

MULTI-CRITERIA DECISION-MAKING IN ROAD MAINTENANCE: AN AHP-GIS APPROACH

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ABSTRACT

Effective road maintenance planning is essential for prioritizing which road segments should receive maintenance interventions, especially in urban areas with limited budgets and growing traffic demands. This study used a structured multi-criteria decision-making approach to address the decision problem of selecting and prioritizing road segments for maintenance. The methodology integrates the Analytic Hierarchy Process (AHP) and Geographic Information System (GIS) to develop an objective and spatially-informed prioritization framework. The AHP was applied to assess expert-defined criteria, and GIS provided a spatial visualization to support resource allocation decisions. The originality of this study lies in its integration of AHP-GIS for spatial decision support in urban road maintenance planning. The evaluated criteria include traffic volume (23.3%), road authority (22.1%), strategic value (20.8%), population density (16.5%), handling type (8.9%), and environmental impact (8.5%). Weighting consistency was verified using SuperDecisions software. The results highlight Persatuan Road, Berlian Road, and LKMD I Road as the top priority segments requiring immediate attention. This adaptable framework enhances decision transparency and sustainability and can be replicated in other urban contexts facing similar infrastructure challenges. Future research should explore real-time data integration and predictive modeling to improve infrastructure management systems.

Keywords: road infrastructure; AHP; GIS; spatial decision support; urban planning; transportation management

1. Introduction

Road infrastructure plays a vital role in supporting urban development, economic activity, and public mobility. However, road deterioration is inevitable due to factors such as aging materials, vehicle overloading, poor drainage, and delayed maintenance planning (Kaba & Assaf, 2019). Effective road maintenance is essential to ensure

safety, comfort, and sustainable transportation services. Yet, decision-makers often face challenges in prioritizing which roads to repair, especially under limited budgets and growing infrastructure demands (Yao et al., 2023; Yannis et al., 2020).

The complexity of road maintenance decisions arises from the need to consider various interrelated factors—technical, economic, strategic, environmental, and demographic. Addressing such complexity requires a Multi-Criteria Decision-Making (MCDM) framework capable of evaluating multiple, often conflicting, criteria systematically and transparently (Hasan et al., 2024; Akpan & Morimoto, 2022). Among the MCDM tools, the Analytic Hierarchy Process (AHP) has proven to be effective in infrastructure planning due to its ability to incorporate both quantitative and qualitative judgments (Saaty, 1987).

In addition to classical factors such as traffic volume and road hierarchy, modern road maintenance prioritization should also include environmental variables such as ecological sensitivity, drainage systems, and erosion risks (Kaba & Assaf, 2019). These aspects are especially relevant for supporting sustainable infrastructure development (Dos Santos et al., 2019).

This article presents an integrated framework using Confirmatory Factor Analysis (CFA), the Analytic Hierarchy Process (AHP), and Geographic Information Systems (GIS) to prioritize road maintenance in an urban context. CFA is employed to validate and refine decision criteria, the AHP determines the priority weights, and GIS supports spatial visualization of priority roads.

The novelty of this study lies in the integration of CFA-AHP-GIS specifically for urban road maintenance prioritization, which is still underexplored in previous research. The proposed framework addresses strategic, technical, socio-economic, and environmental considerations, offering a transparent and spatially informed tool for infrastructure planning.

2. Literature review

Several studies have proposed various methods to evaluate and prioritize road maintenance, ranging from the Analytic Hierarchy Process (AHP) (Saaty, 1987), Weighted Scoring Model (Soltanifar & Hosseinzadeh Lotfi, 2011; Zhang et al., 2023), Cost-Benefit Analysis (CBA) (Biancardo et al., 2023), Rural Access Index (RAI) (McGrail & Humphreys, 2009), Pareto Analysis (Nagar et al., 2023), Scoring Matrices (Gunathilaka & Amarasingha, 2020), Multi-Attribute Utility Theory (MAUT) (Akpan & Morimoto, 2022), Decision Matrix Analysis (Freeman, 2023; Olabanji & Mpofun, 2019), the Delphi Method (Danacı & Yıldırım, 2023), the Nominal Group Technique (Cariñanos-Ayala et al., 2023), and others.

The AHP is a widely used MCDM tool that structures decision problems into a hierarchy and uses pairwise comparisons to derive priority scales. It accommodates subjective expert judgments and ensures consistency in decision-making (Saaty, 1987). The Analytic Hierarchy Process (AHP) is an all-encompassing measuring theory (Rimantho et al., 2018). It is utilized to create ratio scales from paired comparisons that are both discrete and continuous. These comparisons could be made using measurements or a basic scale showing sentiments and preferences' relative potency (Saaty, 1987).

In this case, the AHP method is a useful tool to help decision-makers determine priorities by considering various criteria, such as road conditions, congestion levels, and economic interests (Risdiawati et al., 2021). Road maintenance should not only focus on improving physical infrastructure but also consider environmental aspects. Environmental aspects in road maintenance include the evaluation of ecologically sensitive areas along the road, the presence of drainage systems, nearby water sources, and erosion-prone areas (Kaba & Assaf, 2019).

The AHP method is often combined with other analytical methods to improve accuracy in complex decision-making, including the GIS. Integrating with the AHP enhances decision-making by incorporating spatial data into the analysis GIS (Jay et al., 2000). GIS enables the visualization of priority areas on a map, facilitating better understanding and communication among stakeholders (Nautiyal & Sharma, 2021). Most studies focus on rural or environmental management (Hu et al., 2021), while urban road maintenance applications remain limited.

Although AHP-GIS integration has been widely used, there is limited research that applies this approach in urban settings using statistically validated criteria. This study addresses that gap by combining CFA, AHP, and GIS to prioritize urban road maintenance while considering traffic volume, environmental factors, administrative responsibility, and strategic importance. The proposed model supports transparent, spatially informed, and sustainable decision-making.

3. Problem statement

Urban infrastructure management, particularly road maintenance, is a critical challenge for rapidly growing cities with limited financial and technical resources. Tebing Tinggi City in North Sumatra, Indonesia, exemplifies this situation, where 192 out of 405 existing road segments, equivalent to 89.39 km, are currently categorized as damaged as shown in Figure 1.

The deterioration is due to a combination of aging infrastructure, increasing traffic volume, poor drainage systems, and delayed or insufficient maintenance funding. These issues are compounded by the city's strategic role as a transportation corridor linking Tebing Tinggi City and surrounding industrial zones, making reliable road infrastructure essential for regional mobility and economic activity.

Tebing Tinggi City acts as the main link between the economic center in Medan City (the capital of North Sumatra province) and the surrounding industrial areas, making it a strategic area that requires reliable road infrastructure. Compared to other cities, Tebing Tinggi City has unique complexities in terms of traffic, population density, and environmental conditions, requiring a comprehensive data-driven approach such as the AHP and GIS to ensure optimal and sustainable road maintenance decisions.

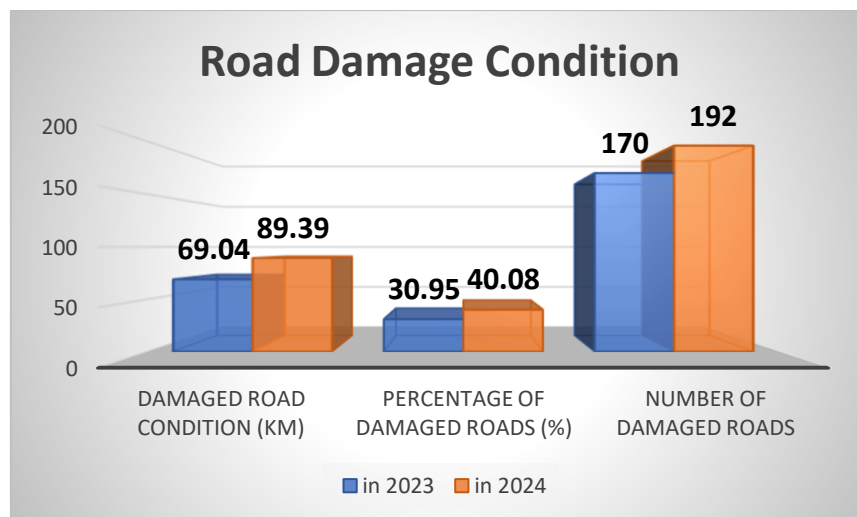


Figure 1 Road conditions in Tebing Tinggi City, 2023-2024
Source: (Dinas PUPR Kota Tebing Tinggi, 2024)

The length of damaged roads was 69.04 km in 2023 and increased to 89.39 km in 2024. Similarly, the percentage of damaged roads rose from 30.95% in 2023 to 40.08% in 2024. The number of damaged road segments also increased from 170 to 192 during the same period.

The core problem in Tebing Tinggi City lies in the absence of a structured decision-making framework to determine which roads should be prioritized for maintenance. Traditional approaches tend to be reactive, lack transparency, and often neglect broader factors such as environmental risks, strategic value, or socio-economic impact. Decision-makers must consider a wide array of variables, ranging from technical and administrative to environmental and demographic, when determining maintenance priorities. Addressing these interrelated and often conflicting factors requires a systematic and multi-criteria-based approach.

To structure this complex decision-making environment, this study integrated CFA, the AHP, and GIS. CFA was used to statistically validate and reduce the number of relevant decision criteria. The AHP supported structured pairwise comparisons among the identified factors to derive consistent priority weights, while GIS enabled spatial visualization of maintenance needs. Together, these tools form a comprehensive decision-support framework for transparent, efficient, and spatially informed road maintenance planning in urban areas like Tebing Tinggi City.

4. Methodology

4.1 Study area

This research was conducted in Tebing Tinggi City, one of the cities in North Sumatra Province, Indonesia. Tebing Tinggi City has an area of 38.438 km² which consists of five sub-districts and 35 urban villages (Bada Pusat Statistik Kota Tebing Tinggi, 2024). This urban area was selected as the study location due to its availability of spatial road data and recent maintenance reports from local authorities. The focus of this research was the city's road network, which was analyzed based on selected

criteria using the AHP-GIS approach. The spatial distribution of road segments used in the analysis is illustrated in Figure 2.

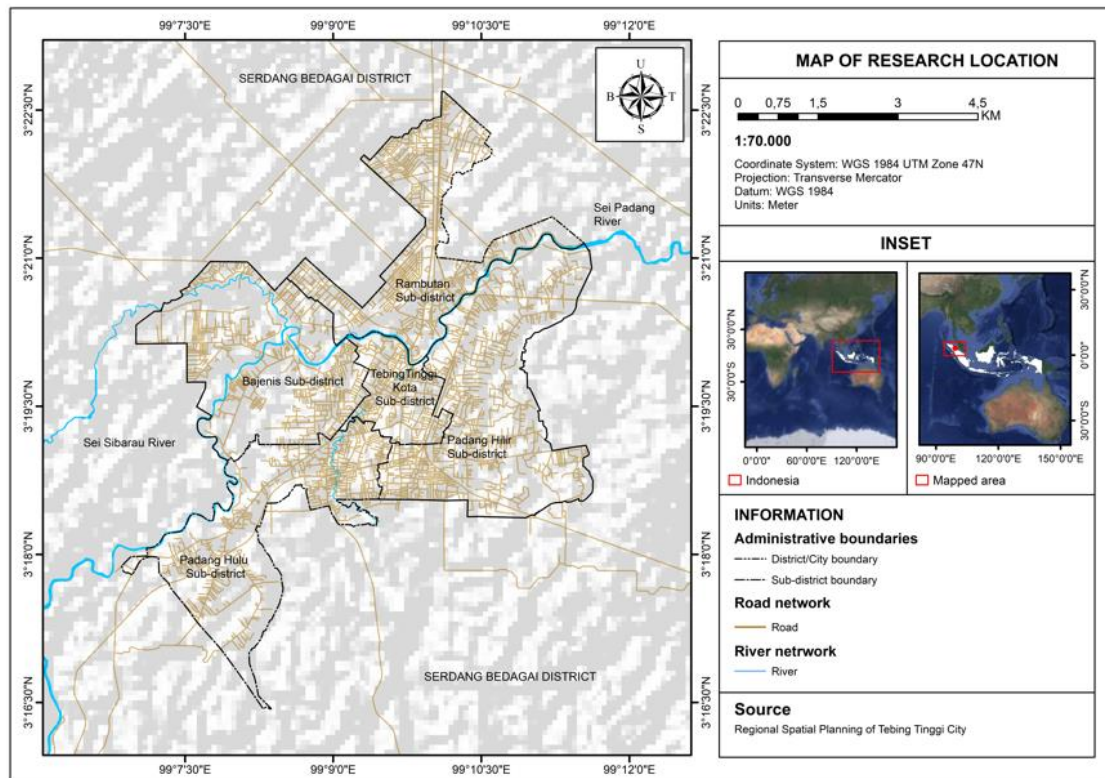


Figure 1 Map of research location

4.2 Data collection

This research used the AHP method. In the initial stage, a hierarchy of the research starting with objectives, criteria, sub-criteria and alternatives was created. Next, primary data, namely data originating from questionnaires from several stakeholders who are considered knowledgeable about road maintenance priorities, was collected along with secondary data, namely data originating from field data and data from Tebing Tinggi City government agencies, and related to the criteria and sub-criteria used in the AHP.

A GIS was used to visualize the road maintenance priorities in Tebing Tinggi City, making the analysis results more intuitive and easy to understand, even by lay readers. The GIS mapped the road sections based on the priority weights obtained from the AHP, allowing stakeholders to clearly see the locations that need improvement. In addition, the GIS supported more accurate and evidence-based spatial analysis, allowing for more efficient, transparent, and targeted road maintenance planning.

4.3 Criteria selection using CFA

The selection criteria and sub-criteria for this research were selected from previous analyses. The previous research analyzed 12 variables sourced from criteria with sub-criteria used to determine road maintenance priorities in previous research. The criteria used are the Physical Condition of the Road (Nautiyal & Sharma, 2021), Traffic Volume (Siswanto et al., 2019), Road Authority (Borghetti et al., 2024a),

Accessibility (Singh et al., 2018), Economy (Akpan & Morimoto, 2022), Social (Majstorović & Japac, 2022), Land Use (Nautiyal & Sharma, 2021), Population (Akpan & Morimoto, 2022), Environment (Kaba & Assaf, 2019), Politics (Akpan & Morimoto, 2022), Strategic Value (Kibria et al., 2024), and Handling Type (Risdiawati et al., 2021).

These variables were analyzed using CFA, conducted with SPSS version 23 and AMOS version 23; CFA analyzed the data obtained from the questionnaire regarding the level of influence of these variables on the determination of road maintenance priorities in Tebing Tinggi City, which was distributed to 108 respondents. The analysis results obtained from six variables (Table 1) were confirmed and met the validity and reliability criteria (Henseler & Schubert, 2020). These remaining variables make the construct more solid and accountable in prioritizing road maintenance (Balogun et al., 2024).

The selection of criteria and sub-criteria was based on the results of previous research, as seen in Table 1.

Table 1
Reference criteria and sub-criteria

Criteria	Sub-criteria	Previous research
Traffic Volume	Daily Traffic Volume Peak Hour Traffic Volume	Nautiyal & Sharma, 2021, Siswanto et al., 2019, Chundi et al., 2022, Borghetti et al., 2024b, Gunathilaka & Amarasingha, 2020, Hendhratmoyo et al., 2017, Ahmed et al., 2017, Singh et al., 2018, Li et al., 2018
Road Authority	Types of Road Authority Maintenance Responsibilities	Nautiyal & Sharma, 2021, Borghetti et al., 2024b, Ahmed et al., 2017, Li et al., 2018
Population	Number of Population in an Area Population Growth Rate	Akpan & Morimoto, 2022, Majstorović and Jajac, 2022
Environment	Sensitive Ecological Area Water Channel Place Water Sources Erosion Area	Kaba & Assaf, 2019, Kibria et al., 2024a
Strategic Value	National Activity Center Regional Activity Center	Majstorović and Jajac, 2022, Kibria et al., 2024
Handling Type	Road Rehabilitation Road Reconstruction	Nautiyal & Sharma, 2021, Risdiawati et al., 2021

4.4 Definition of criteria and sub-criteria

The following table presents the definitions of the criteria and sub-criteria used in the AHP, which aims to ensure uniformity in data collection and assessment. This definition helps identify the key factors that influence road maintenance prioritization, allowing for a more systematic and accurate analysis. The criteria and sub-criteria are described in Table 2.

Table 2
Description of criteria and sub-criteria

Criteria	Sub-criteria	Description
Traffic volume	Daily Traffic Volume	Average number of vehicles per day
	Peak Hour Traffic Volume	Number of vehicles during peak hours
Road priority	Types of Road Authority	Type of road, such as national, provincial, and district/city roads
	Maintenance Responsibilities	Central, provincial, and district/city governments, as well as other agencies handling highway maintenance
Population	Population in an Area	The number of people who live in a road section area
	Population Growth Rate	Projected future population growth in a road section area
Environment	Sensitive Ecological Area	Presence of critical areas of protected ecosystems, such as protected areas for flora or fauna
	Water Channel Place	Existence of water disposal flows around the road, such as drainage
	Water Sources	Presence of water sources such as standpipes, water wells, ponds, and water retaining structures near road sections
	Erosion Area	The situation that occurs due to damage to drainage (disturbed water drainage) around the road section so that it can damage the road structure
Strategic Value	National Activity Center	Urban areas that serve national, international, or provincial scale activities
	Regional Activity Center	Urban areas that serve operations at the scale of a province or several districts/cities
Handling Type	Road Rehabilitation	Restoration of road conditions that have suffered significant damage but can still be repaired, such as: structural repairs, strengthening road foundations, improving drainage and others
	Road Reconstruction	Rebuilding roads that are no longer fit for any purpose through other maintenance, by total or partial demolition of the road structure and construction of new materials and design.

4.5 AHP hierarchy and pairwise comparison

This research was conducted through systematic analyses to determine road maintenance priorities. It began with identifying relevant criteria and sub-criteria, then importance weights were calculated using the AHP method, and the results were visualized with GIS to spatially map maintenance priorities.

1. Creation of the hierarchy

The AHP hierarchy was established to determine the objectives, criteria, sub-criteria, and alternatives for road maintenance priorities (Haque, 2024). The alternatives were assessed based on predetermined criteria and sub-criteria. The alternatives included 11 roads. In 2024, a total of 192 road sections were recorded as damaged compared to 170 sections in 2023. Because of their damaged condition, these 11 roads were included in proposals from the community. The hierarchy is shown in Figure 3.

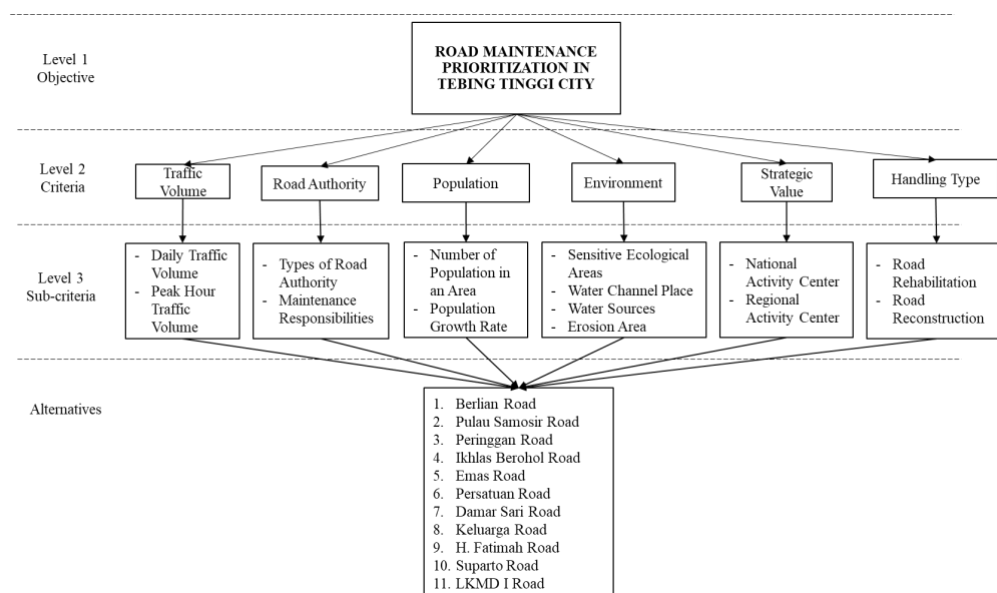


Figure 2 Analytical Hierarchy framework

A total of 11 alternative road segments were selected in the AHP hierarchy framework based on their existing condition and recommendations for repair from the local community. The selection process considered factors such as surface damage, accessibility, and traffic density directly impacting mobility and transportation services. Data was gathered through field surveys and feedback from relevant authorities and residents, ensuring that the analyzed road segments genuinely required maintenance interventions. To provide a clearer understanding of the current conditions, this study presents photographs of the existing road conditions, which are then mapped using a GIS. This visualization allowed stakeholders to objectively assess road deterioration levels and ensured that maintenance priorities were determined based on real and pressing infrastructure needs. These visuals are shown in Figure 4.

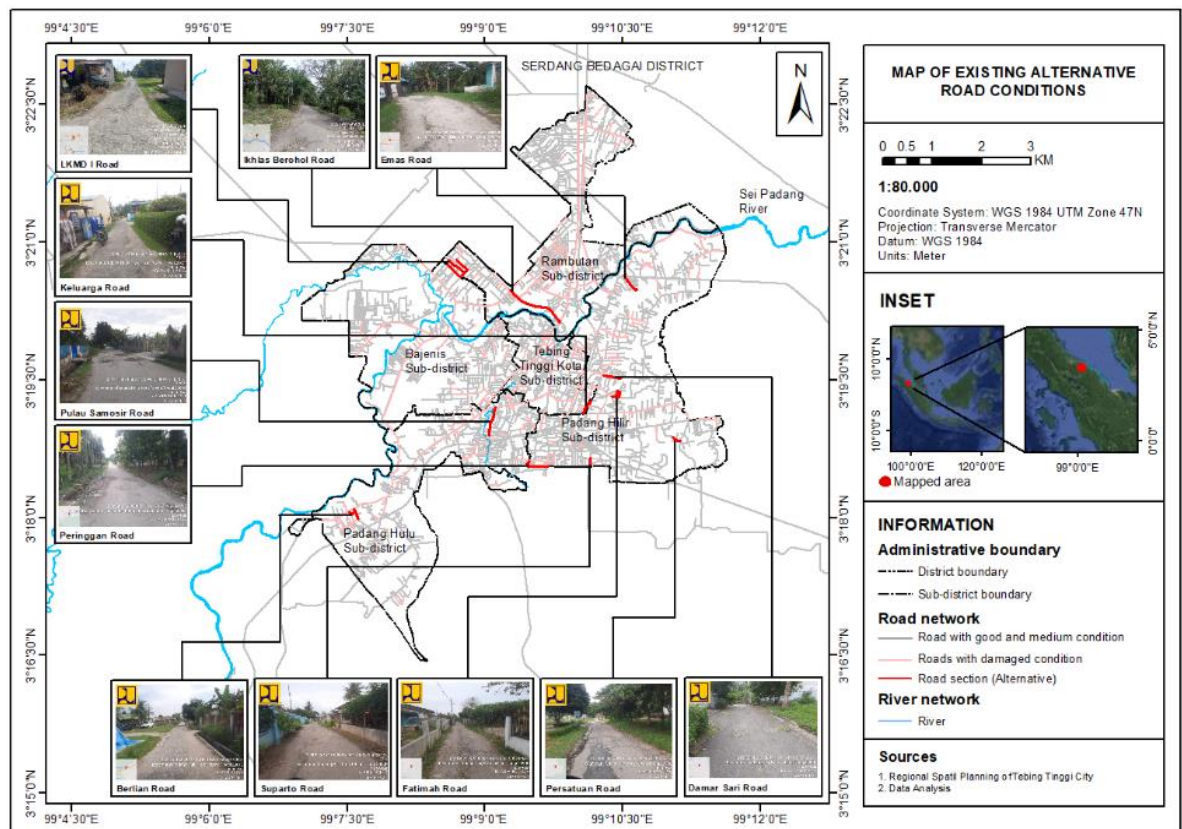


Figure 3 Existing alternative road conditions

2. Pairwise comparisons

In the AHP, pairwise comparisons determine the relative importance of criteria and sub-criteria in road maintenance prioritization. This process involves subjective judgments from experts with expertise in infrastructure, transportation, and road planning often called expert judgments or expert choice (Trivedi et al., 2023). The comparison is made with the Saaty scale which uses a 1 to 9 scale to rank importance (Fadhil et al., 2022; Saaty, 1987). With the number of criteria and sub-criteria being compared, pairwise comparisons were carried out to obtain a total assessment of $n \times [(n - 1) / 2]$ which are shown in Table 1 and Figure 3 (Risdiawati et al., 2021; Budi et al., 2020). The Saaty scale can be seen in Table 3.

Table 3
Pairwise comparison

Intensity of interest	Information
1	Both elements are equally important.
3	One element is somewhat more important than the others.
5	One element is more important than others
7	One element is very much more important than the others.
9	One element is absolutely more important than the others.
2,4,6,8	Values between two adjacent values

4.5 Weight calculation and consistency test

The AHP weight calculation was carried out by comparing the results of calculations using the AHP formula (Risdiawati et al., 2021) adapted from Saaty (1987) with calculations using SuperDecisions software version 3.2 (Aksüt et al., 2024) to assess the accuracy of the weight results obtained. Several equations used in calculating AHP weights for each criterion and sub-criteria can be seen as follows:

- (1) Calculating pairwise assessment results was done using a matrix, in this case a 6X6 matrix (n = 6);

$$\text{Matrix } 6 \times 6 = \begin{bmatrix} 1 & a & b & c & d & e \\ i & 1 & . & . & . & . \\ ii & . & 1 & . & . & . \\ iii & . & . & 1 & . & . \\ iv & . & . & . & 1 & . \\ v & . & . & . & . & 1 \end{bmatrix} \quad (1)$$

With 1 = comparison value between criteria/subcriteria; a is the comparison A:B, b = A:C, c = A:D, d = A:E, and e = A:F; and i,ii,iii ,iv,and v are the inverse comparison values.

- (2) Calculating the W_i and X_i values (Eigenvector = weight);

$$W_i = \sqrt[n]{\text{Number of Rows}} \quad (2)$$

$$X_i = \frac{W_i}{\sum W_i} \quad (3)$$

In the AHP method, the calculation of W_i (criteria priority weights) and X_i (alternative criteria values) has an important role in determining the optimal decision. W_i is the weight obtained from the pairwise comparison matrix and reflects the relative importance of each criterion in decision making. This weight is used to measure how much influence a criterion has in determining priorities, for example, in road maintenance based on damage, traffic, or flood risk factors. Meanwhile, X_i is a value that shows the extent to which an alternative meets a certain criterion, obtained from comparisons between alternatives in the context of each criterion. After obtaining the criterion weights and alternative values against the criteria, the final decision is determined by multiplying W_i and X_i for each alternative and summing the results to obtain the final priority value to determine the optimal decision. W_i is the weight obtained from the pairwise comparison matrix and reflects the relative importance of each criterion in decision making. This weight is used to measure how much influence a criterion has in determining priorities, for example, in road maintenance based on damage, traffic, or flood risk factors. Meanwhile, X_i is a value that shows the extent to which an alternative meets a certain criterion, obtained from comparisons between alternatives in the context of each criterion. After obtaining the criteria weights and alternative values against the criteria, the final decision is determined by multiplying W_i and X_i for each alternative and summing the results to obtain the final priority value.

(3) Performing pairwise comparison consistency tests (CR);

$$CI = \frac{\lambda_{\text{maximum}} - n}{n - 1} \quad (4)$$

$$CR = \frac{CI}{RI} \quad (5)$$

The RI (Random Index) value adjusted for the number of criteria/sub-criteria compared in pairs can be seen in Table 4.

Table 4
Value of RI (Random Index)

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

The value of the Consistency Ratio (CR) must be less than or equal to 0.1 ($CR \leq 0.1$) (Saaty, 1987). If the value obtained is more significant than 0.1, then the pairwise comparison assessment is repeated to reach the specified value; the comparison must be corrected to avoid bias. This step also applies to calculating weights for sub-criteria.

4.6 Field data processing (Xi calculation)

In the AHP, to prioritize road maintenance at the alternative level, field data is crucial in ensuring that each road section is assessed based on actual conditions. This data was collected in accordance with the predefined sub-criteria, thus reflecting the factors that influence maintenance needs. The collection was done through direct surveys and official sources, ensuring the accuracy and relevance of the information obtained. Furthermore, the data collected was converted into measurable weights, allowing for a more objective and systematic analysis in prioritizing road maintenance. Alternative weight calculations were carried out before obtaining the order of priority of the road sections. To obtain alternative weight values, field data from Tebing Tinggi City was needed by multiplying the weights of criteria and sub-criteria with field data (which was already in the form of weights) (Siswanto et al., 2019). This was done so that the priority order obtained involved the existing conditions on each road section and expert decisions.

To evaluate each road segment (alternative) against the selected criteria and sub-criteria, field data were collected and transformed into comparable weights. Quantitative data, such as daily traffic volume and peak hour volume, were normalized by dividing the values for each road segment by the total city-wide values. Qualitative criteria such as the presence of ecological sensitivity, drainage systems, or road authority responsibility were translated into binary scores (1 = present, 0 = absent) or weighted formulas. This transformation ensured that each road segment was assessed objectively and consistently across all criteria. The scoring method for each sub-criterion is detailed in Table 5.

Table 5
Field data weight formula

Sub-criteria	Field data weight formula
Daily Traffic Volume	$\frac{\text{daily traffic volume on the road section}}{\text{total daily traffic volume}}$
Peak Hour Traffic Volume	$\frac{\text{peak hour traffic volume on the road section}}{\text{total peak hour traffic volume}}$
Types of Road Authority	$\frac{\text{road length}}{\text{total length of city roads}}$
Maintenance Responsibilities	Central or Provincial Government = 0; City Government = 1
Number of Population in an Area	$\frac{\text{total population in sub – district where the road section is located}}{\text{total population of Tebing Tinggi City}}$
Population Growth Rate	$\frac{\text{population growth rate in sub – district where the road section is located}}{\text{population growth rate of Tebing Tinggi City}}$
Sensitive Ecological Area	Exist = 1; Does not exist = 0
Water Channel Place	$\frac{\text{length of drainage in road section}}{\text{length of Tebing Tinggi City drainage}}$
Water Sources	Exist = 1; Does not exist = 0
Erosion Area	Exist = 1; Does not exist = 0
National Activity Center	Exist = 1; Does not exist = 0
Regional Activity Center	Exist = 1; Does not exist = 0
Road Rehabilitation	$\frac{\text{length of road section for rehabilitation}}{\text{length of Tebing Tinggi City road section}} ; \text{not rehab.} = 0$
Road Reconstruction	$\frac{\text{length of road section for reconstruction}}{\text{length of Tebing Tinggi City road section}} ; \text{not recons.} = 0$

4.7 Integration with GIS

The results of the AHP were integrated with GIS to spatially visualize road maintenance priorities, allowing for a more intuitive and location-based interpretation. This integration not only clarifies the distribution of road sections in need of maintenance, but also supports more effective decision-making by considering geographical factors (Pereira et al., 2024). In addition, GIS was used to present maps of the field data weights of each sub-criteria, providing a detailed picture of the factors affecting road conditions. The final result is a road maintenance prioritization map, which facilitates more strategic and targeted planning and resource allocation (Borghetti et al., 2024a).

The integration process begins with converting the AHP result weights into a spatial format, which is then used in an overlay analysis to produce a road maintenance prioritization map. Visualization in GIS provides significant benefits in interpreting results by presenting a map of field data weights of each sub-criteria and a map of road maintenance priorities. These maps illustrate the distribution of road sections based on the urgency of maintenance, allowing policymakers to easily identify locations that require more attention. In addition, the GIS also supports the validation

of results with field data, ensuring a match between the AHP and the actual conditions at the study site.

This approach improves accuracy in road maintenance planning and supports more efficient data-driven decision-making. Considering environmental aspects, traffic, and road conditions, AHP-GIS integration can be a strategic planning tool for budget and resource optimization.

5. Results

In road infrastructure management, choosing the correct route for maintenance is very important, especially amidst limited resources and high costs. Maintenance decisions can be more accurate and efficient if various important factors are considered, such as physical road conditions, traffic volume, safety risks, and environmental impacts (Borghetti et al., 2024b).

As part of the MCDM approach, the AHP method assists in route selection by focusing funds on interventions that are most important and have the most significant impact on road users and the surrounding public (Chundi et al., 2022). This method also minimizes non-public interest so road maintenance is carried out on target and benefits the community.

5.1 Weight calculation for criteria and sub-criteria

In road infrastructure management, selecting the right segments for maintenance is crucial due to limited resources and high costs. The AHP facilitates multi-criteria decision-making by assigning weights to key factors influencing priority road maintenance. The AHP questionnaire was distributed to ten selected experts, and pairwise comparisons were conducted. A total of ten expert respondents were selected, including practitioners, academics, and government officers involved in road maintenance. These experts contributed to the prioritization process, as shown in Table 6.

Table 6
AHP respondents

Field of work	Institution	Number
Academic	Lecturer / Department of Civil Engineering, University of North Sumatera	1
Practitioner	Consultant / JICA Expert	2
Government	State Civil Servants / Government of Tebing Tinggi City	7

Table 6 shows that the respondents in this study consisted of academics, practitioners, and government officials to ensure a comprehensive AHP assessment. The academic from Universitas Sumatera Utara represented the scientific perspective, while practitioners from JICA contributed technical experience. Most of the respondents came from government agencies responsible for road planning and maintenance, ensuring the analysis results were relevant and applicable to infrastructure policy. The

results can be seen in the Appendix. Table 7 presents the pairwise comparison matrix for the main criteria, while Table 8 provides the final calculated weights.

Table 7
Pairwise Comparison Matrix of criteria

Criteria	Traffic Volume	Road Authority	Population	Environment	Strategic Value	Handling Type
Traffic Volume	1.000	1.726	1.927	2.833	1.081	1.192
Road Authority	0.580	1.000	2.251	2.787	0.846	2.834
Population	0.519	0.444	1.000	2.550	1.111	2.345
Environment	0.353	0.359	0.392	1.000	0.531	1.045
Strategic Value	0.925	1.182	0.900	1.883	1.000	3.307
Handling Type	0.839	0.353	0.426	0.957	0.302	1.000

The values in Table 7 reflect the preference between criteria, where a number greater than 1 indicates that the criteria in the row are more important than the criteria in the column, while a number less than 1 indicates the opposite. For example, Traffic Volume is rated 2.833 times more important than the environment, indicating that traffic volume is a major factor in determining road maintenance priorities. Similarly, Strategic Value is more dominant than Handling Type (3.307), indicating that the strategic value of a road is more influential than the type of handling.

5.2 Consistency test in the AHP

Once the new criteria matrix was formed, then W_i and Eigenvector (X_i) calculations were carried out using Equations 2 and 3. Based on the results of the AHP conducted with 10 expert respondents, the analysis identified Criteria A as the most important, with a normalized priority weight of approximately 0.233. This was followed closely by Criteria B (0.221) and Criteria E (0.208), indicating their significant influence in the decision-making process.

Criteria C ranked fourth with a weight of 0.165, while Criteria F and D received the lowest weights, 0.089 and 0.085, respectively, suggesting relatively lower importance. These weights were derived through normalization of the weighted sum vectors and reflect the aggregated judgments of all participating experts. From these results, Traffic Volume (A) has the highest weight ($X_i = 0.233$), followed by Road Authority (B = 0.221) and Strategic Value (E = 0.208), indicating that these factors have the greatest influence in determining road maintenance priorities. In contrast, Environment (D = 0.085) and Handling Type (F = 0.089) have the lowest weights, indicating that environmental aspects and handling type have less influence than other factors.

To ensure the reliability of the pairwise comparisons, a consistency test was conducted using the Consistency Index (CI) and Consistency Ratio (CR). The CI was calculated as shown in Equations 4 and 5, where RI depends on the number of

criteria, as shown in Table 5. The results showed that all CR values remained within the acceptable threshold (CR value ≤ 0.1 is 0.048), confirming that the judgments were consistent. The final weights of the criteria derived from this consistent evaluation are presented in Table 8.

Table 8
Weight of road maintenance priority criteria

Criteria	Weight
Traffic Volume	0.233
Road Authority	0.221
Strategic Value	0.208
Population	0.165
Handling Type	0.089
Environment	0.085

The highest weight was given to Traffic Volume (0.233), indicating that Traffic volume is a major factor in determining which roads should be prioritized for maintenance. This is logical as high-traffic roads tend to deteriorate faster and have a greater impact on mobility. The Road Authority (0.221) and Strategic Value (0.208) factors also have significant weights, indicating that the road management authority and its strategic value (e.g. access to important facilities) are also key considerations in maintenance. The Population factor (0.165) indicates that the number of people affected also has a considerable influence, although not as much as the traffic and road authority factors. Meanwhile, Handling Type (0.089) and Environment (0.085) have the lowest weights, indicating that Handling Type and Environmental factors, while important, have less influence on decisions than other factors. However, in the context of MCDM, all these factors still contribute to determining the best decision based on multiple interrelated perspectives.

Calculations in the AHP method are not only performed at the level of the main criteria but are also applied to the sub-criteria to ensure that each factor in decision-making is analyzed hierarchically. After determining the priority weights between criteria through a pairwise comparison matrix, the same step is performed on the sub-criteria under each main criterion to assess their importance relative to the research objectives. With this process, road maintenance prioritization not only considers the main factors such as Traffic Volume or Road Authority, but also takes into account the specific factors within them, resulting in a more accurate decision. To enhance clarity in viewing the calculation results, Table 9 summarizes the weights for each criterion and sub-criterion.

Table 9
Summary of the results of the weight value of criteria and sub-criteria

Criteria	Weight of criteria	Sub-criteria	Weight of sub-criteria	Final weight
Traffic Volume	0.233	Daily Traffic Volume	0.728	0.170
		Peak Hour Traffic Volume	0.272	0.063
Road Authority	0.221	Types of Road Authority	0.705	0.156
		Maintenance Responsibilities	0.295	0.065
Population	0.165	Population in an Area	0.668	0.110
		Population Growth Rate	0.332	0.055
Environment	0.085	Sensitive Ecological Area	0.364	0.031
		Water Channel Place	0.224	0.019
		Water Sources	0.219	0.019
		Erosion Area	0.193	0.016
Strategic Value	0.208	National Activity Center	0.614	0.128
		Regional Activity Center	0.386	0.080
Handling Type	0.089	Road Rehabilitation	0.805	0.072
		Road Reconstruction	0.195	0.017

After obtaining the results from calculating road maintenance priority weights, both criteria and sub-criteria weights, as well as the accuracy of the weight values, a weight calculation test using SuperDecisions software version 3.2 was performed. SuperDecisions is a software designed to assist decision-making based on the AHP and Analytical Network Process (ANP). The software allows the analysis of various criteria and sub-criteria that interconnect or influence the decision-making process. It is designed to help users create complex hierarchical models (Aksüt et al., 2024). This application enables pairwise comparisons for each element in the hierarchy, weight calculations, and consistency tests to ensure accurate results. The software is particularly useful for multi-criteria analysis on various topics, such as infrastructure planning, resource management, and policy prioritization (Ishak et al., 2020).

The calculation procedure using SuperDecisions is the same as what was done previously, only the calculations were performed by the application.

5.3 Priority ranking of road segments

As explained in the research methodology, alternative calculations were carried out by multiplying the results of each criterion with its sub-criteria with field data for each road segment. The weights of the criteria and sub-criteria and the data were taken from the field with the help of government agencies in Tebing Tinggi City (formula as shown in Table 5). The results of the alternative weights are shown in Table 10.

Table 10
Alternative weights

Alternative	Traffic Volume		Road Authority		Population		Environment				Strategic Value		Handling Type		Alternative Weight
	0.233		0.221		0.165		0,085				0,208		0,089		
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.728	0.272	0.705	0.295	0.668	0.332	0.364	0.224	0.219	0.193	0.614	0.386	0.805	0.195	
Berlian Road	0.128	0.128	0.003	1.000	0.019	2.102	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.213
Pulau Samosir Road	0.128	0.128	0.003	1.000	0.040	0.568	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.131
Peringgann Road	0.086	0.086	0.003	1.000	0.033	1.022	0.000	0.002	0.000	0.000	0.000	0.000	0.002	0.000	0.145
Ikhlas Berohol Road	0.037	0.037	0.003	1.000	0.042	1.580	0.000	0.006	0.000	0.000	0.000	0.000	0.006	0.000	0.166
Emas Road	0.086	0.086	0.002	1.000	0.022	0.904	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.137
Persatuan Road	0.092	0.092	0.006	1.000	0.059	2.836	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.249
Damar Sari Road	0.092	0.092	0.002	1.000	0.031	1.326	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.163
Keluarga Road	0.128	0.128	0.001	1.000	0.029	0.804	0.000	0.003	0.000	0.000	0.000	0.000	0.003	0.000	0.143
H. Fatimah Road	0.086	0.086	0.001	1.000	0.031	1.326	0.000	0.003	0.000	0.000	0.000	0.000	0.003	0.000	0.162
Suparto Road	0.086	0.086	0.003	1.000	0.033	1.022	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.145
LKMD I Road	0.050	0.050	0.004	1.000	0.042	1.580	0.000	0.004	0.000	0.000	0.000	0.000	0.004	0.000	0.169

Description:



Criteria weight



Sub-criteria weight



Field data weight

A: Daily traffic volume
B: Peak hour traffic volume
C: Types of road authority
D: Maintenance responsibilities
E: Number of population in area
F: Population growth rate
G: Sensitive ecological area
H: Water channel place
I: Water sources
J: Erosion area
K: National activity center
L: Regional activity center
M: Road rehabilitation
N: Road reconstruction

Table 10 shows the results of calculating alternative road maintenance weights based on the Traffic Volume, Road Authority, Population, Environment, Strategic Value, and Handling Type criteria in the AHP. The weight of each criterion (green row) has been multiplied by the weight of the sub-criteria (blue row) and the alternative value on each criterion, resulting in a total weight for each road in the alternative weight column. Persatuan Road has the highest weight (0.249), indicating that this road has the highest priority level for maintenance compared to other alternatives. It is followed by Berlian Road (0.213) and Damar Sari Road (0.163), which also have significant weights. Meanwhile, roads with lower weights, such as Pulau Samosir Road (0.131) and Suparto Road (0.145), have lower maintenance urgency than other alternatives. The weights between roads are influenced by the weights of the predetermined criteria, where Traffic Volume and Road Authority have a major influence in determining maintenance priorities. This shows that roads with high traffic volume and more complex maintenance authority are more prioritized.

Based on the calculation of alternative weights using the AHP method, the maintenance priority order for the 11 road sections was obtained, as shown in Table 11.

Table 11
List of road maintenance priorities for Tebing Tinggi City

Road section	Weight	Priority order
Persatuan Road	0.249	1
Berlian Road	0.213	2
LKMD I Road	0.169	3
Ikhlas Berohol Road	0.166	4
Damar Sari Road	0.163	5
H. Fatimah Road	0.162	6
Peringgann Road	0.145	7
Suparto Road	0.145	7
Keluarga Road	0.143	8
Emas Road	0.137	9
Pulau Samosir Road	0.131	10

The results of the alternative weighting of eleven Tebing Tinggi City roads show that Persatuan Road is the first priority for recommended road maintenance, followed by Berlian Road in second place, and LKMD I Road in third. In fourth place is Ikhlas Berohol Road, fifth is Damar Sari Road, and sixth is H. Fatimah Road. Interestingly, the roads in seventh place have the same weight value of 0.145. Considering the location of the two roads in adjacent areas, the field assessment is also close to the same value, so Peringgann Road and Suparto Road occupy the seventh priority order, eighth is Keluarga Road, ninth is Emas Road, and tenth is Pulau Samosir Road.

These results show the relationship between the weights obtained from the AHP calculation and the priority order of road maintenance. Roads with the highest weights are prioritized, as the weights reflect the level of importance or need for maintenance based on predetermined criteria. Persatuan Road has the highest weight (0.249), so it ranks first in the maintenance priority list. This indicates that this road has more urgent conditions or factors than other road sections. In contrast, Pulau Samosir Road has the lowest weight (0.131), placing it last (10th priority). This indicates that Pulau Samosir Road has a lower maintenance urgency compared to other road sections.

This priority ranking is directly influenced by the weights obtained from the AHP process, which has considered factors such as traffic volume, road authority, population density, environmental conditions, strategic value, and type of treatment required. With this approach, decision-making becomes more objective and data-driven, allowing resources to be allocated efficiently to maintain the road sections that need the most improvement first.

6. Discussion

Integrating GIS in this study provides a spatial representation of prioritized road maintenance, allowing decision-makers to visually assess and analyze critical road sections. By overlaying the priority scores derived from the AHP onto a geospatial map, this visualization highlights high-priority roads that require immediate intervention, facilitating a more data-driven and systematic approach to resource allocation. Decision-makers can quickly identify roads that are severely damaged, have high traffic volumes, or are of strategic value, ensuring that maintenance efforts are directed where they are most needed. In addition, GIS mapping allows the integration of other spatial factors, such as environmental conditions and land use, further enhancing the decision-making process. Visualizing road maintenance needs in a geographical context increases transparency, supports infrastructure planning, and ensures that budget allocations match actual conditions on the ground, ultimately resulting in a more efficient and sustainable road management strategy. The visualization of the results of priority roads for road maintenance in Tebing Tinggi City is shown in Figure 5.

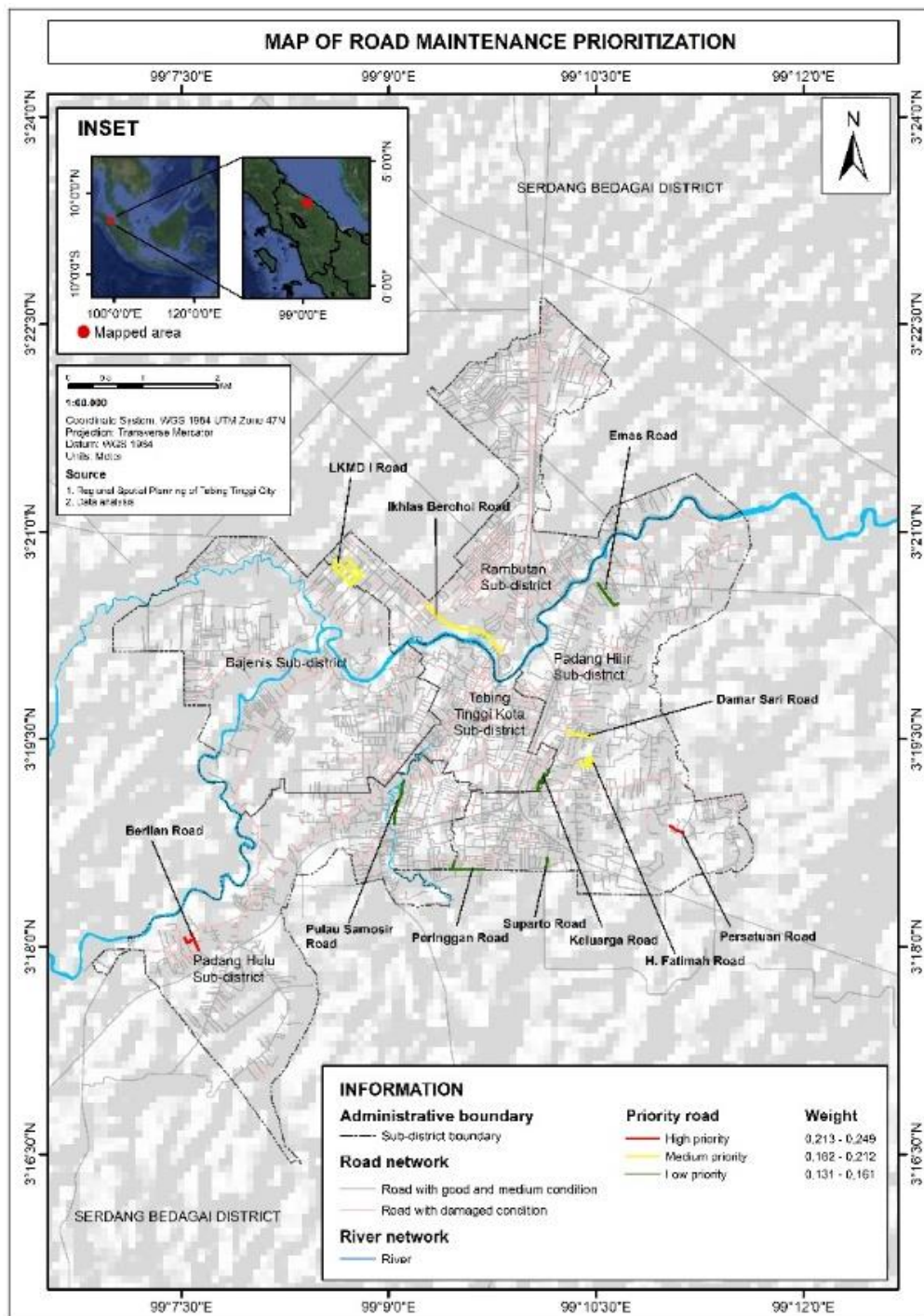


Figure 4 Map of road maintenance priority segments

This overlay map shows the prioritization of road maintenance in Tebing Tinggi City based on the results of an analysis using the AHP method combined with a GIS. This map categorizes road sections into three priority levels based on the calculated weights:

1. High priority (0.213 - 0.249): Marked in red, this category includes Persatuan Road, Berlian Road, and LKMD I Road. These roads have the highest level of urgency for maintenance due to high traffic volume, population density, strategic value, and potential environmental impacts.

2. Medium priority (0.162 - 0.212): Marked in yellow, this category includes Ikhlas Berohol Road, Damar Sari Road, and H. Fatimah Road. While these roads require maintenance, the urgency level is lower than the high-priority category. Factors such as moderate deterioration and lower traffic density compared to the highest category are considered in this grouping.
3. Low priority (0.131 - 0.161): Marked in green, this category includes Peringgian Road, Suparto Road, Keluarga Road, Emas Road, and Pulau Samosir Road. Roads in this category are still in better condition than the other categories so that maintenance can be scheduled over a longer period of time or focused on preventive measures.

Geographically, the high- and medium-priority road sections are spread across various sub-districts, where the infrastructure is more vulnerable to damage, due to high traffic loads and environmental factors such as proximity to rivers, which increase the risk of flooding and erosion. Meanwhile, low-priority road sections are generally located in areas with less impact on the city's main connectivity.

The map also displays sub-district administrative boundaries to provide a clearer spatial context for road maintenance planning. This GIS-based analysis enables policymakers to determine effective, efficient, and data-driven maintenance strategies that optimize resource allocation according to the needs on the ground.

In the visualization process, the results of road maintenance priorities are mapped, and the weights of field data are obtained from various determining variables. These weights reflect the level of importance of each criterion and sub-criteria used in the analysis, such as Traffic Volume, Road Authority, Population density, Environmental factors, Strategic Value, and type of treatment required. By utilizing GIS-based mapping techniques, this weight data was visualized to provide a more comprehensive picture of the spatial distribution of road conditions and characteristics in Tebing Tinggi City. This visualization helps identify the distribution pattern of roads with high weights and their relationship with environmental factors and existing infrastructure. Thus, decision-making related to road maintenance can be done more objectively and data-based (see Appendix for field data weight maps attached).

The results of this study indicate that Traffic Volume (23.3%) and Road Authority (22.1%) are the most influential factors in determining road maintenance priorities. This finding suggests that roads with high traffic intensity require immediate attention to maintain mobility, safety, and overall infrastructure reliability. Simultaneously, road authority is crucial in ensuring that the designated administrative body—municipal, provincial, or national—has the necessary responsibility and resources for maintenance. Roads under municipal or provincial control may experience different levels of maintenance urgency based on budget constraints and strategic planning priorities.

The integration of the AHP and GIS in this study offers a systematic, objective, and data-driven approach to decision-making in road maintenance planning. The AHP provides a structured framework for quantifying decision factors, while GIS visualizes and analyzes spatial data to pinpoint high-priority road sections. This combined methodology optimizes resource allocation and ensures that maintenance efforts are targeted, efficient, and justified based on empirical data. By leveraging GIS, decision-makers can geospatially assess which areas require immediate intervention, reducing the risk of subjective or politically driven decisions.

Furthermore, the study's findings align with previous research highlighting the importance of strategic value and environmental considerations in infrastructure planning. Roads contributing to economic activity, regional connectivity, and disaster resilience often require proactive maintenance to ensure long-term sustainability. Considering environmental factors, such as drainage systems, ecological sensitivity, and erosion risks, supports sustainable development by mitigating potential negative impacts on the surrounding ecosystem.

By developing a replicable framework, this study provides a methodology that can be applied in other urban areas facing similar infrastructure challenges. Integrating the AHP and GIS offers a scalable solution that can be adapted to different cities, ensuring that road maintenance planning remains data-driven, sustainable, and aligned with urban development goals. Future research could expand upon this approach by incorporating real-time traffic data, climate resilience indicators, and predictive maintenance models, further enhancing the efficiency and accuracy of road infrastructure management.

6.1 Sensitivity Analysis

To test the robustness of the decision-making model, a sensitivity analysis was conducted by adjusting the weights of the main criteria and observing the impact on the ranking of road maintenance priorities. In particular, the three most influential criteria, Traffic Volume (23.3%), Road Authority (22.1%), and Strategic Value (20.8%) were selected for the sensitivity test.

For each scenario, the weight of one criterion was increased by 10%, while the remaining criteria were proportionally adjusted so that the total weight remained 100%. This approach is commonly applied in MCDM studies to examine the stability of outcomes when decision-maker preferences vary slightly. For more details, the scenario for the sensitivity analysis is shown in Table 12.

Table 12
Sensitivity scenarios

Scenario	Adjusted	New weight	Effect on ranking
Baseline	Original Weight	Traffic Volume: 23.3% Road Authority: 22.1% Strategic Value: 20.8%	Persatuan Road > Berlian Road > LKMD I Road
Scenario 1	Traffic Volume +10%	Traffic Volume: 25.6%, others adjusted proportionally	No change in top 3
Scenario 2	Road Authority +10%	Road Authority: 24.3%	No change in top 3
Scenario 3	Strategic Value +10%	Strategic Value: 22.9%	Minor shift in Ikhlas Berohol Road (Rank 4 th) and Damar Sari Road (Rank 5 th)

The sensitivity analysis shows that the top-priority road segments, Persatuan Road, Berlian Road, and LKMD I Road, remain unchanged across all tested scenarios. This indicates that the decision model is robust and not overly sensitive to slight variations in the weight of individual criteria. Minor changes were observed in the middle and lower ranks (e.g., Suparto and Pulau Samosir Roads), but these did not affect the strategic decision-making at the top level. The stability of results under different weighting scenarios increases the confidence in the AHP model and supports its use for road maintenance prioritization in similar urban contexts. Note that in Scenario 1, the weight of Traffic Volume was increased from 0.233 to 0.256. The remaining criteria weights were proportionally decreased to maintain a total of 1.000.

7. Conclusion

This study successfully integrates the AHP with a GIS to determine road maintenance priorities based on multiple criteria. The results indicate that Traffic Volume (23.3%) and Road Authority (22.1%) are the most influential factors, highlighting the importance of maintaining roads with high traffic demand and ensuring that administrative responsibility is properly managed. Other significant factors, such as Strategic Value (20.8%) and Population (16.5%), also play crucial roles in prioritizing road maintenance, while Handling Type (8.9%) and Environmental considerations (8.5%) have relatively lower weights.

Integrating the AHP and GIS in this study enhances decision-making efficiency by providing a structured, quantitative approach to evaluating maintenance priorities while leveraging spatial visualization for more effective resource allocation. The GIS-based mapping of priority roads facilitates a clear, intuitive understanding of which sections require urgent intervention, ensuring that decision-makers can optimize budget distribution and maintenance strategies accordingly. The study also reinforces the importance of environmental factors in sustainable infrastructure planning, ensuring that maintenance decisions align with long-term urban development goals.

Future research could refine this approach by exploring the integration of real-time traffic flow monitoring using IoT (Internet of Things) sensors, development of climate-resilient road infrastructure indicators (e.g., flood susceptibility, heat resistance), and predictive maintenance modeling using AI-based approaches. These improvements would enable decision-makers to not only react to existing road conditions but to also anticipate potential degradation, improving both the accuracy and timeliness of infrastructure management decisions.

This study underscores the critical role of integrated spatial and multi-criteria decision-making tools in optimizing infrastructure maintenance, supporting urban sustainability, and enhancing road network reliability. By employing AHP-GIS integration, policymakers and urban planners can ensure a more efficient, transparent, and scientifically driven approach to road maintenance prioritization.

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APPENDIX

Results of paired comparison criteria

Criteria/ Respondents	A:B	A:C	A:D	A:E	A:F	B:C	B:D	B:E	B:F	C:D	C:E	C:F	D:E	D:F	E:F
R1	1/5	1/7	1	1/2	2	1/7	1	1	5	5	3	7	1	3	3
R2	1	1	1	1/3	1/9	1	1/5	1/5	1/9	1/2	1/3	1/9	1/3	1/9	1/5
R3	3	5	3	3	1	3	1	1	1/2	1	1	1/3	1	1/3	1/3
R4	1/3	3	3	1/3	1/7	9	9	3	1	1	1/3	1/7	1/7	1/7	1
R5	1/9	2	5	1/3	1	5	9	2	9	3	1/3	3	1/9	1	9
R6	1/2	3	5	1/5	1	3	5	1/7	3	2	1/9	1/3	1/9	1/3	7
R7	3	1	5	2	1/3	1/3	1	1/3	1/5	5	3	1/3	1/2	1/3	1/3
R8	5	3.	3	3	1/3	1/5	1/3	1/3	1/5	3	1	1/5	1	1/5	1/5
R9	4	1	2	1	5	1/3	1/3	1/5	1/3	1	1	3	1	3	3
R10	1/9	1/8	1/3	1/9	1	1/2	1	1/4	9	4	1	9	1/9	2	9

Description:

R1 to R10: Respondents 1 to 10

A: Criteria of Traffic Volume

B: Criteria of Road Authority

C: Criteria of Population

D: Criteria of Environment

E: Criteria of Strategic Volume

F: Criteria of Handling Type

Result of paired comparison sub-criteria

Criteria/ Respondents	A:B	C:D	E:F	G:H	G:I	G:J	H:I	H:J	I:J	K:L	M:N
R1	1/7	9	5	1/2	1	1/5	2	1/3	1/5	5	1
R2	1/5	1/9	1/7	1/5	1/5	1/9	1/2	1/5	1/2	1/7	9
R3	3	1/3	1	1	1	1	1	1	1	1	3
R4	3	1	1/3	1/3	1/3	1/7	1	1/3	1/3	1/3	3
R5	9	9	7	1	1	1	1	1	1	1/9	5
R6	5	1/5	1/5	9	3	5	1/5	1/2	2	5	5
R7	3	3	3	1/2	1/3	1/5	1/2	1/3	1/3	3	1/5
R8	3	1	1/3	1	1	1	1	3	3	1/5	3
R9	1/3	1/5	3	1/5	1/5	1/7	1	1/3	1/3	1	3
R10	1/9	1/9	1/9	3	9	9	2	5	3	1/9	9

Description:

R1 to R10: Respondents 1 to 10

A: Sub-criteria of Daily Traffic Volume (Average Daily Traffic/ADT)

B: Sub-criteria of Peak Hour Traffic Volume

C: Sub-criteria of Types of Road Authority

D: Sub-criteria of Maintenance Responsibilities

E: Sub-criteria of Number of Population in an Area

F: Sub-criteria of Population Growth Rate

G: Sub-criteria of Sensitive Ecological Areas

H: Sub-criteria of Water Channel Place

I: Sub-criteria of Water Sources

J: Sub-criteria of Eros Area

K: Sub-criteria of National Activity Center

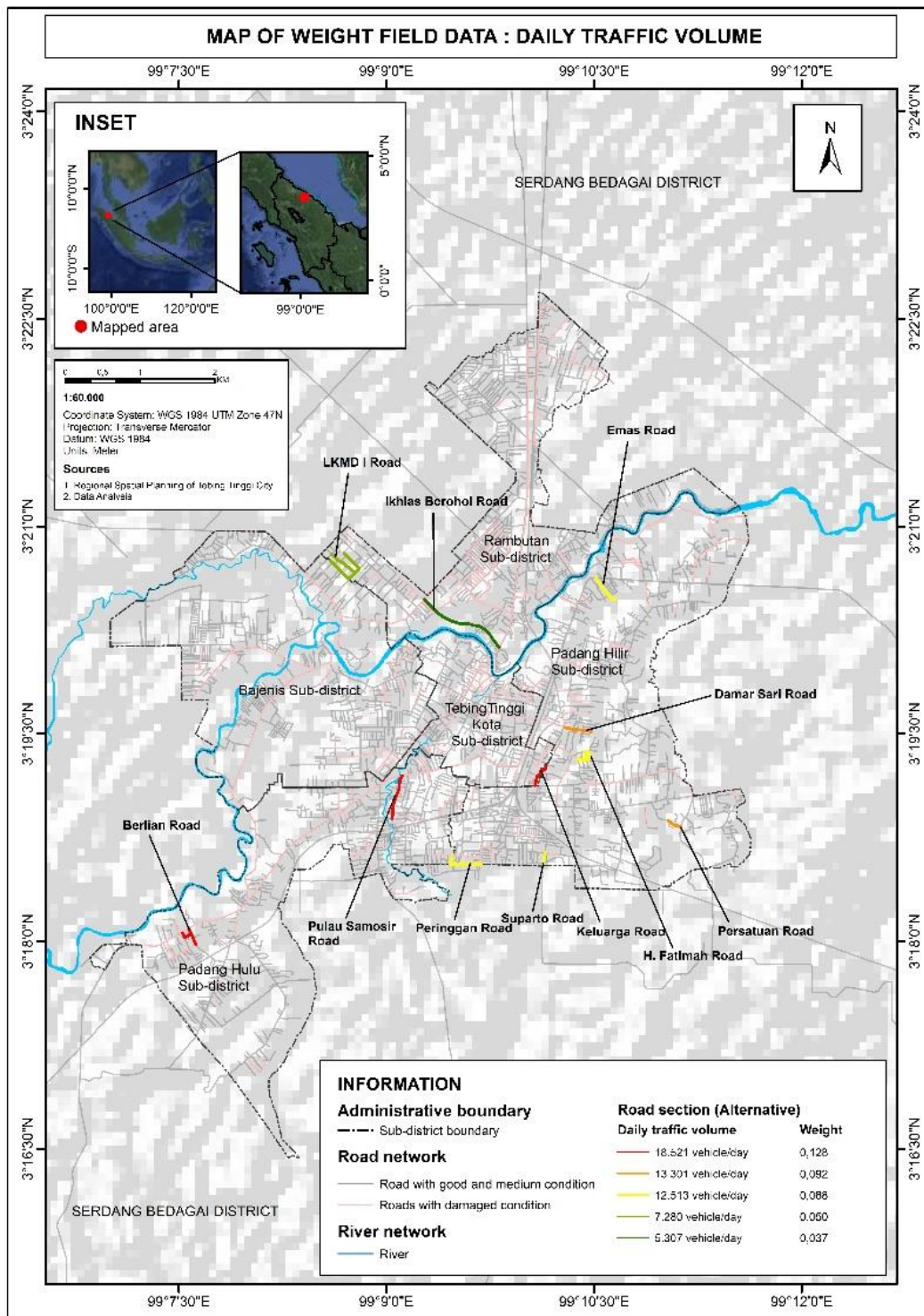
L: Sub-criteria of Regional Activity Center

M: Sub-criteria of Road Rehabilitation

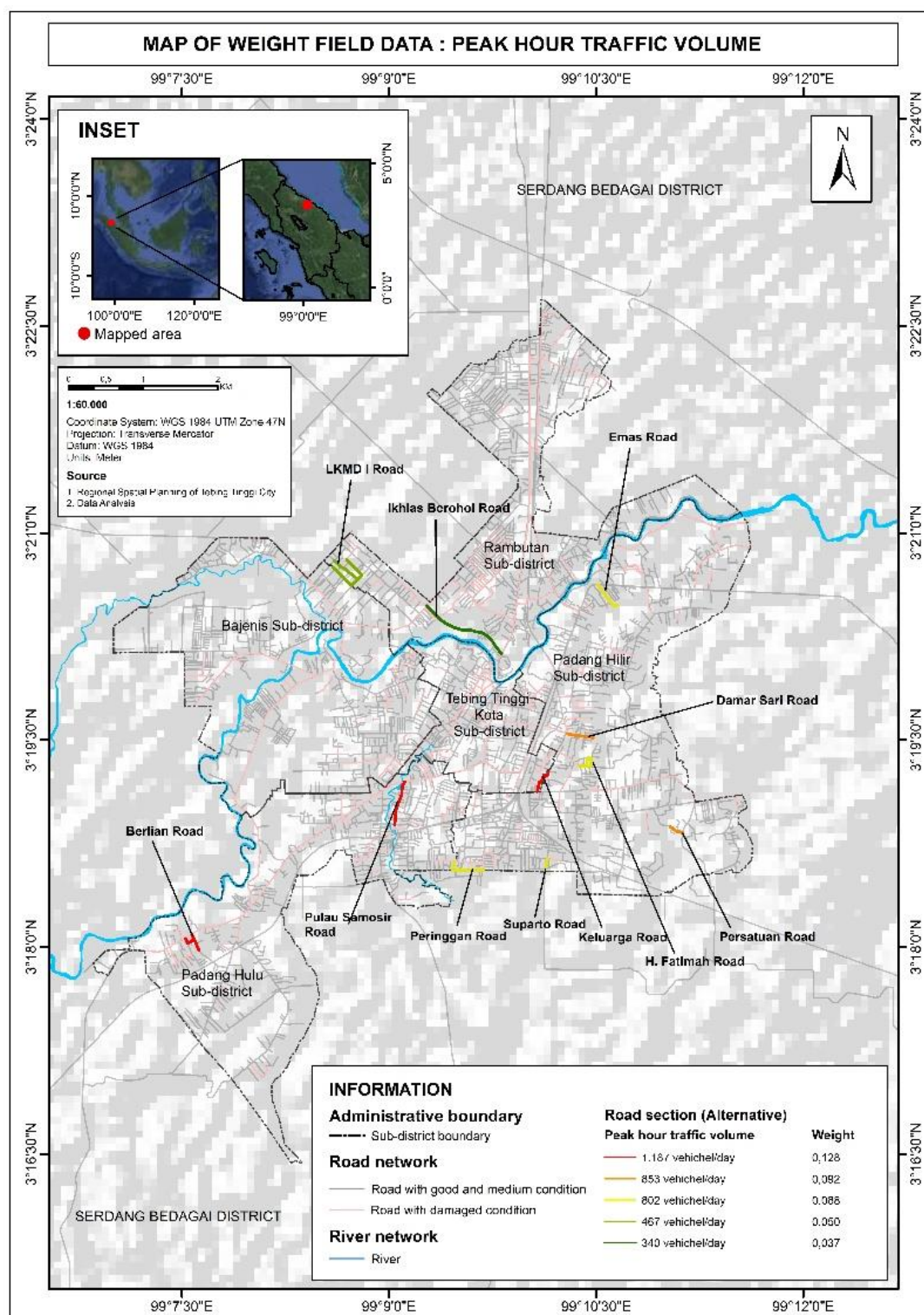
N: Sub-criteria of Road Reconstruction

Maps of Field Data

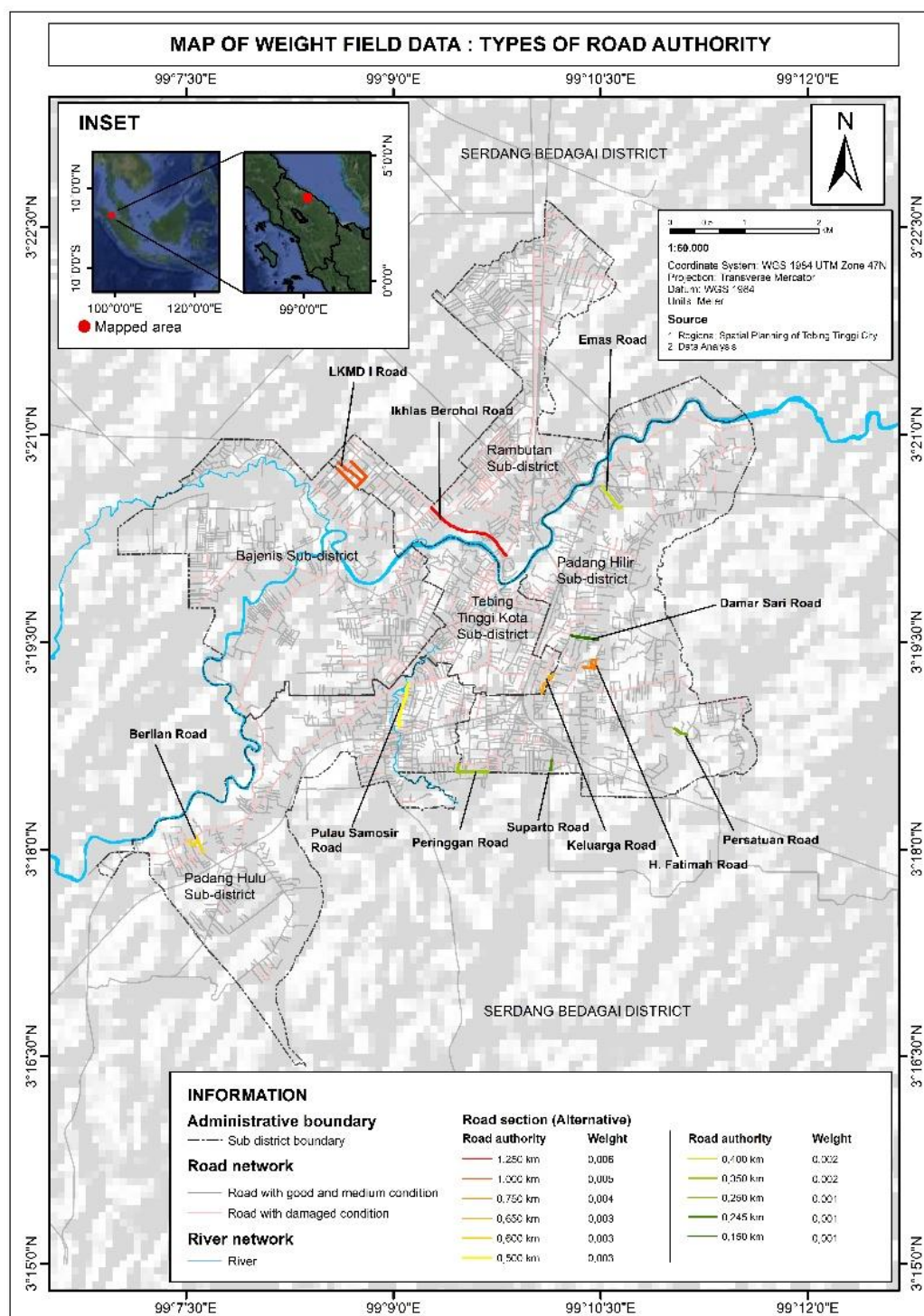
Daily Traffic Volume



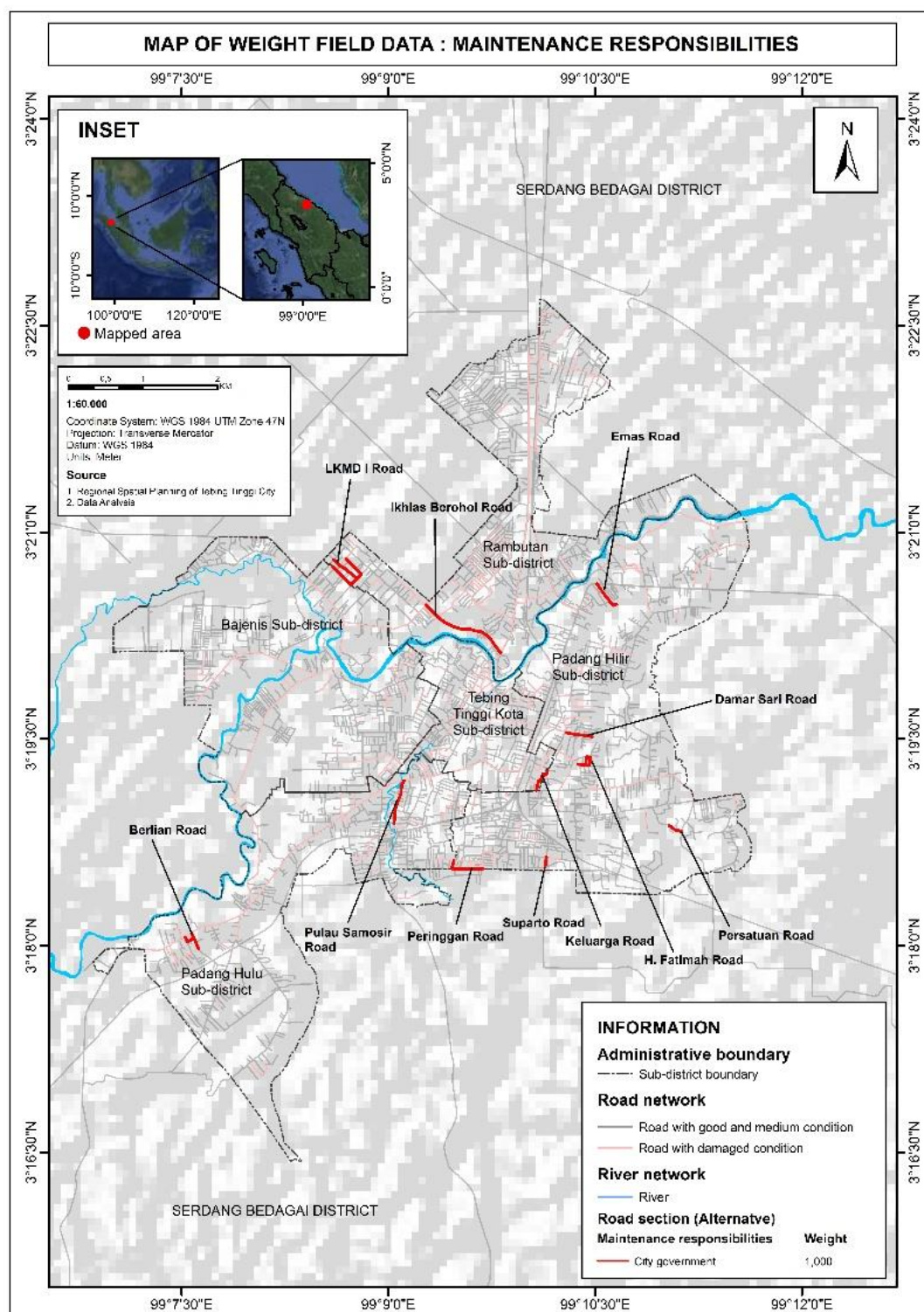
Peak Hour Traffic Volume



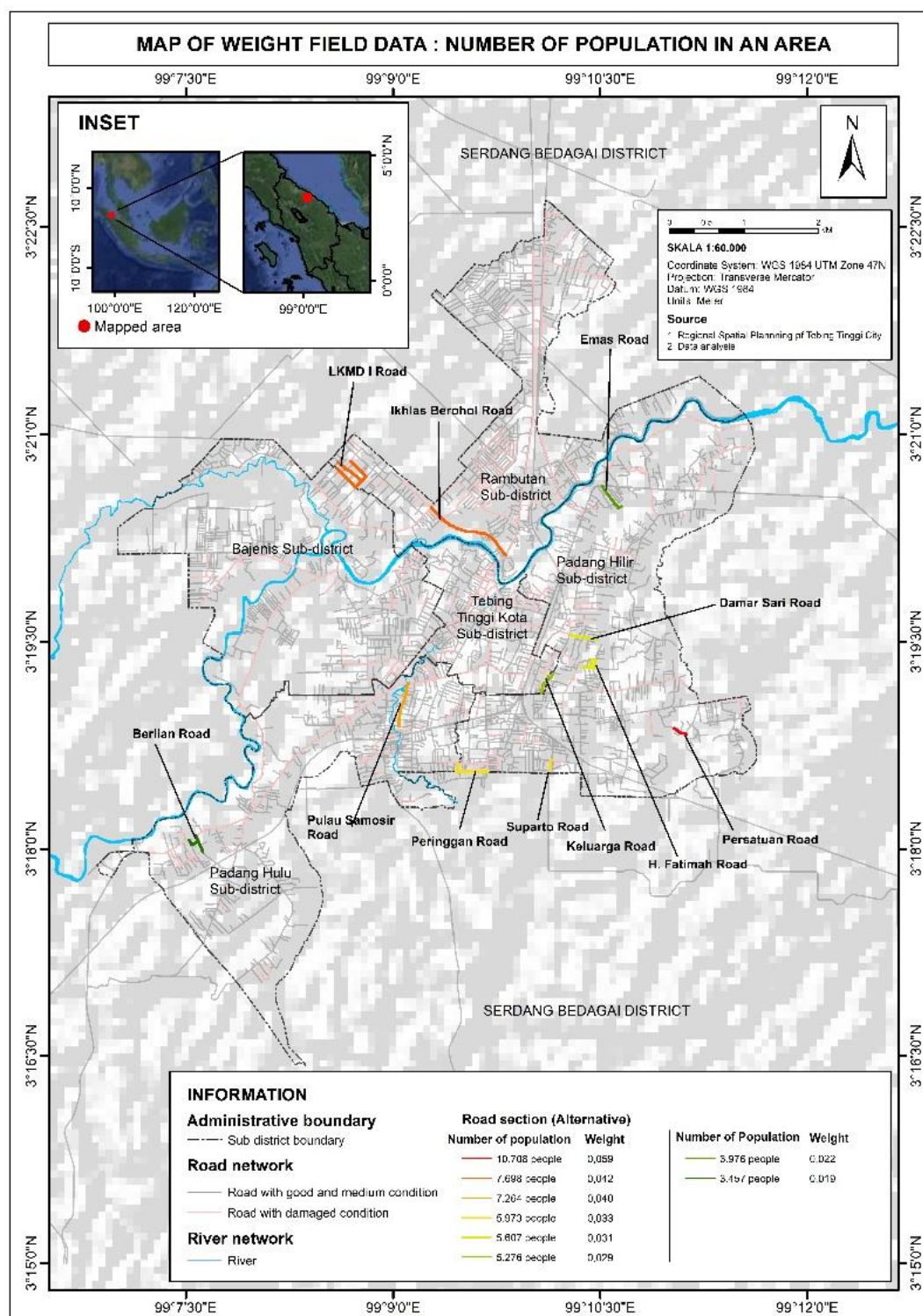
Road Authority



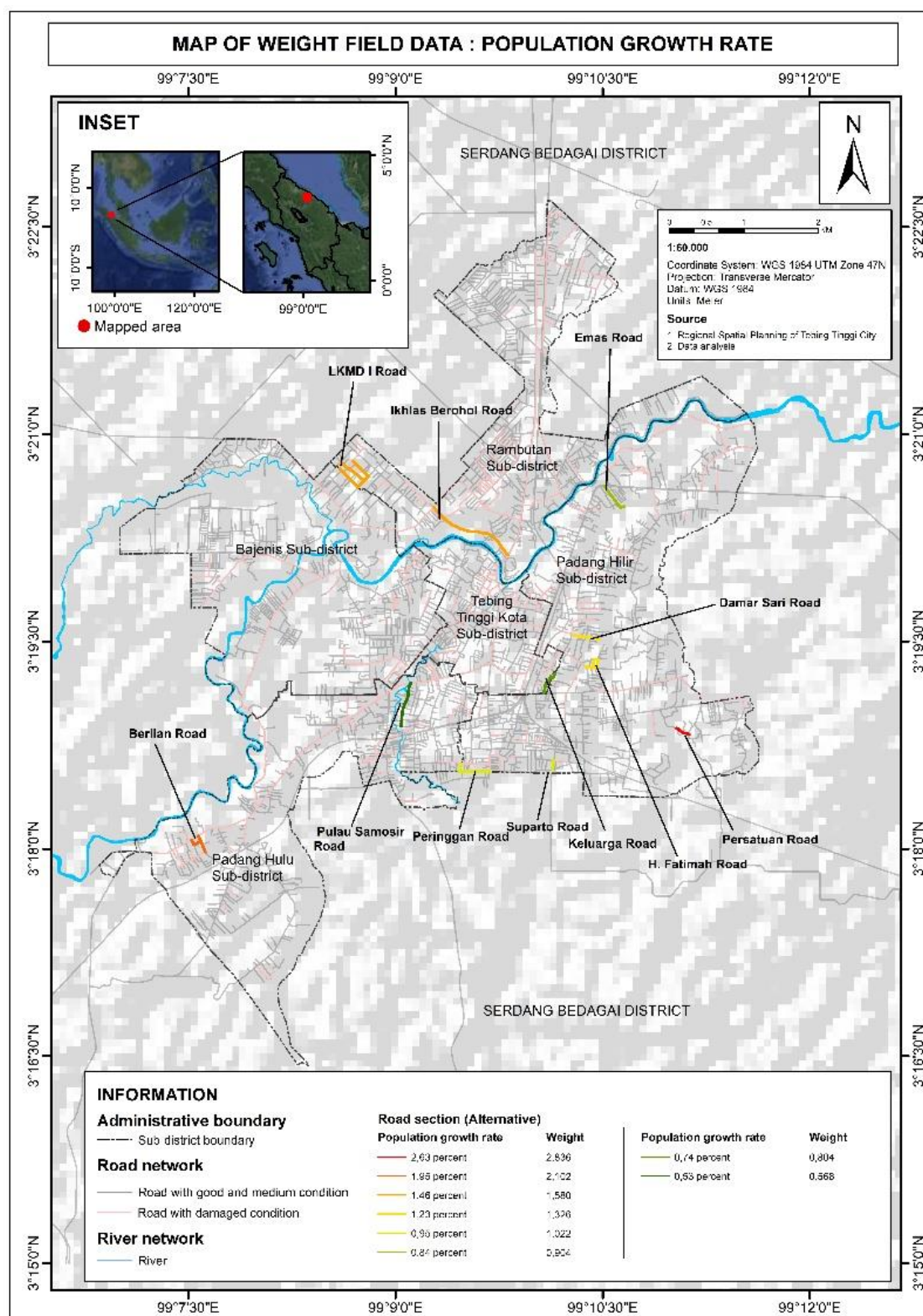
Maintenance Responsibilities



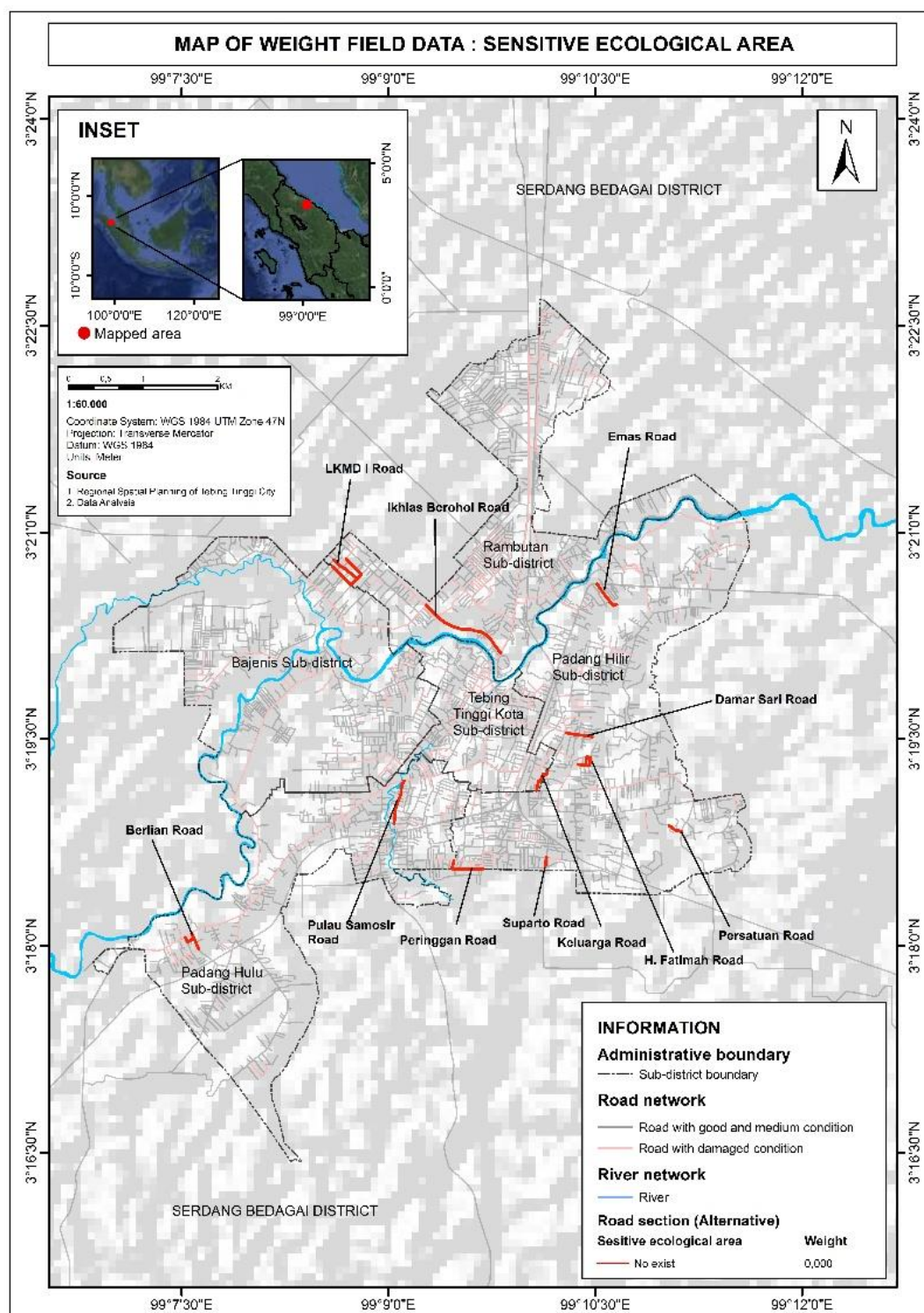
Population in An Area



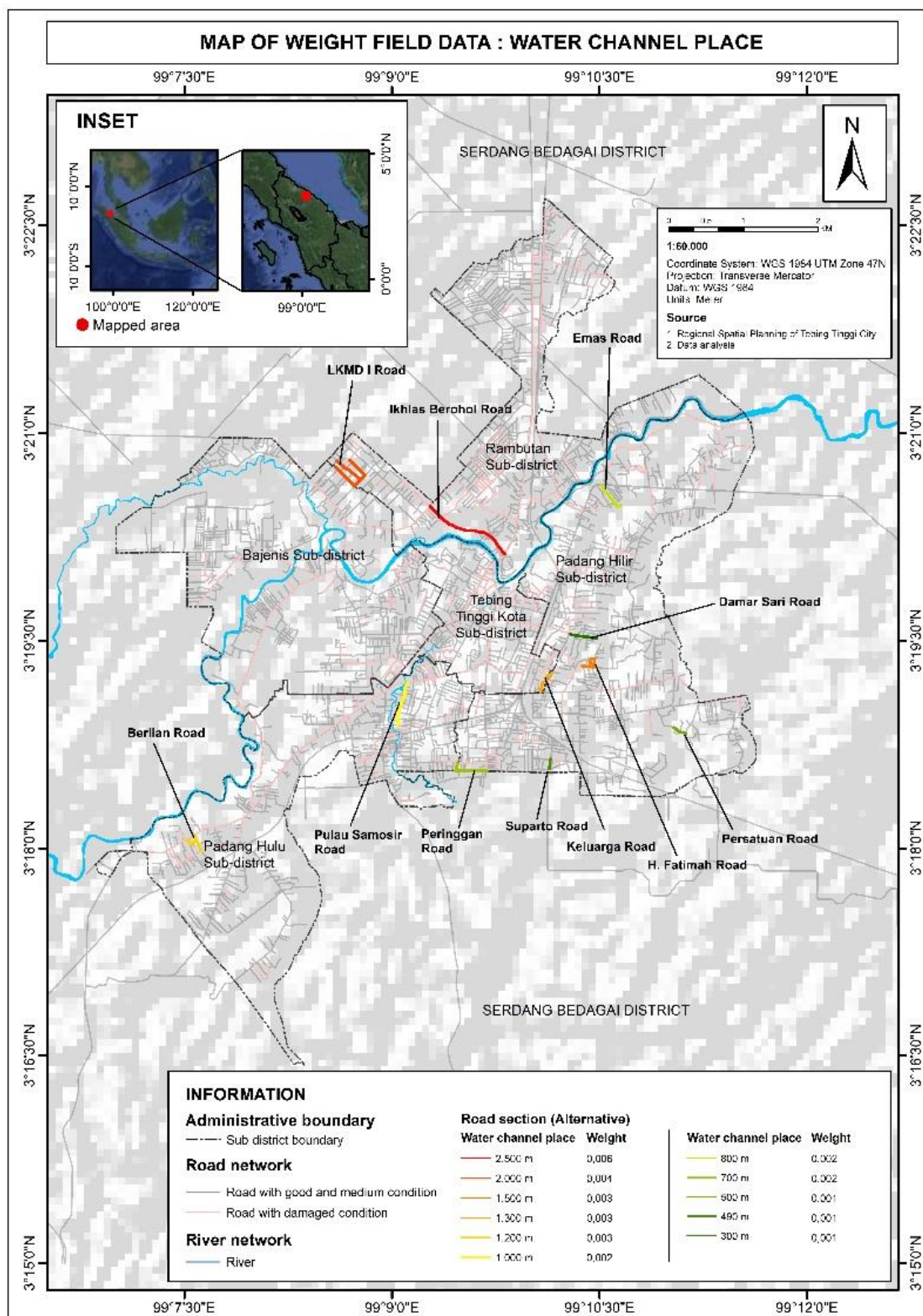
Population Growth Area



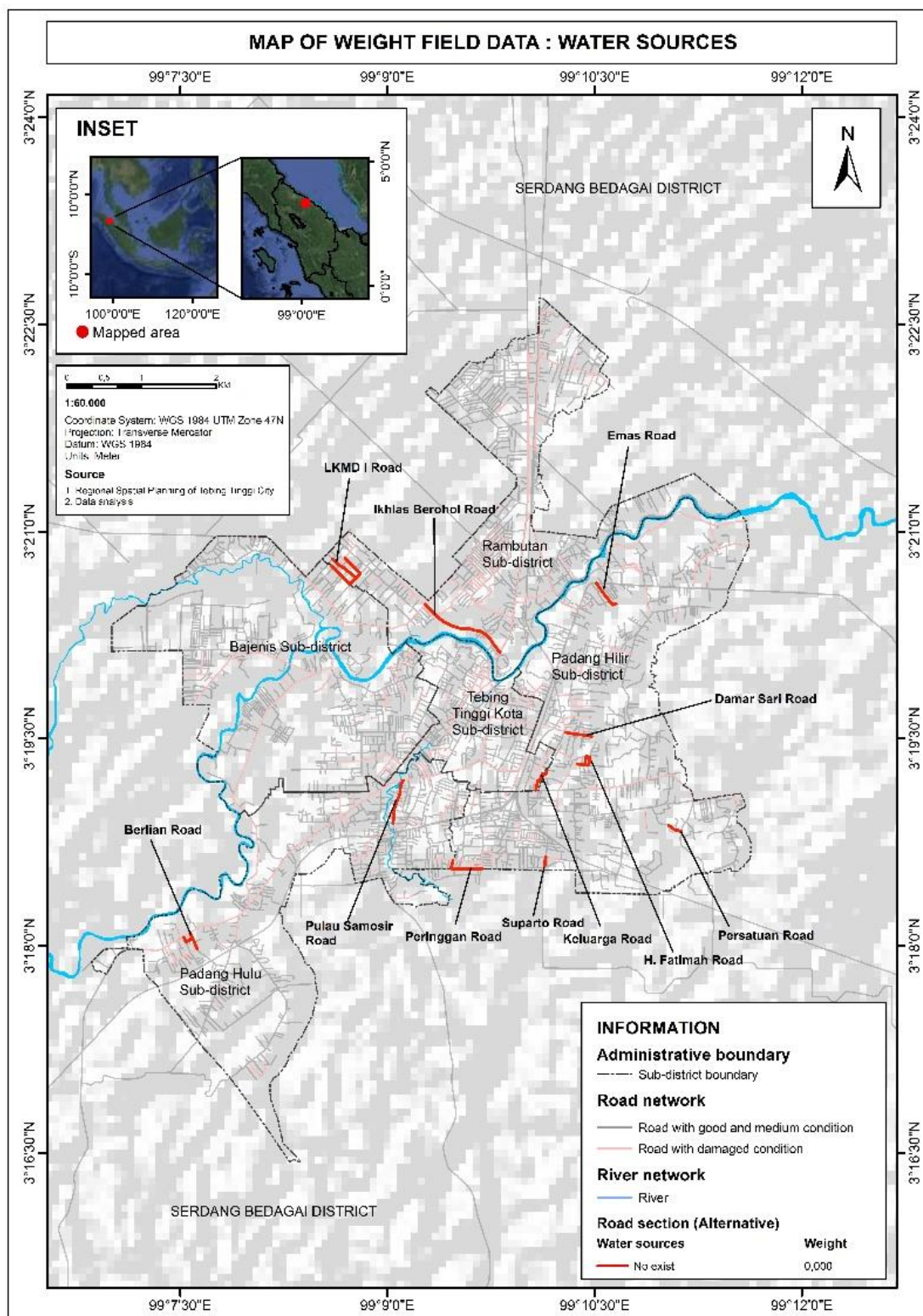
Sensitive Ecological Area



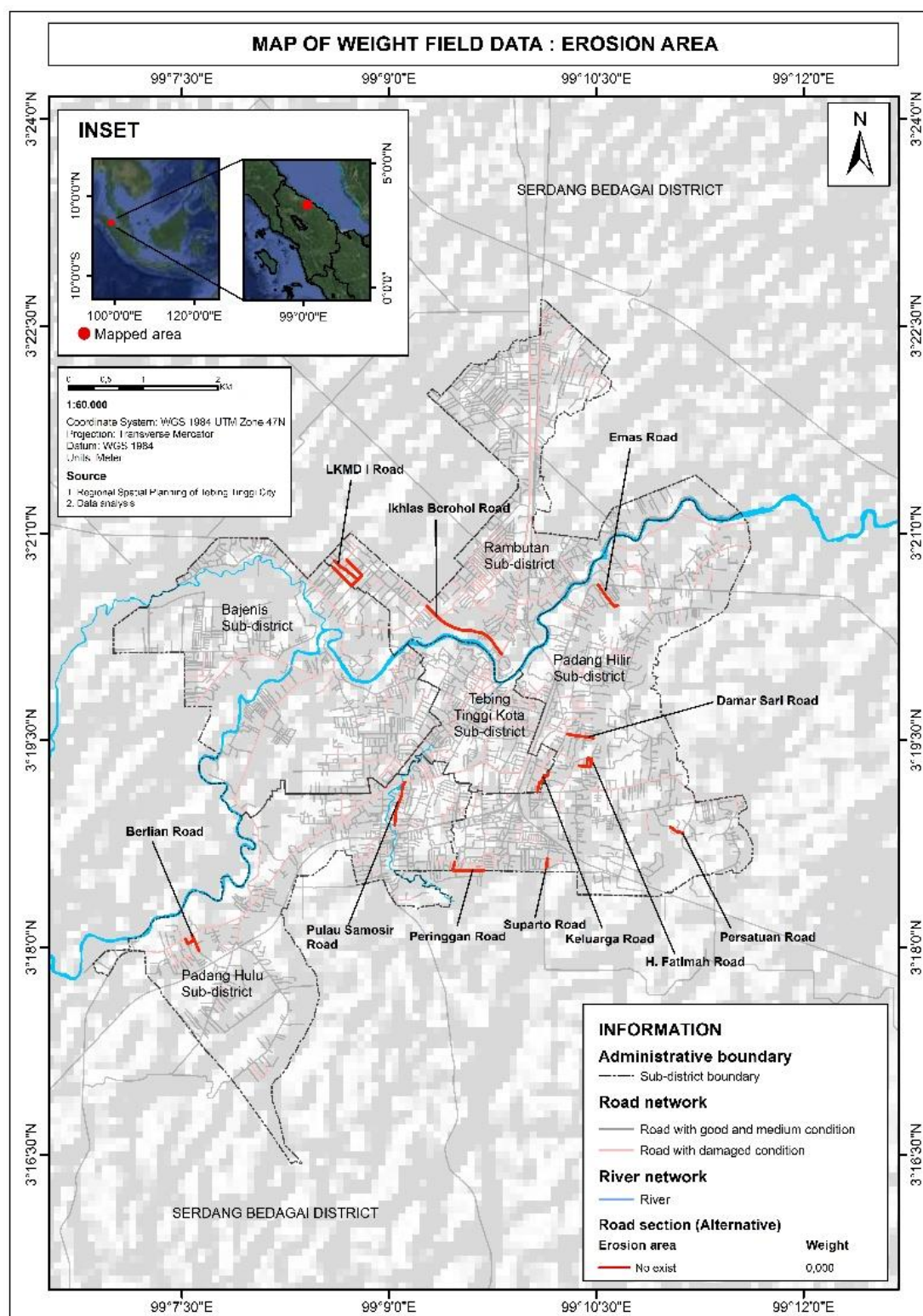
Water Channel Place



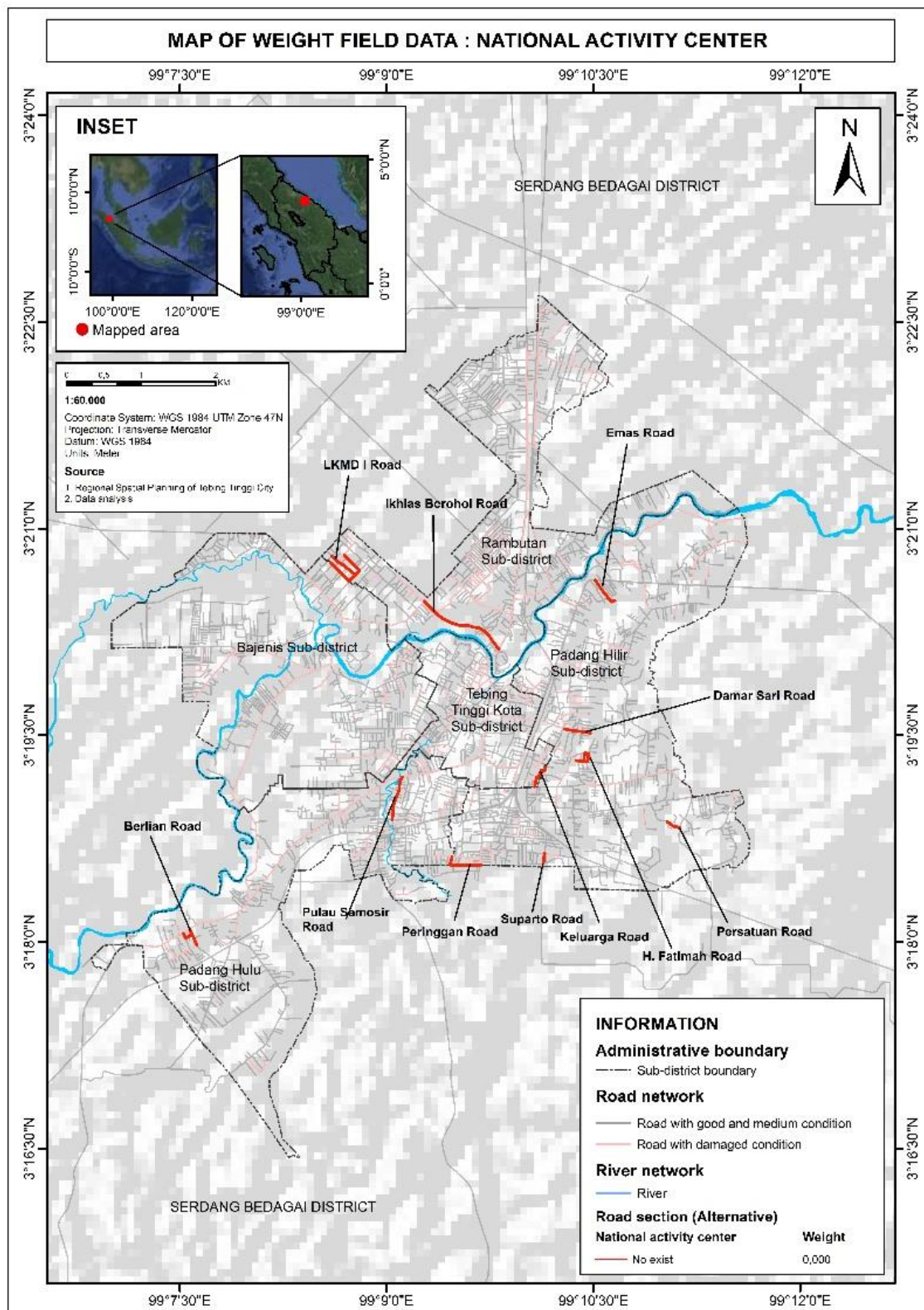
Water Sources



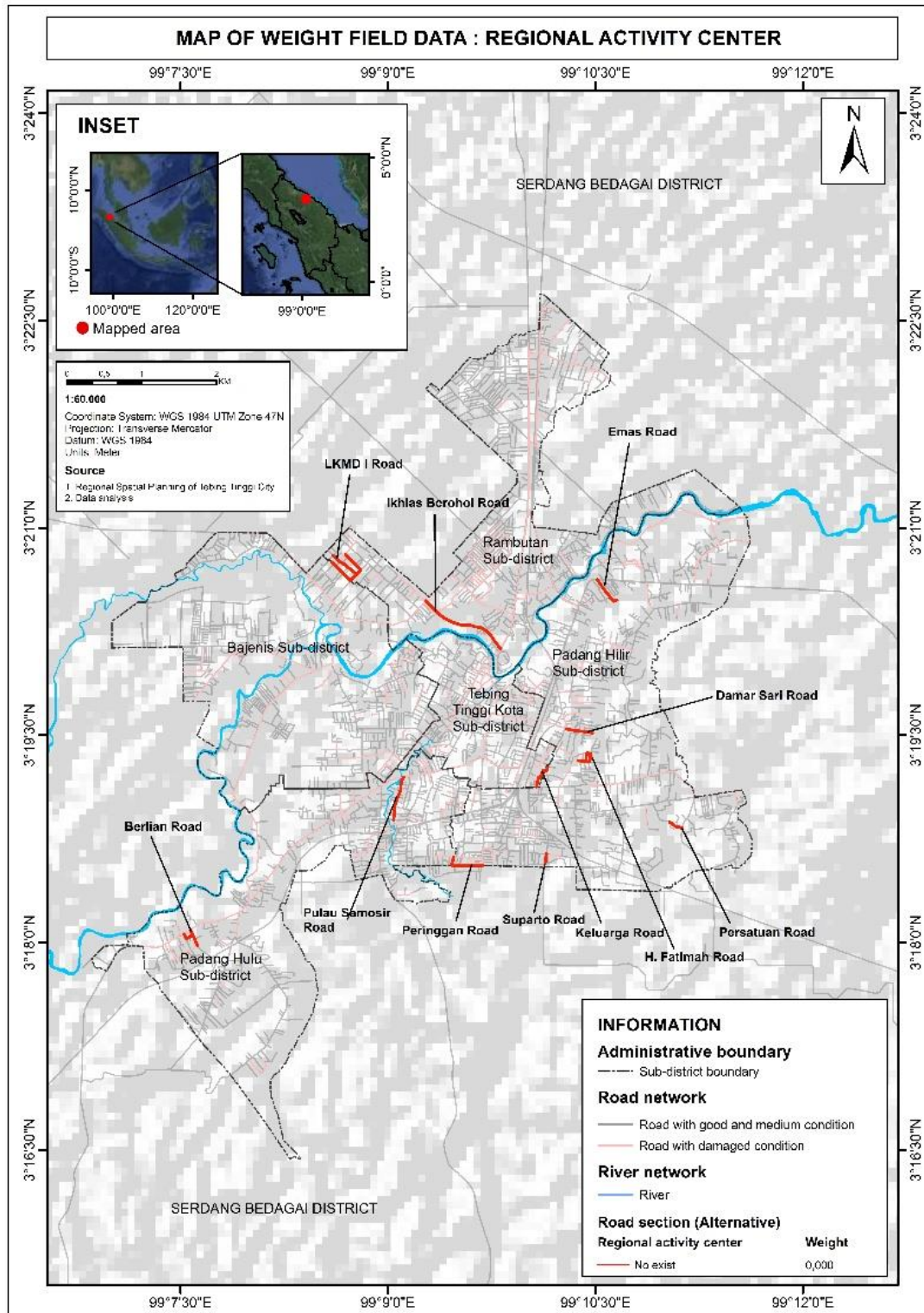
Erosion Area



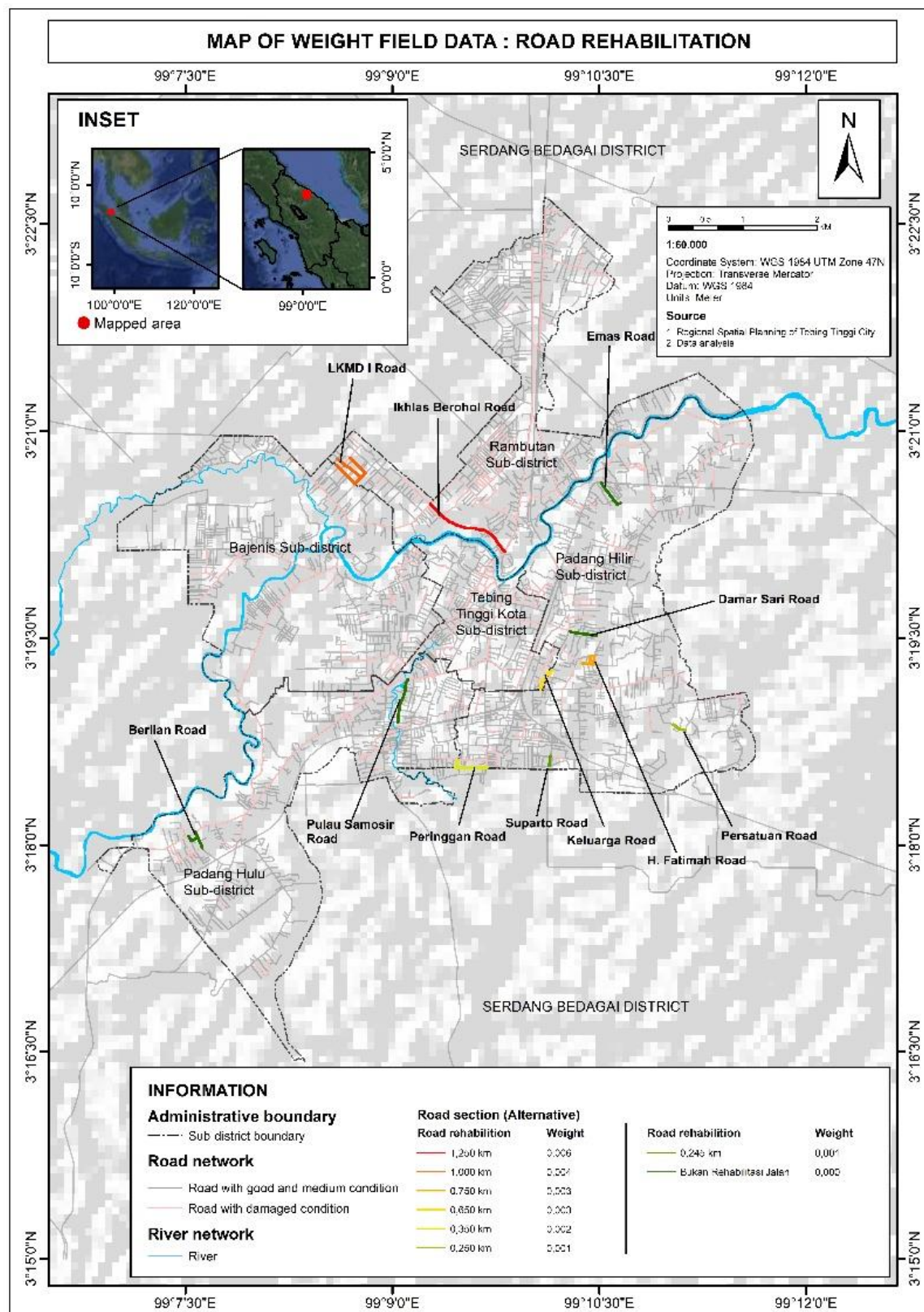
Central Activity Area



Regional Activity Area



Road Rehabilitation



Road Reconstruction

