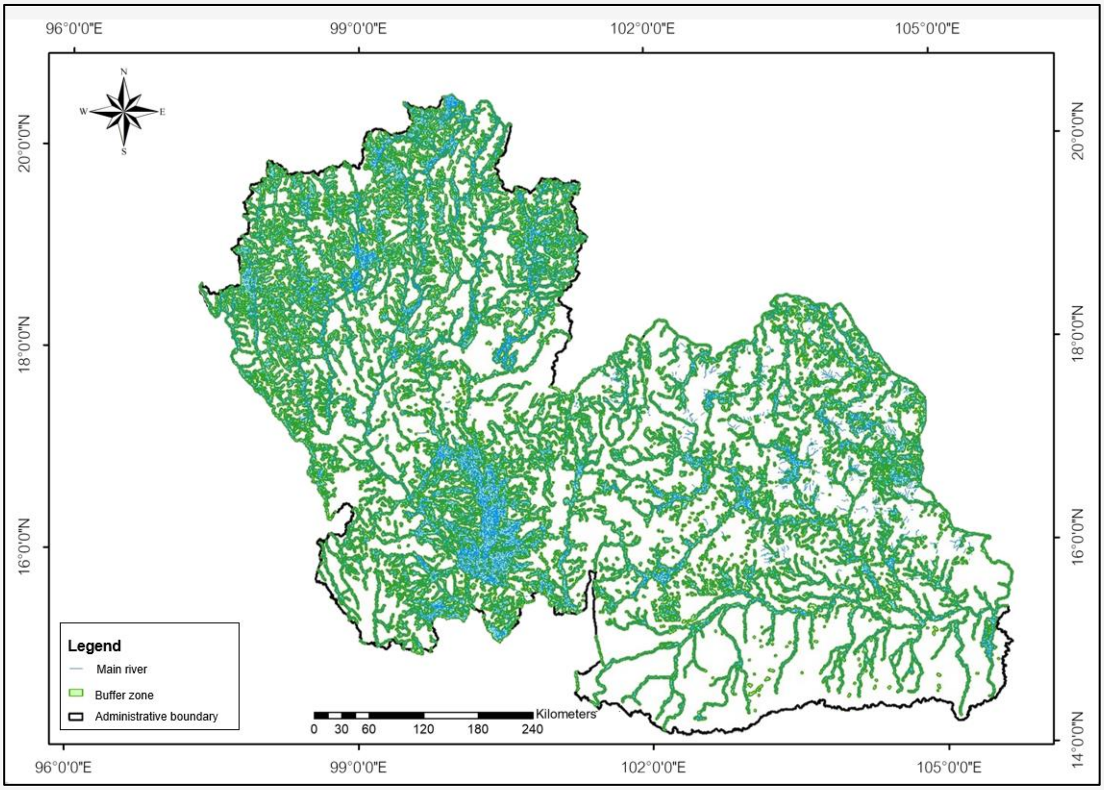

Figure 7: Stream network

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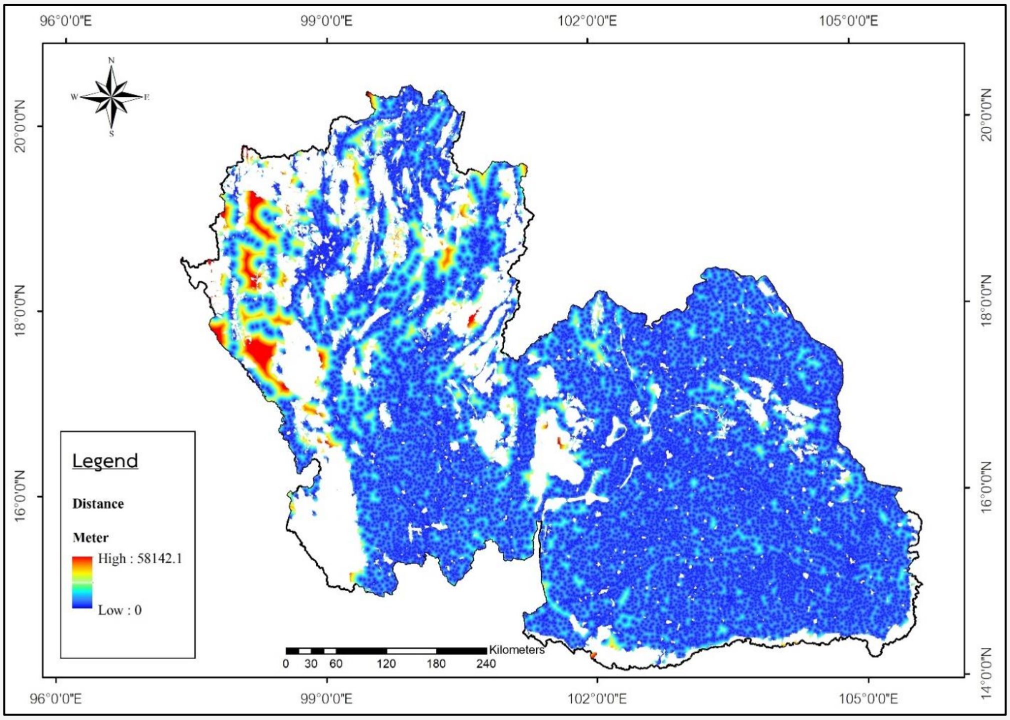

Figure 8: Accessibility to educational institutions/government activities

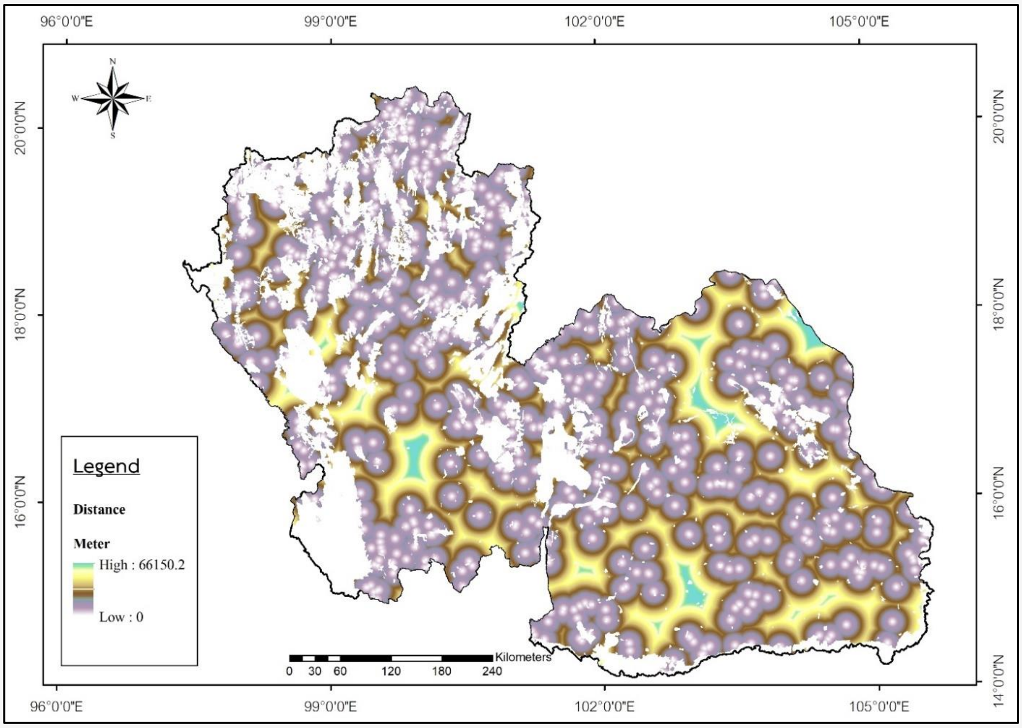

Figure 9: Accessibility to tourist activities

Tourist Attraction Site: The ease of access to tourist attractions was another key factor indicating each area's potential for travel and tourism activities. Similar to the accessibility factors for educational institutions and government offices, this component was examined through a distance analysis involving 1,272 significant tourist sites in the area, as shown in Figure 9.

The findings suggest that areas with better access to tourist attractions are more likely to be selected for new bridges and connecting roads, as improved accessibility to these sites would enhance tourism and local economic development.

Hospital: Accessibility to hospitals was a crucial factor, reflecting each area's potential for accessing medical services. Using the same distance analysis method as the previous factors, we analyzed data from 5,403 hospital locations, as shown in Figure 10. The analysis revealed that areas with faster access to hospitals have a higher potential for future bridge and road expansion compared to less accessible locations. Improved hospital accessibility would significantly benefit community health and emergency response times.

Agricultural Lands: The accessibility of agricultural land was a factor indicating each area's potential to access agricultural activities. This study utilized agricultural land center data from areas larger than one square kilometer. Subsequently, we applied the same distance analysis method used for other accessibility factors, as shown in Figure 11. Areas in closer proximity to agricultural land centers were found to have a greater opportunity for constructing new bridges and connecting roads compared to less accessible regions, facilitating better transportation of agricultural products and enhancing economic activities.

Village and municipality: The distance from villages and municipalities was a crucial factor indicating community accessibility. Unlike the previous factors, this study specifically used data on the locations of villages and municipalities, as illustrated in Figure 12. Areas within a certain proximity to these communities are identified as potential sites for constructing new bridges and connecting roads. Such locations are considered beneficial because they enhance connectivity for local populations, making transportation more efficient and accessible for residents.

4.3.1 Specific area

Figure 13 illustrates the environmental factors used to screen out unrelated areas, ensuring the preservation of ecologically sensitive regions and mitigating disaster risks. These factors include national park areas, wildlife sanctuaries, wetland boundaries, watershed Class 1A areas, and disaster-prone areas such as flood zones, earthquake-prone regions, and landslide-prone areas. By excluding these areas from consideration, we ensure that new bridge and road constructions do not negatively impact critical environmental and disaster-sensitive zones, promoting sustainable development.

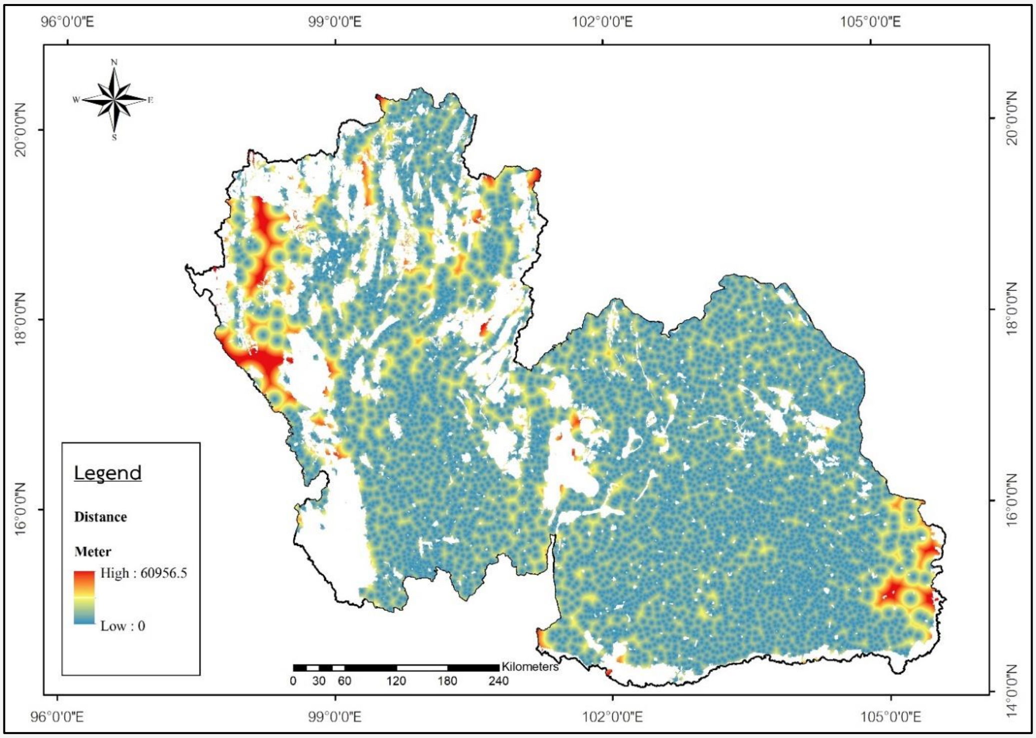

Figure 10: Accessibility to hospitals

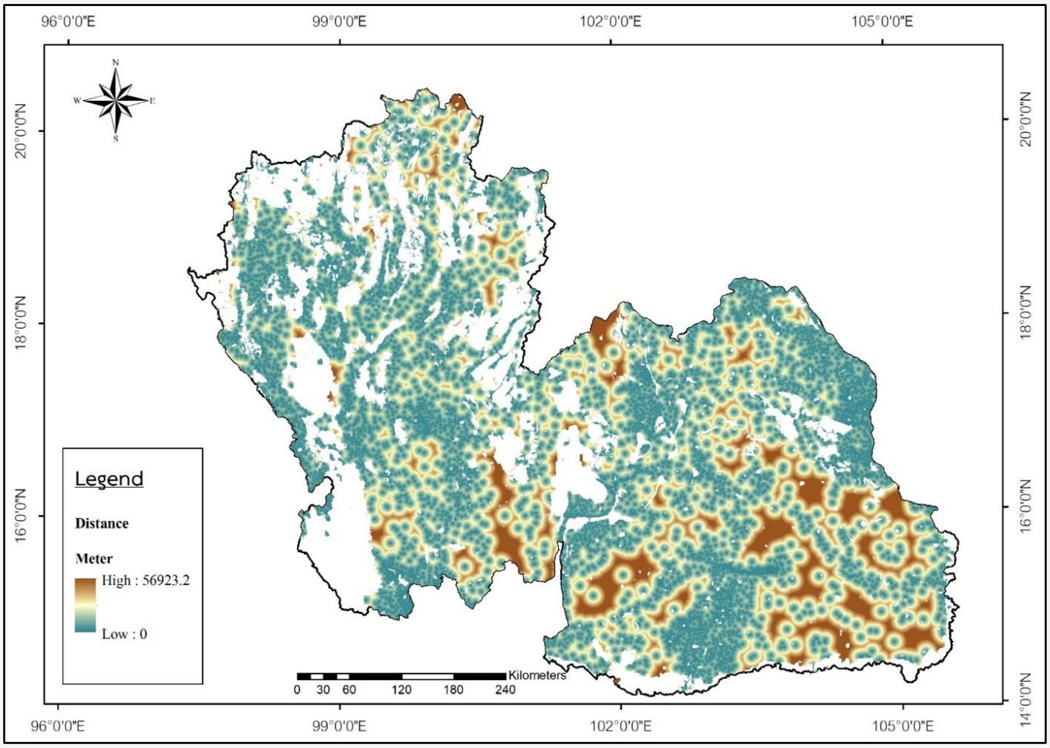

Figure 11: Access to agricultural activities

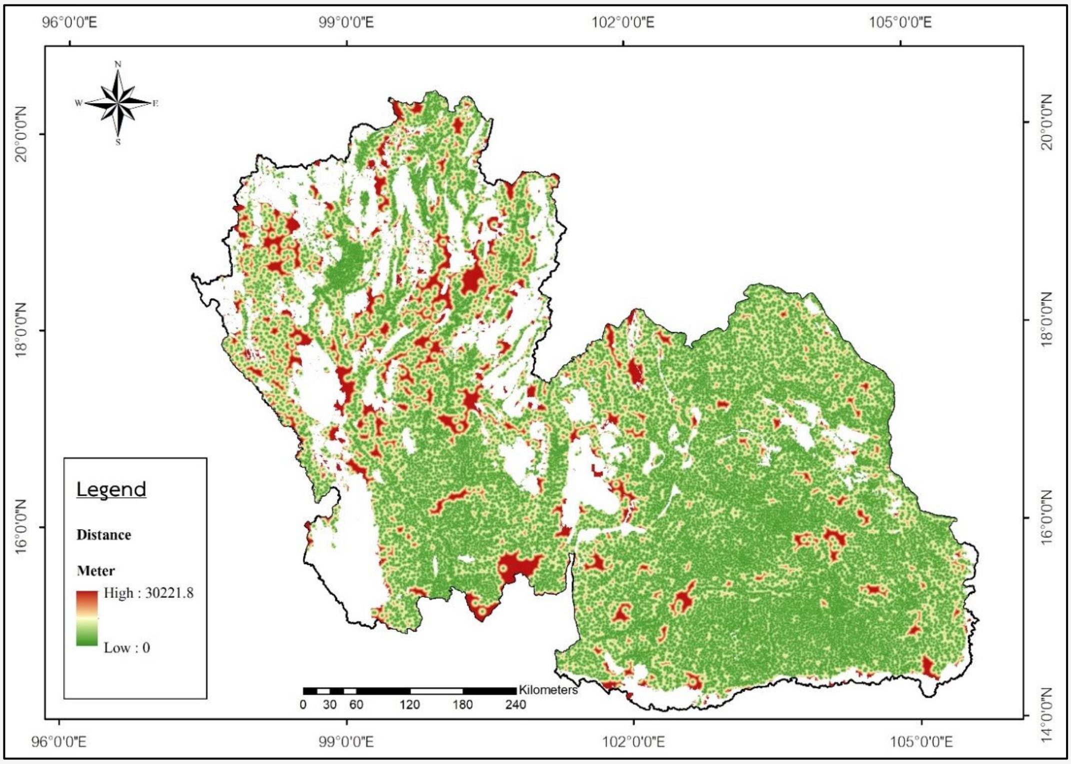

Figure 12: Distance from villages and municipalities

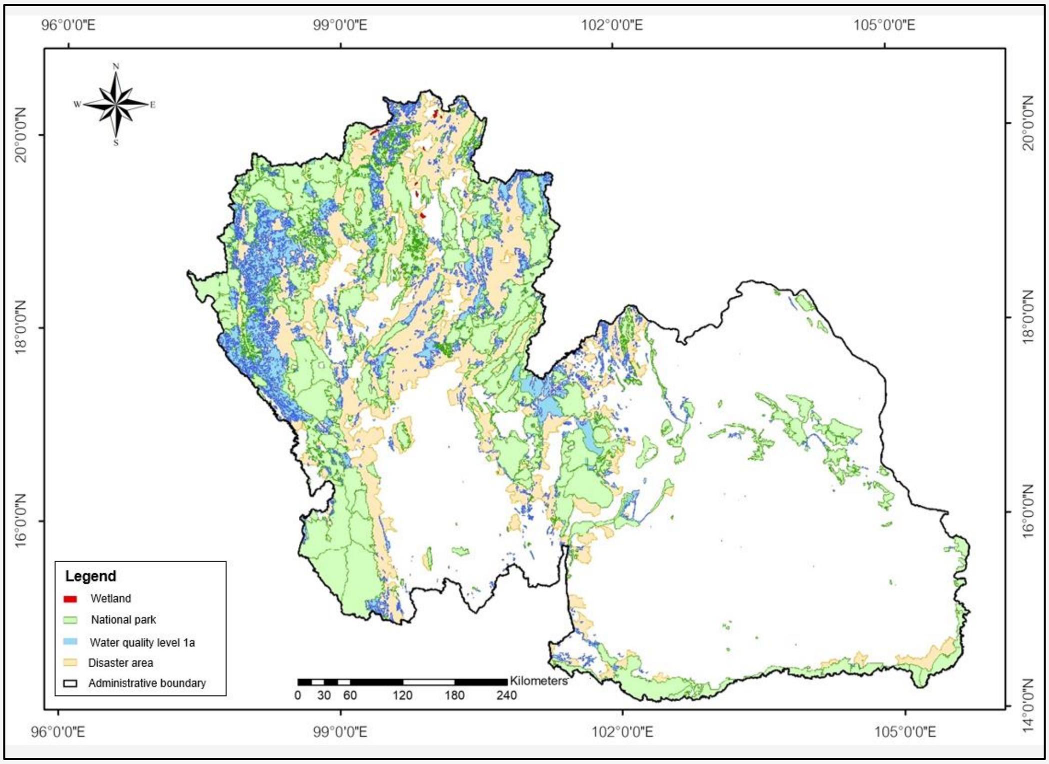

Figure 13: Environmental factors

4.4 Site Selection Analysis for New Bridges and Connecting Road

In this study, several factors were considered for the site selection analysis. Each region was assigned an importance score ranging from 1 to 5 based on the standard deviation of each factor, establishing a hierarchy. A score of 1 indicates an area with low potential for new bridges and connecting roads, while a score of 5 indicates high potential. As shown in Table 3 and Table 4, the factors were determined by eight experts in bridge and road construction using the AHP technique.

Each factor group comprised distinct sub-criteria specific to different travel types. After determining the weight scores, these were multiplied by the suitability scores for each factor. Once the scores for each factor group were obtained, they were subjected to another round of weighting using the AHP method. The second AHP was crucial as it allowed for the integration of various travel types and their specific importance in the overall decision-making process. By doing so, we could effectively prioritize areas for new bridge and road connections, taking into account the relative significance of different travel categories, such as school and government office accessibility, hospital proximity, agricultural land accessibility, and tourist attraction accessibility. This step was necessary to balance and rank the travel categories according to their importance, ensuring that the selected sites would optimally serve the primary travel needs of the region.

Notably, the weight values achieved a CR of less than 0.1, indicating that the weights are reliable and can be effectively utilized in the analysis. The final score map is shown in Figure 14.

4.5 Preliminary Results of Analysis of Suitable Bridge Locations

The preliminary analysis identified potential sites for constructing new bridges and connecting roads across opposite sides of rivers. By using a near-distance analysis technique, the study connected areas with high potential for bridge construction. This analysis resulted in determining the locations and paths for connecting road bridges. Initially, 1,534 suitable bridge locations were identified. However, some of these locations were deemed unsuitable, such as those in forest areas. Out of the 1,534 preliminary locations, 848 were near existing bridges, and 326 were close to each other, resulting in 185 optimal preliminary bridge locations. These were further divided into 98 locations in the northern region and 87 in the Northeastern region, as detailed in Table 5 and Figure 15.

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Table 3: Spatial data and weight evaluation of the criteria parameters

Criteria Parameters	Sub Criteria	Suitability Score	The Weighting of the Accessibility to: School and Government Office (CR = 0.088)	Hospital (CR= 0.077)	Agriculture Land (CR = 0.089)	Tourist Attraction (CR = 0.046)
Slope (%)	0 - 1.17	5	3.27	3.32	3.09	3.62
	1.17 - 11.44	4				
	11.44- 21.71	3				
	21.71 - 31.99	2				
	31.99 – 163.26	1				
Distance from the existing bridge (m)	0 – 3,798.32	1	14.61	27.15	10.64	26.28
	3,798.32 – 10,276.88	2				
	10,276.88 – 16,755.44	3				
	16,755.44 – 23,234.01	4				
	23,234.01 – 56,767.80	5				
Road density (m/10,000 m^2)	0 - 0.000041	5	7.44	7.87	10.54	5.81
	0.000041 - 0.000683	4				
	0.000683 - 0.001325	3				
	0.001325 - 0.001968	2				
	0.001968 - 0.013027	1				
Distance from village and municipality (m)	0 – 1,049.26	5	17.22	15.13	28.72	10.25
	1,049.26 – 2,603.12	4				
	2,603.12 – 4,156.97	3				
	4,156.97 – 5,710.83	2				
	5,710.83 – 30,560.26	1				
Accessibility to school and government office (m)	1	5	57.46	-	-	-
	1 - 5	4				
	5 - 15	3				
	15 - 30	2				
	>30	1				
Accessibility to hospital (m)	1	5	-	-	46.54	-
	5 - 15	3				
	15 - 30	2				
	>30	1				
Accessibility to tourist attraction (m)	1	5	-	54.04	-	-
	1 - 5	4				
	5 - 15	3				
	15 - 30	2				
	>30	1				
Distance from agricultural land (m)	1	5	-	-	-	47.01
	1 - 5	4				
	5 - 15	3				
	15 - 30	2				
	>30	1				
Total (%)			100	100	100	100

Remark: CR = Consistency Ratio

Table 4: The weight of the journey into each activity area

Traveling to the Activity Area	**Weight Score** (CR Value = 0.069)
School and working place	0.34
Hospital	0.45
Agricultural land	0.13
Tourist attraction	0.08
Total	1.00

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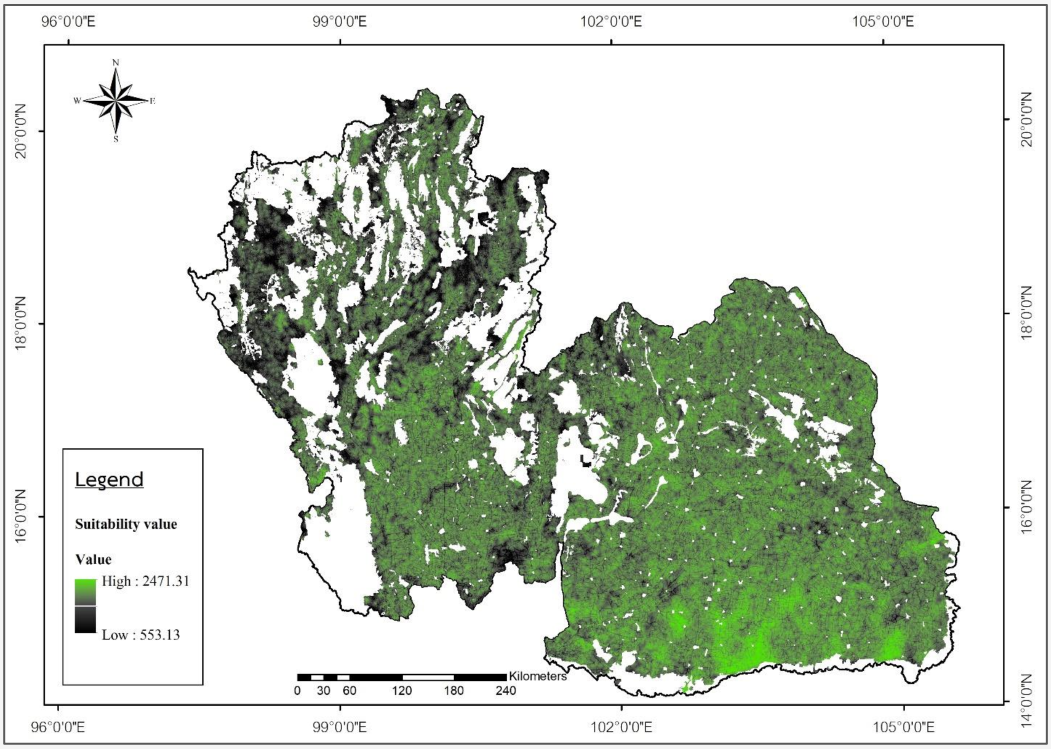

Figure 14: The final score for new bridge and road connecting

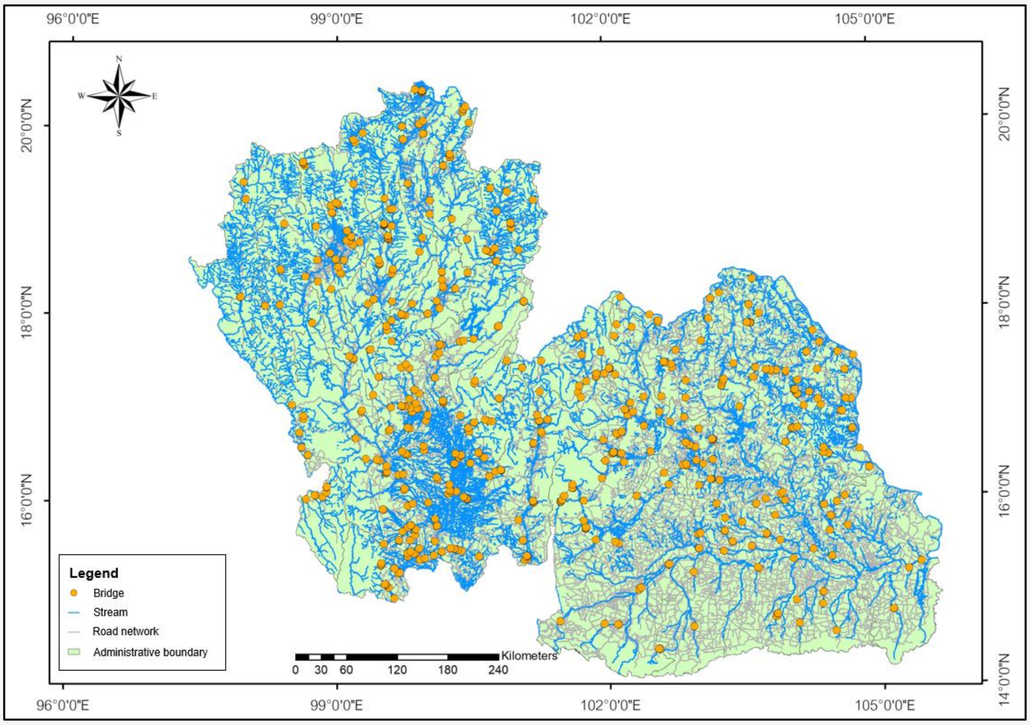

Figure 15: The potential of new bridges construction location and connecting roads

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Table 5: Types of bridges and connecting road locations

Types of the bridge and connecting road locations	Number of bridges
1) The location of the new bridge and connecting road.	185
2) The location of the bridge and the connecting road near the existing bridge.	848
3) The location of the bridge and the connecting road is in the forest and abandoned areas.	175
4) The location of the bridge and the connecting road where the position is close to each other.	326
Total	**1,534**

5. Discussions

The study aimed to identify potential locations for new bridges and connecting roads across 37 provinces in Northern and Northeastern Thailand by considering a range of factors. The analysis incorporated eight key factors: slope, road density, distance from existing bridges, proximity to schools and workplaces, proximity to attractions, proximity to hospitals, proximity to agricultural land, and proximity to villages. These factors were analyzed using multi-criteria decision-making and hierarchical analysis methods integrated with GIS technology. The origin-destination method in network analysis was utilized to identify suitable areas and establish potential locations for new bridges and connecting roads. The initial analysis identified 1,534 potential bridge locations. However, a significant number of these locations presented limitations. Specifically, 848 locations were near existing bridges, 175 were situated in forest areas, and 326 were located too close to each other. These limitations underscore the need for careful consideration of environmental and spatial constraints in infrastructure planning. After addressing these limitations, 185 suitable bridge locations were identified. This refined selection included 98 locations in the Northern region and 87 in the Northeastern region, demonstrating a more targeted and feasible approach to infrastructure development.

The study's methodology effectively integrated various factors to provide a comprehensive assessment of potential bridge locations. However, there are opportunities for improvement in future studies. Alternative methodologies could be explored to enhance the precision of the results. Additionally, considering other relevant factors, such as the economic and social conditions of the areas, could provide a more holistic understanding of the potential impacts of new bridge and road construction.

6. Conclusion

This study successfully identified potential locations for new bridges and connecting roads in 37 provinces of Northern and Northeastern Thailand by integrating multiple factors and employing advanced analytical techniques. Initially, 1,534 potential bridge locations were identified, but after addressing spatial and environmental limitations, the number was refined to 185 suitable locations. This included 98 locations in the Northern region and 87 in the Northeastern region. The findings highlight the importance of considering a range of factors in infrastructure planning, including physical geography, accessibility, and environmental constraints. By using MCDA and GIS-based AHP, the study provided a robust framework for identifying suitable locations for new infrastructure projects.

For future research, incorporating alternative methodologies and additional factors such as economic and social conditions could improve the precision and relevance of the findings. Comparing the accessibility index before and after construction will also be valuable in evaluating the impact of new bridges and connecting roads, ensuring that infrastructure development effectively meets the needs of the communities it serves.

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