A Multi-Indicator Green Infrastructure Framework for Sustainable District Road Network Assessment in Tropical Regions (Case Study: Manokwari Regency, West Papua Province, Indonesia)

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ABSTRACT

This study developed an integrated green infrastructure assessment framework to evaluate transportation sustainability, pavement resilience, and environmental vulnerability across district road networks in Manokwari Regency, West Papua Province, Indonesia. The novelty of this research lies in three major contributions with spesific affects of tropical cyclone in the coastal area: (1) the integration of multiple pavement sustainability indicators, including Road Condition Index (RCI), Infrastructure Damage Ratio (IDR), Road Resilience Coefficient (RRC), International Roughness Index (IRI), Surface Distress Index (SDI), and Pavement Condition Index (PCI) ; (2) comparative spatial sustainability assessment among districts using Green Infrastructure Performance Index (GIPI); and (3) the integration of climate-resilient governance with Provincial/Kabupaten Road Management System (PKRMS)-based adaptive asset management. The results demonstrated substantial spatial disparities in green infrastructure performance. Manokwari Barat achieved the highest GIPI score (51.12) and RRC value (0.90), indicating relatively strong transportation sustainability and infrastructure resilience. Conversely, Manokwari Utara recorded the lowest GIPI score (19.09), the highest IDR value (80.91%), a PCI value of 20–35, and a critical PKRMS priority level, reflecting severe pavement deterioration and very high environmental vulnerability. Masni had the longest road network (189.344 km) but ranked high in rehabilitation priority because of deteriorating pavement conditions. The findings emphasize that climate-responsive rehabilitation, ecosystem-based drainage systems, predictive maintenance, and low-carbon pavement technologies are essential for strengthening sustainable transportation governance in tropical developing regions.

Keywords: Green Infrastructure, Transportation Sustainability, Climate-Resilient Infrastructure, Pavement Management System, Environmental Vulnerability.

INTRODUCTION

Transportation infrastructure plays a fundamental role in supporting regional economic growth, social connectivity, accessibility, and territorial development (Ahmed, 2024; Yin et al., 2024; Varghese & Pradhan, 2025). However, the rapid expansion of road infrastructure in developing regions has simultaneously generated significant environmental challenges, including increased greenhouse gas emissions, ecosystem fragmentation, land degradation, hydrological disruption, and climate vulnerability (de Abreu et al., 2022; Youjin et al., 2024; Mtweve et al., 2025). In recent years, green infrastructure has emerged as a critical framework for integrating environmental sustainability, climate resilience, and infrastructure performance within transportation systems. Green infrastructure in the road sector emphasizes not only engineering functionality but also ecological integration, sustainable accessibility, lifecycle efficiency, climate adaptation,

and environmental resilience (Alhjouj et al., 2022). Consequently, modern transportation assessment frameworks increasingly emphasize integrated sustainability indicators that link pavement performance to climate adaptation, environmental protection, and resilient infrastructure governance (Das et al., 2022; Leal et al., 2024; Mukhtar et al., 2025).

Globally, the transportation sector contributes significantly to climate change and environmental degradation. The International Energy Agency (IEA, 2023) reported that transportation activities account for nearly one-quarter of global energy-related carbon dioxide emissions, with road transportation being the dominant source due to fuel combustion, deteriorating pavement conditions, and inefficient mobility systems. Poor road conditions increase rolling resistance, vehicle vibration, travel delays, fuel consumption, particulate emissions, and infrastructure lifecycle costs. Radwan et al. (2024) demonstrated that pavement deterioration, characterized by high roughness and severe surface distress, substantially reduces road sustainability because deteriorated roads increase vehicle energy demand and accelerate environmental impacts. Similarly, Kargah-Ostadi et al. (2024) examined the reconciliation of connected-vehicle pavement data with the International Roughness Index (IRI) from standard monitoring equipment, highlighting the need to validate roughness measurements. These findings indicate that deteriorating road conditions directly affect both transportation functionality and environmental sustainability, particularly in developing tropical regions with limited capacity for infrastructure maintenance.

Indonesia's district and provincial road networks continue to face substantial sustainability challenges due to deteriorating infrastructure, limited maintenance budgets, climate-related pressures, and uneven regional development. These conditions are particularly evident in eastern Indonesia, including Manokwari Regency in West Papua Province, where transportation infrastructure plays a strategic role in supporting regional accessibility, agricultural distribution, economic connectivity, and social mobility among districts. However, the growing prevalence of damaged road segments has created significant challenges, including transportation inefficiency, accessibility inequality, environmental degradation, and concerns about resilience under tropical rainfall conditions. Previous studies in Indonesia have examined both pavement condition and broader road sustainability; Sumabrata et al. (2022), for example, evaluated sustainability indicators using stakeholder perceptions. Furthermore, pavement-condition assessments often emphasize technical pavement performance while providing limited attention to ecological resilience, sustainable accessibility, climate adaptation, and integrated infrastructure governance.

This study addresses these limitations by developing a multidimensional green infrastructure assessment framework for district road networks using integrated sustainability indicators, including Road Condition Index (RCI), Infrastructure Damage Ratio (IDR), Sustainable Accessibility Index (SAI), Green Infrastructure Performance Index (GIPI), Road Resilience Coefficient (RRC), International Roughness Index (IRI), Surface Distress Index (SDI), Pavement Condition Index (PCI), and Provincial/Kabupaten Road Management System (PKRMS). Integrating these indicators provides a comprehensive analytical framework that simultaneously evaluates pavement functionality, infrastructure deterioration, accessibility performance, resilience capacity, environmental implications, and maintenance prioritization. Kaira et al. (2022) emphasized that integrated sustainability frameworks are essential because transportation systems interact dynamically with environmental, economic, social, and institutional dimensions. Therefore, this research contributes a more holistic transportation sustainability model by combining engineering-based pavement indicators with green infrastructure and climate resilience perspectives at the district level.

The novelty of this research lies in three major contributions to green infrastructure assessment studies in regions affected by tropical cyclones in the northern Pacific Ocean. First, this study develops an integrated green infrastructure assessment framework that combines multiple pavement sustainability indicators, including RCI, IDR, GIPI, RRC, IRI, SDI, PCI, and PKRMS, to evaluate transportation infrastructure performance comprehensively at the district level. Second, the research introduces a comparative spatial sustainability assessment across multiple districts in Manokwari Regency to identify disparities in infrastructure resilience, accessibility, pavement deterioration, and environmental vulnerability within tropical developing regions. Third, this study integrates climate resilience and sustainable infrastructure governance into pavement assessment by linking PKRMS-based asset management with green infrastructure principles,

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climate-adaptive rehabilitation strategies, ecosystem-based drainage systems, and low-carbon transportation management to support long-term sustainable regional development (Fang et al., 2022; Ramísio et al., 2022; Chang & Hossain, 2024).

MATERIALS AND METHODS

Study area

The study was conducted in Manokwari Regency, West Papua Province, Indonesia, a strategic regional transportation corridor in eastern Indonesia. Administratively, the study area comprises eight districts: Manokwari Barat, Manokwari Selatan, Manokwari Timur, Manokwari Utara, Masni, Prafi, Sidey, and Warmare. These districts were selected because they collectively represent the primary district road network that supports regional accessibility, economic distribution, agricultural transportation, and social connectivity across Kabupaten Manokwari. The total district road network analyzed in this study was approximately 583.071 km, distributed unevenly among the districts. Masni District possessed the largest road network length (189.344 km), followed by Prafi (121.376 km), Manokwari Barat (74.812 km), Manokwari Selatan (59.172 km), Sidey (58.277 km), Warmare (57.339 km), Manokwari Timur (16.413 km), and Manokwari Utara (6.338 km) (Figure 1). Detailed information on road network characteristics, pavement composition, and district-level road-condition distributions is presented in Appendix Tables A1 – A5.

Manokwari Regency has complex topography, including coastal zones, lowland agricultural regions, hilly terrain, and tropical forest landscapes. These environmental characteristics strongly influence pavement deterioration, drainage performance, erosion vulnerability, and infrastructure resilience. According to Dimnet (2022), transportation infrastructure in tropical developing regions is highly vulnerable to climate-induced deterioration because of intense rainfall variability, flooding, landslides, and limited maintenance capacity. Consequently, the district road networks in Manokwari Regency provide an important case study for evaluating green infrastructure performance, climate resilience, and sustainable transportation management in tropical regions.

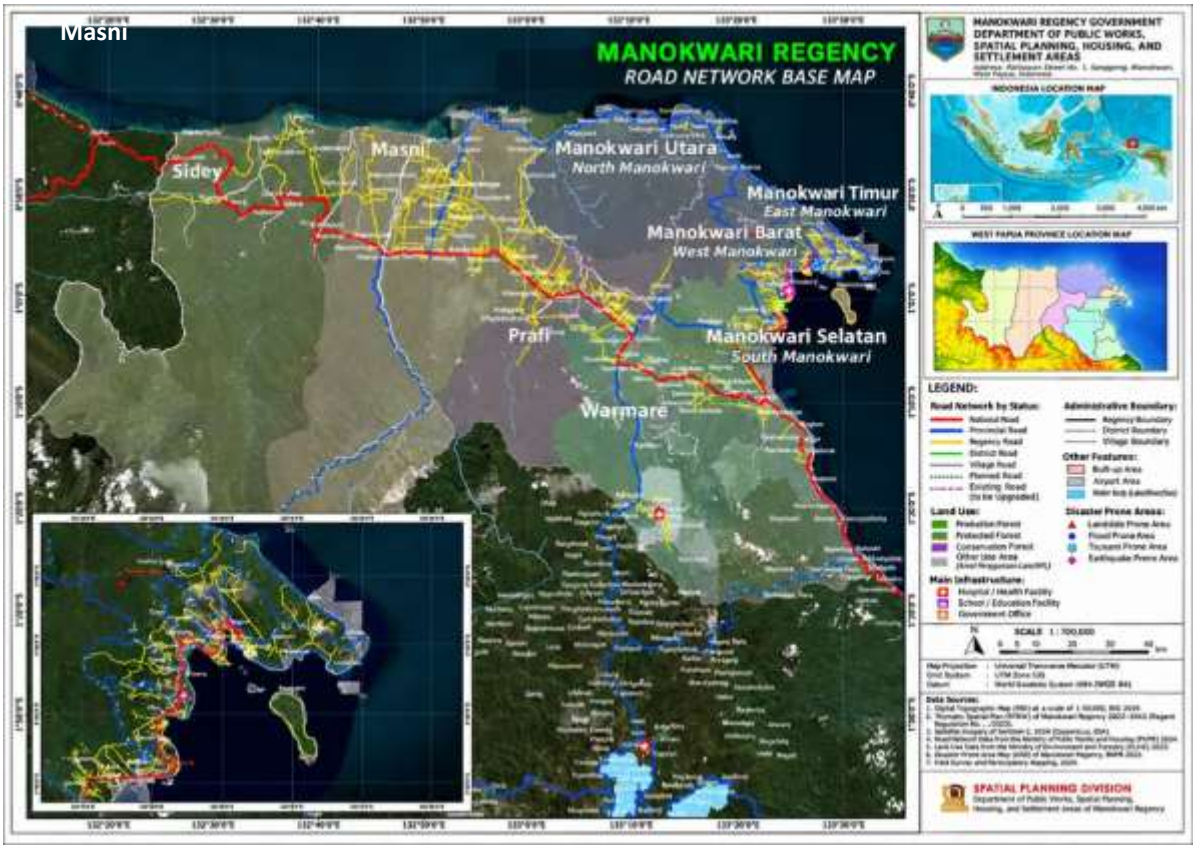


Figure 1. District road network in Manokwari Regency

The climatic characteristics of Manokwari Regency strongly influence the sustainability and resilience of transportation infrastructure systems, particularly within the context of green infrastructure assessment in tropical coastal regions. The region has a humid tropical climate with average annual rainfall of about 2928 mm (ranging from 2535 mm to 3241 mm) and a bimodal rainfall distribution. Two major rainfall peaks occur in December and March in the reported climatic summary. Conversely, the dry season generally occurs in June, July, and August, with relatively low precipitation intensity during the monsoon transition period outside the Papua region. Furthermore, average annual temperature ranges from 23.3°C to 31.5°C (approximately 27.1°C), while annual relative humidity remains consistently high at approximately 84% (82–85%) (Bureau of Meteorology, Climatology, and Geophysics of Manokwari, 2025).

From a green infrastructure perspective, these climatic conditions substantially accelerate pavement deterioration processes, increase hydrological vulnerability, and intensify environmental pressures on transportation systems. High rainfall intensity combined with elevated humidity levels contributes to surface runoff accumulation, erosion, pavement weakening, drainage failure, and accelerated surface distress, particularly on roads with inadequate maintenance capacity. Transportation infrastructure in tropical coastal regions is highly vulnerable to climate-induced deterioration due to increasing rainfall variability, more frequent flooding, and extreme weather events associated with climate change (Mashwama & Phesa, 2025). Consequently, district road networks located near coastal and lowland areas adjacent to the Pacific Ocean require site-specific assessment of infrastructure vulnerability.

Based on spatial characteristics and road-condition performance, districts can be classified into high-, medium-, and low-vulnerability categories within the green infrastructure framework. High-vulnerability districts include Manokwari Utara and Manokwari Selatan due to severe pavement deterioration, low resilience capacity, high rainfall exposure, and direct environmental sensitivity to Pacific Ocean climatic influences. Medium-vulnerability districts include Masni, Prafi, and Manokwari Timur, where extensive road networks combined with moderate deterioration increase susceptibility to long-term environmental degradation and infrastructure stress. Meanwhile, Sidey, Warmare, and Manokwari Barat can be categorized as relatively low-vulnerability districts due to better pavement performance and accessibility conditions, although these areas remain exposed to hydrological risks associated with tropical rainfall intensity and coastal climate variability. Therefore, climate-responsive green infrastructure strategies, including resilient pavement design, ecosystem-based drainage systems, low-carbon rehabilitation technologies, and predictive maintenance approaches, are essential to strengthen transportation sustainability and adaptive infrastructure governance across Manokwari Regency. These provisional groups are descriptive and do not constitute a validated hazard or climate-vulnerability classification.

Data Collection

The study assembled information on district road infrastructure conditions, pavement performance indicators, transportation accessibility, and environmental vulnerability characteristics associated with green infrastructure assessment. Secondary data comprised supporting information obtained from government agencies, statistical reports, climate databases, spatial maps, and relevant literature, including rainfall characteristics, temperature conditions, humidity levels, topographic information, and transportation infrastructure policies that support sustainable road infrastructure analysis.

Researchers collected primary data through field observations, road-condition surveys, pavement performance assessments, and stakeholder consultations with local government institutions and transportation infrastructure authorities. The study area encompassed district road networks across Manokwari Regency, which the study subsequently classified into high-, medium-, and low-vulnerability categories based on pavement deterioration, environmental exposure, accessibility performance, and climate resilience capacity. Table 1 comprehensively presents the variables, data sources, data collection methods, and analytical procedures employed in this study. Table 2 addresses the classification and analytical roles of indicators in the integrated green infrastructure assessment framework. The inventory contains 227 road sections across eight districts; district counts and total lengths are presented in Appendix Tables A1 and A2. These inventory counts do not establish the number of directly measured IRI, SDI, or PCI observations.

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Table 1. Variables, data sources, data collection methods, and analytical procedures

Research Objective	Variables	Data Sources	Data Collection Methods	Analytical Procedures
Development of an Integrated Green Infrastructure Assessment Framework combining multiple pavement sustainability indicators (RCI, IDR, RRC, IRI, SDI, and PCI)	Road condition, pavement deterioration, accessibility, resilience capacity, pavement roughness, surface distress, sustainability performance, infrastructure management priority	Primary road condition survey data; District road inventory; Public Works and Spatial Planning Office (PUPR) of Manokwari Regency; PKRMS database; Climate and environmental reports	Field observation; Pavement condition survey; Road inventory assessment; Infrastructure performance measurement; Documentation	Quantitative pavement assessment; RCI analysis; IDR analysis; RRC analysis; IRI estimation; SDI analysis; PCI evaluation
Comparative spatial sustainability assessment across districts in Manokwari Regency to identify disparities in infrastructure resilience, accessibility, pavement deterioration, and environmental vulnerability (GIPI)	District road distribution, spatial accessibility, infrastructure vulnerability, climate exposure, pavement performance disparity, transportation sustainability	Spatial maps; GIS database; District road network maps; Climate data from BMKG Manokwari; Topographic and environmental data; Transportation statistics	Spatial mapping; Comparative district assessment; GIS-based infrastructure interpretation; Environmental vulnerability observation	Comparative spatial analysis; District sustainability classification; Vulnerability assessment (high, medium, low); Transportation accessibility analysis; Integrated green infrastructure interpretation (GIPI analysis)
Integration of climate resilience and sustainable infrastructure governance into pavement assessment through PKRMS-based asset management and green infrastructure principles	Climate resilience, adaptive infrastructure capacity, sustainable maintenance systems, ecosystem-based drainage, low-carbon rehabilitation strategies, infrastructure governance	PKRMS reports; Climate resilience literature; Government transportation policies; Sustainable infrastructure guidelines; Environmental management reports	Policy review; Infrastructure governance analysis; Stakeholder consultation; Sustainable road management evaluation	Climate resilience assessment; PKRMS-based governance analysis; Green infrastructure policy analysis; Sustainable transportation evaluation; Strategic rehabilitation and maintenance framework development

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Table 2. Classification and analytical roles of indicators in the integrated green infrastructure assessment framework

Indicator group	Indicators	Analytical role
Primary network-condition indicator	RCI	Measures the proportion of roads in good and moderate condition
Derived condition indicators	IDR, RRC	Describes deterioration severity and the ratio of good to damaged roads
Complementary pavement-performance indicators	IRI, SDI, PCI	Evaluates roughness, surface distress, and overall pavement condition
Green infrastructure dimensions	GIPI (RCI, SAI, EI)	Evaluates accessibility and environmental performance independently
Infrastructure management	PKRMS	Supports maintenance and rehabilitation prioritization

Data analysis

The first research objective emphasizes the development of an integrated green infrastructure assessment framework that combines multiple pavement sustainability indicators, including Road Condition Index (RCI), Infrastructure Damage Ratio (IDR), Road Resilience Coefficient (RRC), International Roughness Index (IRI), Surface Distress Index (SDI), and Pavement Condition Index (PCI) (Kanchanamala et al., 2023; Lendra & Wibowo, 2023; Manuranga & Pasindu, 2023; Balram et al., 2025; Witjaksana et al., 2025; Rasha et al., 2026).

$$RCI = ((B + S) / T) \times 100 \quad \text{eq.1}$$

where RCI is the Road Condition Index, B is the length of roads in good condition (km), S is the length of roads in moderate condition (km), and T is the total road length (km). The four condition classes are treated as mutually exclusive and exhaustive, so T = B + S + RR + RB. Calculations use the reported lengths before rounding; district results are rounded to two decimals.

Road Condition Index (RCI). The Road Condition Index (RCI) assesses overall road network performance by calculating the percentage of roads in good and moderate condition relative to the total road length. RCI values of 80–100% are classified as Very Good, 60–<80% as Good, 40–<60% as Moderate, 20–<40% as Poor, and 0–<20% as Very Poor. Higher RCI values indicate better road network conditions, improved accessibility, and reduced infrastructure maintenance requirements. This classification provides a quantitative basis for evaluating road serviceability and identifying maintenance priorities within the Manokwari Regency road network (Kanchanamala et al., 2023; Lendra & Wibowo, 2023). The proposed thresholds are research-specific operational criteria and require validation against official road-condition records from the Manokwari Regency Department of Public Works. Here, RCI denotes a road-length percentage and should not be confused with a separate visual road-condition rating scale.

$$IDR = ((RR + RB) / T) \times 100 \quad \text{eq.2}$$

where IDR is the Infrastructure Damage Ratio, RR is the length of lightly damaged roads (km), RB is the length of heavily damaged roads (km), and T is the total road length (km). Consequently, IDR = 100 − RCI.

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IDR is retained as a complementary description of damaged road length and is not counted as an independent dimension of GIPI.

The Infrastructure Damage Ratio (IDR) is classified into five categories: Very Low Damage (IDR < 20%), indicating highly sustainable and resilient transportation infrastructure with minimal environmental impacts; Low Damage (20–40%), representing good pavement sustainability and moderate maintenance requirements; Moderate Damage (40–60%), reflecting increasing pavement deterioration and environmental pressures that require preventive maintenance; High Damage (60–80%), indicating significant transportation inefficiency, weak infrastructure resilience, and elevated environmental vulnerability; and Very High Damage (IDR > 80%), representing severe pavement deterioration, high climate vulnerability, and urgent rehabilitation priorities. These categories provide a basis for identifying infrastructure deterioration levels and prioritizing sustainable road maintenance and climate-resilient rehabilitation interventions. This indicator supports infrastructure vulnerability assessment and evidence-based maintenance planning, particularly in regions exposed to high rainfall, flooding, and landslides (Lendra & Wibowo, 2023; Manuranga & Pasindu, 2023). The proposed classification thresholds require validation against official road-damage data from the Manokwari Regency Department of Public Works.

$$RRC = B / (RR + RB) \quad \text{eq.3}$$

where RRC is the Road Resilience Coefficient, B is the length of roads in good condition (km), RR is the length of roads in lightly damaged condition (km), and RB is the length of roads in heavily damaged condition (km). RRC is dimensionless and undefined if RR + RB = 0. The term is retained for consistency with the proposed framework, but this ratio is not a direct resilience measurement.

The Road Resilience Coefficient (RRC) is classified descriptively as High (RRC > 1.0), Moderate ($0.5 \leq RRC \leq 1.0$), or Low ($0 \leq RRC < 0.5$), based on the ratio of good-condition to damaged road length.

Higher RRC values indicate a greater proportion of roads in good condition relative to damaged roads, suggesting stronger overall network functionality. Lower values indicate greater infrastructure deterioration and potentially higher maintenance requirements (Manuranga & Pasindu, 2023; Balram et al., 2025). These classifications are proposed research-specific criteria rather than established resilience standards. The indicator measures road-condition balance and does not independently quantify infrastructure resistance, recovery capacity, or adaptation to climate-related hazards.

$$IRI = VSM / D \quad \text{eq.4}$$

where IRI is the International Roughness Index, VSM is Vertical Suspension Movement, and D is the total length of the measured road segment (km). VSM is not an arbitrary suspension reading from an uncalibrated vehicle (Sayers et al., 1986).

International Roughness Index (IRI). The International Roughness Index (IRI) measures pavement surface roughness as the accumulated vertical suspension movement of a standardized reference vehicle per unit length of road, expressed in meters per kilometer (m/km). IRI values of $0 \leq IRI \leq 4$ m/km are classified as Good; $4 < IRI \leq 8$ m/km as Moderate; $8 < IRI \leq 12$ m/km as Lightly Damaged; and greater than 12 m/km as Heavily Damaged. Lower IRI values indicate smoother pavement surfaces, better riding comfort, and improved vehicle operating efficiency, whereas higher values indicate greater surface irregularities and potential maintenance needs. IRI measurements can be obtained using calibrated road profilometers or validated vehicle-response measurement systems, and the resulting values can be interpreted in accordance with applicable Indonesian road-condition assessment criteria (Sayers et al., 1986).

$$SDI = C + R + P + D \quad \text{eq.5}$$

where SDI is Surface Distress Index, C is the crack score, R is the rutting score, P is the pothole score and D is the deformation score.

Surface Distress Index (SDI). The Surface Distress Index (SDI) evaluates pavement surface deterioration using four principal distress parameters: cracked pavement area, average crack width, pothole frequency, and wheel-rutting depth, following the sequential scoring procedure established in the Indonesian Bina Marga Road Condition Survey methodology. SDI values below 50 are classified as Good, 50–100 as Moderate, greater than 100–150 as Lightly Damaged, and greater than 150 as Heavily Damaged. Lower SDI values indicate relatively limited surface deterioration and better pavement functionality, whereas higher values indicate increasing distress severity and greater maintenance or rehabilitation requirements. The calculation incorporates standardized distress measurements and scoring adjustments rather than arbitrarily adding individual damage scores. SDI provides an important indicator for evaluating pavement deterioration and identifying priority road segments for maintenance interventions (Lendra & Wibowo, 2023; Witjaksana et al., 2025; Rasha et al., 2026).

PCI = 100 – CDV …… eq.6

where PCI is Pavement Condition Index and CDV is the maximum Corrected Deduct Value obtained through the prescribed sample-unit correction procedure.

Pavement Condition Index (PCI). The Pavement Condition Index (PCI) provides a standardized quantitative assessment of pavement condition based on the type, severity, and extent of observed surface distress, using the Corrected Deduct Value (CDV) procedure established in ASTM D6433. PCI values of 85–100 are classified as Excellent, 70–<85 as Very Good, 55–<70 as Good, 40–<55 as Fair, 25–<40 as Poor, 10–<25 as Very Poor, and 0–<10 as Failed. Higher PCI values indicate better pavement integrity, limited distress, and lower rehabilitation requirements, whereas lower values indicate more extensive pavement deterioration and increasing maintenance urgency. CDV is determined by evaluating distress density and severity, obtaining deduct values from standardized distress-specific curves, and applying the prescribed correction procedure. PCI supports systematic pavement condition monitoring, maintenance prioritization, and infrastructure asset management (ASTM International, 2024). PCI does not directly measure structural capacity, skid resistance, or longitudinal roughness. A range crossing a rating boundary must not be assigned a single class without the underlying observations.

The data analysis was conducted quantitatively, using integrated engineering and environmental assessment approaches, to comprehensively evaluate pavement functionality, infrastructure deterioration, transportation accessibility, environmental efficiency, and climate resilience at the district level. The indicators and equations were selected because they provide multidimensional measures that assess transportation sustainability performance from both technical and green-infrastructure perspectives (Table 3).

The second component of the table describes the comparative spatial sustainability analysis conducted across districts in Manokwari Regency. This analysis focused on identifying disparities in infrastructure resilience, accessibility performance, pavement deterioration, and environmental vulnerability among districts categorized as high-, medium-, and low-vulnerability areas. Spatial data analysis used district-based road condition indicators and environmental exposure characteristics to examine the relationship between transportation infrastructure performance and tropical climatic conditions. In this stage, the indicators and equations included GIPI models to determine district sustainability performance and infrastructure vulnerability levels. This stage aimed to evaluate spatial differences in transportation sustainability and identify districts requiring priority rehabilitation and climate-adaptive infrastructure interventions.

GIPI = (0.4 × RCI) + (0.3 × SAI) + (0.3 × EI) …….. eq.7

where GIPI is the Green Infrastructure Performance Index, RCI is the Road Condition Index, SAI is the Sustainable Accessibility Index, and EI is the Environmental Indicator.

$SAI_i = 0.25C_i + 0.25A_i + 0.25P_i + 0.25E_i$ eq.8

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Where C_i is the normalized road network connectivity score, A_i is the normalized access to essential services, P_i is the normalized population accessibility score, E_i is the normalized access to economic centers, and i is the district.

$EI_i = 0.25D_i + 0.25S_i + 0.25V_i + 0.25F_i$ eq.9

where Di is the drainage performance score, Si is the erosion and slope protection score, Vi is the vegetation and green infrastructure score, Fi is the flood and climate resilience score, and i is the district.

Green Infrastructure Performance Index (GIPI). The Green Infrastructure Performance Index (GIPI) provides an integrated assessment of road infrastructure sustainability by combining road condition, sustainable accessibility, and environmental performance. The index incorporates three dimensions, namely the Road Condition Index (RCI), Sustainable Accessibility Index (SAI), and Environmental Indicator (EI), with respective weights of 0.40, 0.30, and 0.30. Before aggregation, all three indicators are normalized to a common 0–100 scale, with higher values indicating better performance. GIPI scores ranging from 80–100 are classified as Very High, 60–<80 as High, 40–<60 as Moderate, 20–<40 as Low, and 0–<20 as Very Low. Higher GIPI scores indicate better overall green infrastructure performance, reflecting improved road conditions, more equitable and sustainable accessibility, and reduced environmental impacts. The proposed weighting scheme provides an initial multi-criteria assessment framework and should be validated through expert consultation, the Analytical Hierarchy Process (AHP), and sensitivity analysis to confirm the composite index's robustness. These performance categories represent operational thresholds developed for this study, not an internationally standardized GIPI classification.

The final table explains how climate resilience and sustainable infrastructure governance are integrated into pavement sustainability assessment through PKRMS-based asset management and green infrastructure principles. Data analysis at this stage included climate resilience assessment, infrastructure governance evaluation, adaptive maintenance prioritization, and interpretation of sustainable pavement management. The analytical indicators included PKRMS prioritization models, climate-responsive pavement assessment, ecosystem-based drainage evaluation, and low-carbon rehabilitation analysis to support long-term transportation sustainability.

This stage aimed to evaluate infrastructure adaptive capacity, strengthen sustainable transportation governance, and formulate strategic recommendations for climate-resilient rehabilitation and predictive maintenance systems. Overall, integrating novelty, data analysis, indicators/equations, and analytical purposes provides a comprehensive framework for evaluating sustainable transportation infrastructure and adaptive green infrastructure management in tropical developing regions.

Proposed research priority score = $(C \times T \times S) / B$ …….. eq.10

where PKRMS refers to the Provincial/Kabupaten Road Management System, and in the proposed research score, C is the road condition score, T is the traffic importance, S is the strategic function, and B is the available budget.

Provincial/Kabupaten Road Management System (PKRMS) Priority Index. The PKRMS Priority Index provides a decision-support approach to identify road segments that require maintenance, rehabilitation, or improvement, based on infrastructure condition, traffic importance, strategic function, and available maintenance funding. The proposed priority scores are calculated using the combined effects of road condition (C), traffic importance (T), and strategic function (S), relative to the available maintenance budget (B). The resulting scores are classified using a relative ranking approach: the highest 20% are Very High Priority, the next 20% are High Priority, the middle 20% are Moderate Priority, the next 20% are Low Priority, and the lowest 20% are Very Low Priority.

Roads classified as Very High and High Priority require urgent consideration for maintenance or rehabilitation, particularly where they provide essential access to settlements, public facilities, economic

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centers, and disaster-prone areas. Moderate Priority roads require periodic maintenance, while Low and Very Low Priority roads generally require routine maintenance and condition monitoring. This classification is a proposed research-based prioritization scheme and should be distinguished from the official PKRMS programming procedures established by the Directorate General of Highways, Ministry of Public Works and Housing, Indonesia (PKRMS Manual No. 04/M/BM/2021).

Table 3. Data analysis, indicators/equations, analytical purpose and references

Research Novelty	**Data Analysis**	**Indicators/Equations**	**Analytical Purpose**	**References**
Development of an integrated green infrastructure assessment framework combining multiple pavement sustainability indicators	Quantitative pavement sustainability assessment using integrated engineering and environmental indicators	RCI, IDR, RRC, IRI, SDI, and PCI	To evaluate pavement functionality, infrastructure deterioration, accessibility, sustainability performance, environmental efficiency, and transportation resilience comprehensively at the district level	Kaira et al. (2022); Sumabrata et al. (2022); Radwan et al. (2024)
Comparative spatial sustainability assessment across districts in Manokwari Regency	Comparative district-based spatial analysis using vulnerability classification and transportation sustainability interpretation	High-, medium-, and low-vulnerability classification based GIPI	To identify spatial disparities in pavement deterioration, transportation accessibility, climate vulnerability, and infrastructure resilience among districts in tropical developing regions	Alhjouj et al. (2022); Dimnet (2022); Kargah-Ostadi et al. (2023)
Integration of climate resilience and sustainable infrastructure governance into pavement assessment through PKRMS and green infrastructure principles	Climate resilience analysis, sustainable infrastructure governance assessment, and adaptive pavement management evaluation	PKRMS-based maintenance prioritization; Climate-resilient pavement evaluation; Ecosystem-based drainage interpretation; Low-carbon rehabilitation assessment	To evaluate infrastructure adaptive capacity, sustainable maintenance governance, climate-responsive rehabilitation strategies, and long-term transportation sustainability	Dimnet (2022); Radwan et al. (2024); Alhjouj et al. (2022)

RESULTS AND DISCUSSION

Integrated Green Infrastructure Assessment Using Multi-Pavement Sustainability Indicators

Road Condition Index (RCI)

The Road Condition Index (RCI) is used here to determine the proportion of roads in good and moderate condition relative to total road length. The RCI results for each district are presented in Table 4.

Table 4. RCI per district in Manokwari Regency

District	Total Length (km)	RCI (%)	RCI Category
Manokwari Barat	74.812	51.12	Moderate
Sidey	58.277	46.54	Moderate
Warmare	57.339	43.37	Moderate
Prafi	121.376	40.17	Moderate
Masni	189.344	36.71	Poor
Manokwari Timur	16.413	32.71	Poor
Manokwari Selatan	59.172	32.04	Poor
Manokwari Utara	6.338	19.09	Very Poor

Source: primary data (2025)

The Road Condition Index (RCI) results reveal considerable differences in road serviceability across the eight districts of Manokwari Regency (Table 4). Manokwari Barat recorded the highest RCI (51.12%), followed by Sidey (46.54%), Warmare (43.37%), and Prafi (40.17%), all classified as Moderate. In contrast, Masni (36.71%), Manokwari Selatan (32.04%), and Manokwari Timur (32.71%) fell within the Poor category, while Manokwari Utara recorded the lowest value (19.09%), classified as Very Poor. These results indicate that the proportion of roads in good and moderate condition remains limited across much of the study area. Masni is particularly important because it has the longest road network (189.344 km), yet its RCI remains below 40%. This finding demonstrates that extensive road coverage does not necessarily correspond to satisfactory infrastructure condition.

The district-level variation is consistent with the broader findings of Sumabrata et al. (2022), who highlighted the importance of pavement condition and maintenance management in evaluating sustainable transportation infrastructure in Indonesia. However, the present study extends the assessment from conventional road-condition evaluation to a comparative district-level framework. The relatively low RCI values in Manokwari Utara, Manokwari Selatan, and Manokwari Timur identify these districts as important areas for road-condition verification and rehabilitation planning. Nevertheless, RCI measures the proportion of serviceable road length rather than directly measuring accessibility, greenhouse gas emissions, or climate resilience. These broader sustainability outcomes therefore require additional indicators and supporting evidence.

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Infrastructure Damage Ratio (IDR)

The Infrastructure Damage Ratio (IDR) measures the proportion of roads that are lightly or heavily damaged. Table 5 presents the IDR results by district.

Table 5. IDR per district in Manokwari Regency

District	IDR (%)	IDR Category
Manokwari Barat	48.88	Moderate
Sidey	53.46	Moderate
Warmare	56.63	Moderate
Prafi	59.83	Moderate
Masni	63.29	High
Manokwari Timur	67.29	High
Manokwari Selatan	67.96	High
Manokwari Utara	80.91	Very High

Source: Primary data (2025)

The Infrastructure Damage Ratio (IDR) complements this by describing the proportion of lightly and heavily damaged roads in each district (Table 5). Manokwari Utara recorded the highest IDR (80.91%), followed by Manokwari Selatan (67.96%), Manokwari Timur (67.29%), and Masni (63.29%). These districts fall within the High or Very High Damage categories. Conversely, Manokwari Barat recorded the lowest IDR (48.88%), while Sidey (53.46%), Warmare (56.63%), and Prafi (59.83%) were classified as Moderate Damage. The results indicate that damaged road sections account for a substantial proportion of the district road networks, particularly in Manokwari Utara.

High pavement deterioration substantially increases fuel consumption, greenhouse gas emissions, vehicle operating costs, and lifecycle infrastructure expenses, thereby reducing transportation sustainability and environmental efficiency, according to Radwan et al. (2024). Additionally, Alhjouj et al. (2022) underscored that deteriorating transportation infrastructure, particularly in tropical developing regions susceptible to extreme rainfall and hydrological instability, exacerbates environmental vulnerability and diminishes climate resilience.

Road Resilience Coefficient (RRC)

The Road Resilience Coefficient measures the ratio of good condition to damaged road length. The results by district are presented in Table 6.

Table 6. RRC per district in Manokwari Regency

District	RRC	RRC Category
Manokwari Barat	0.90	Moderate

Sidey	0.83	Moderate
Warmare	0.62	Moderate
Prafi	0.57	Moderate
Masni	0.54	Moderate
Manokwari Timur	0.43	Low
Manokwari Selatan	0.38	Low
Manokwari Utara	0.24	Low

Source: Primary data (2025)

The Road Resilience Coefficient (RRC) measures the ratio of good-condition road length to the combined length of lightly and heavily damaged roads. Manokwari Barat recorded the highest RRC (0.90), followed by Sidey (0.83), Warmare (0.62), Prafi (0.57), and Masni (0.54). These five districts fall within the Moderate category under the study's operational thresholds. Manokwari Timur (0.43), Manokwari Selatan (0.38), and Manokwari Utara (0.24) fall within the Low category. The results indicate that the balance between good-condition and damaged road sections differs across the study area. Although Masni has the longest road network, its RRC of 0.54 indicates that the length of good-condition roads remains relatively limited compared with damaged roads.

The RRC results provide a ratio-based interpretation of the same road-condition inventory used to calculate RCI and IDR. Consequently, RRC should not be interpreted as an independent measurement of the capacity of road infrastructure to resist, recover from, or adapt to climate hazards. Rather, it represents the relative balance between good and damaged road lengths. Delcroix et al. (2026) asserted that sustainable transportation infrastructure must incorporate resilience-focused management, environmental sustainability, and lifespan efficiency to enhance adaptable infrastructure systems. Consequently, districts such as Manokwari Utara and Manokwari Selatan require immediate climate-responsive rehabilitation strategies, ecosystem-based drainage systems, predictive maintenance methodologies, and low-carbon pavement management to enhance infrastructure resilience and promote the long-term sustainability of green infrastructure.

International Roughness Index (IRI)

The International Roughness Index (IRI) evaluates pavement surface roughness and ride quality. Table 7 displays the IRI results by district.

Table 7. IRI per district in Manokwari Regency

District	**Estimated IRI (m/km)**	**Rating span of estimate**
Manokwari Barat	4 – 8	Good-Moderate
Sidey	4 – 8	Good-Moderate
Warmare	8 – 12	Moderate-Lightly Damaged
Prafi	8 – 12	Moderate-Lightly Damaged
Masni	> 12	Heavily Damaged

District	Estimated IRI (m/km)	Rating span of estimate
Manokwari Timur	8 – 12	Moderate-Lightly Damaged
Manokwari Selatan	> 12	Heavily Damaged
Manokwari Utara	> 12	Heavily Damaged

Source: Primary data (2025)

The estimated International Roughness Index (IRI) values indicate differences in pavement roughness among the eight districts (Table 6). Manokwari Barat and Sidey have estimated values of 4–8 m/km, corresponding to the Moderate category under the study's operational classification. Warmare, Prafi, and Manokwari Timur fall within the estimated range of 8–12 m/km, spanning the Moderate boundary and Lightly Damaged category. In contrast, Masni, Manokwari Selatan, and Manokwari Utara have estimated IRI values exceeding 12 m/km and are classified as Heavily Damaged. These estimates identify potential pavement roughness concerns, particularly in districts with extensive or strategically important road networks.

IRI measures longitudinal pavement roughness and riding quality. Higher values generally indicate greater surface irregularity and poorer ride quality. This relationship is consistent with the pavement sustainability literature, including Kargah-Ostadi et al. (2024), which discusses the relevance of pavement roughness to transportation performance. However, this study presents IRI values as estimated ranges rather than verified profilometer measurements. They should therefore be treated as preliminary indicators for comparative assessment, not as definitive measurements of vehicle operating costs, fuel consumption, or greenhouse gas emissions. Field measurements using calibrated equipment are necessary to establish actual IRI values and confirm the district classifications.

From a green infrastructure perspective, the spatial distribution of IRI values suggests that infrastructure resilience and adaptive transportation capacity are unevenly distributed across districts in Manokwari Regency. In the Pacific Ocean region, districts with high IRI values are more susceptible to accelerated pavement deterioration due to climate variability, inundation, drainage inefficiency, and increasing transportation pressure. Conversely, districts with lower IRI values show stronger adaptive capacity and better transportation sustainability performance. Consequently, districts with severe pavement roughness need climate-responsive rehabilitation strategies, ecosystem-based drainage infrastructure, predictive maintenance systems, and low-carbon pavement technologies to enhance the resilience of long-term green infrastructure and transportation efficiency. To support adaptive transportation systems in climate-sensitive regions, sustainable road infrastructure management should incorporate resilience-oriented approaches, environmental sustainability, and pavement functionality, as Sáenz de Tejada et al. (2024) emphasize.

Surface Distress Index (SDI)

The Surface Distress Index (SDI) evaluates visible pavement deterioration. The SDI results by district are presented in Table 8.

Table 8. SDI per district in Manokwari Regency

District	Estimated SDI	Rating span of estimate
Manokwari Barat	50 – 100	Moderate
Sidey	50 – 100	Moderate
Warmare	100 – 150	Moderate-Lightly Damaged

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District	Estimated SDI	Rating span of estimate
Prafi	100 – 150	Moderate-Lightly Damaged
Masni	> 150	Heavily Damaged
Manokwari Timur	100 – 150	Moderate-Lightly Damaged
Manokwari Selatan	> 150	Heavily Damaged
Manokwari Utara	> 150	Heavily Damaged

Source: Primary data (2025)

The estimated Surface Distress Index (SDI) results show a spatial pattern broadly consistent with the IRI assessment (Table 8). Manokwari Barat and Sidey fall within the estimated range of 50–100, corresponding to Moderate pavement distress. Warmare, Prafi, and Manokwari Timur have estimated values of 100–150 and span the Moderate boundary and Lightly Damaged category. Meanwhile, Masni, Manokwari Selatan, and Manokwari Utara have estimated SDI values exceeding 150, indicating Heavily Damaged conditions under the study's stated thresholds. These results suggest that surface deterioration may be particularly important in districts where the road network requires more systematic inspection and maintenance. Unlike IRI, which evaluates longitudinal roughness, SDI assesses visible pavement distress through prescribed observations and scoring procedures. The indicators therefore provide complementary engineering perspectives. Blaauw et al. (2022) also discuss the relationship between pavement deterioration and infrastructure sustainability, particularly in relation to pavement performance under changing climatic conditions. Nevertheless, the SDI estimates presented here require validation through systematic field surveys of cracking, potholes, rutting, and other relevant distress parameters. Apply the sequential scoring procedure specified in the applicable Bina Marga guidance rather than assuming that individual distress components can be combined through an unrestricted simple summation.

Pavement Condition Index (PCI)

The Pavement Condition Index (PCI) evaluates overall pavement quality based on the severity and extent of distress. The PCI results by district are displayed in Table 9.

Table 9. PCI per district in Manokwari Regency

District	Estimated PCI	Rating span of estimate
Manokwari Barat	58 – 62	Good
Sidey	52 – 58	Fair–Good
Warmare	48 – 55	Fair-Good
Prafi	45 – 52	Fair
Masni	40 – 48	Fair
Manokwari Timur	35 – 45	Poor-Fair
Manokwari Selatan	35 – 42	Poor-Fair

District	Estimated PCI	Rating span of estimate
Manokwari Utara	20 – 35	Very Poor-Poor

Source: Primary data (2025)

The estimated Pavement Condition Index (PCI) values indicate differences in overall pavement surface condition across the districts (Table 9). Manokwari Barat has the highest estimated range (58–62), followed by Sidey (52–58). Warmare and Prafi have estimated ranges of 48–55 and 45–52, respectively. Masni has an estimated PCI range of 40–48, while Manokwari Timur and Manokwari Selatan have ranges of 35–45 and 35–42. Manokwari Utara records the lowest estimated range (20–35). These results suggest relatively poorer pavement conditions in Manokwari Utara, Manokwari Selatan, and Manokwari Timur. Masni also requires particular attention because its extensive road network coincides with an estimated PCI range indicating substantial pavement deterioration. PCI summarizes visible pavement distress and supports maintenance assessment; it does not directly measure structural capacity (ASTM International, 2024). Masni's estimated IRI and SDI classes differ from its PCI interpretation. A study on West Seram roads in Maluku likewise found differences among PCI, SDI, and IRI assessments (Hasrudin & Maha, 2024). That segment-based comparison supports examining the measurement basis of each indicator; its values are not directly comparable with the district aggregates presented here.

District-Based Spatial Analysis of Green Infrastructure Performance and Environmental Vulnerability

The district-based spatial analysis demonstrates substantial disparities in green infrastructure performance, transportation sustainability, pavement deterioration, and environmental vulnerability across Manokwari Regency. Spatially, districts exhibit varying levels of infrastructure resilience and transportation functionality as reflected by integrated indicators including Road Condition Index (RCI), Infrastructure Damage Ratio (IDR), Green Infrastructure Performance Index (GIPI), Road Resilience Coefficient (RRC), International Roughness Index (IRI), Surface Distress Index (SDI), Pavement Condition Index (PCI), and Provincial/Kabupaten Road Management System (PKRMS). These variations indicate that transportation sustainability is not uniformly distributed across districts and may be influenced by pavement conditions, accessibility performance, environmental exposure, and adaptive infrastructure capacity. According to Alhjouj et al. (2022), sustainable transportation infrastructure should be evaluated spatially because environmental pressures, maintenance capacity, and infrastructure performance vary significantly across regions, particularly within climate-sensitive tropical areas. The preliminary district comparison using the Green Infrastructure Performance Index (GIPI) indicates substantial disparities in transportation sustainability, infrastructure resilience, and environmental vulnerability across the eight districts of Manokwari Regency. Based on the GIPI classification presented in Table 9, Manokwari Barat records the highest GIPI score of 51.12, followed by Sidey (46.54), Warmare (43.37), and Prafi (40.17) (Table 10), all of which fall within the Moderate performance category. These results indicate relatively better green infrastructure performance than in other districts, particularly in pavement functionality, transportation accessibility, and infrastructure resilience. However, their moderate classification also suggests that continuous preventive maintenance and climate-responsive infrastructure management remain necessary to maintain transportation functionality and minimize environmental pressures. The relatively higher GIPI scores indicate better sustainability performance, although further improvements are required to achieve high-performing, climate-resilient transportation infrastructure.

Table 10. GIPI per district in Manokwari Regency

District	RCI	SAI	EI	GIPI	Provisional GIPI Category
Manokwari Barat	51.12	65.00	37.24	51.12	Moderate

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Sidey	46.54	43.00	50.08	46.54	Moderate
Warmare	43.37	46.00	40.74	43.37	Moderate
Prafi	40.17	48.00	32.34	40.17	Moderate
Masni	36.71	42.00	31.42	36.71	Low
Manokwari Timur	32.71	38.00	27.42	32.71	Low
Manokwari Selatan	32.04	36.00	28.08	32.04	Low
Manokwari Utara	19.09	24.00	14.18	19.09	Very Low

Source: Primary data (2025)

A calculation check shows that SAI + EI = 2 × RCI in every row of Table 10 at the reported precision. Thus, Equation (7) gives GIPI = 0.4RCI + 0.3(SAI + EI) = RCI. This equality does not require SAI and EI individually to equal RCI; their deviations cancel. Accordingly, the GIPI interpretations below remain provisional.

Conversely, Masni records a GIPI score of 36.71, categorized as Low, indicating a comparatively low provisional score a need to examine maintenance requirements. Although Masni possesses the longest district road network, covering 189.344 km, its relatively low GIPI score indicates considerable challenges in maintaining pavement functionality, transportation accessibility, and infrastructure resilience across extensive road corridors. Manokwari Timur (32.71) and Manokwari Selatan (32.04) are also classified as Low, reflecting weaker green infrastructure performance, accelerating pavement deterioration, reduced transportation efficiency, and limited adaptive infrastructure capacity. These conditions potentially increase vehicle operating costs, fuel consumption, greenhouse gas emissions, and long-term infrastructure rehabilitation requirements. Barbosa et al. (2023) highlighted the importance of pavement sustainability in reducing environmental impacts, particularly because pavement characteristics and deterioration influence transportation energy consumption and associated emissions.

Manokwari Utara has the lowest GIPI score (19.09) and is classified as Very Low, indicating the lowest provisonal composite score among the eight districts. This result indicates substantial infrastructure sustainability challenges, including deteriorating pavement conditions, limited transportation accessibility, and inadequate adaptive capacity to environmental and climatic pressures. The relatively low GIPI score also suggests a need for more intensive infrastructure rehabilitation, improved drainage performance, and stronger climate adaptation measures.

Considering Manokwari Regency's tropical coastal environment, characterized by high rainfall intensity and exposure to Pacific Ocean climatic influences, inadequate pavement conditions and drainage systems may increase vulnerability to flooding, surface runoff, erosion, and accelerated infrastructure deterioration. Therefore, Manokwari Utara should receive particular attention in sustainable transportation planning through climate-responsive pavement rehabilitation, ecosystem-based drainage infrastructure, and predictive maintenance strategies

Potential environmental vulnerability should be assessed in relation to climatic characteristics and geographic conditions influenced by the Pacific Ocean region. High annual rainfall intensity, elevated humidity, and bimodal precipitation patterns accelerate pavement deterioration by increasing runoff accumulation, drainage failure, erosion, and structural weakening. Districts characterized by low resilience capacity and severe pavement deterioration are particularly vulnerable to climate-induced transportation disruptions. Alhjouj et al. (2022) explained that transportation infrastructure resilience is inseparable from environmental sustainability

because deteriorated pavements increase ecological pressures and reduce adaptive capacity to environmental hazards. Consequently, districts exhibiting low RCI, PCI, and RRC values combined with high IDR, IRI, and SDI values warrant investigation of environmental exposure alongside the recorded pavement deterioration.

The integrated spatial assessment raises questions about differences in transportation accessibility and infrastructure governance across districts in Manokwari Regency. Districts with higher accessibility and pavement performance generally demonstrate stronger adaptive transportation systems, while districts with severe deterioration experience increasing transportation isolation and socioeconomic vulnerability. The reported Sustainable Accessibility Index (SAI) values provisionally suggest that districts with low serviceability experience reduced connectivity to economic centers, healthcare services, educational facilities, and regional transportation networks. As emphasized in United Nations ESCAP (2022), sustainable mobility systems require reliable access to transportation, as it directly influences economic productivity, social inclusion, and regional resilience. Consequently, unequal accessibility conditions contribute to spatial disparities in sustainable regional development and environmental sustainability performance.

Overall, the district-based spatial analysis suggests that transportation sustainability and environmental vulnerability in Manokwari Regency may vary with pavement condition, accessibility performance, infrastructure resilience, maintenance capacity, and climatic exposure. Integrating green infrastructure indicators provides a comprehensive framework for identifying priority rehabilitation areas, strengthening adaptive transportation systems, and supporting sustainable regional development in tropical coastal regions. These findings reinforce the importance of resilience-oriented transportation planning, climate-responsive infrastructure governance, and ecosystem-based rehabilitation strategies to improve long-term transportation sustainability and environmental resilience in developing regions.

A conditional sensitivity check used the reported RCI, SAI, and EI values with four weight sets: (0.4, 0.3, 0.3), (1/3, 1/3, 1/3), (0.4, 0.4, 0.2), and (0.4, 0.2, 0.4), respectively. District ranks were unchanged across these scenarios (Appendix Table A6). Baseline and equal-weight agreement follows algebraically from SAI + EI = 2RCI; it is not independent validation. These calculations assess only sensitivity to the selected weights, not uncertainty in the undocumented component data.

Integrated Climate-Resilient Governance and Sustainable Asset Management for Green Transportation Infrastructure

The integrated climate-resilient governance analysis demonstrates that sustainable transportation infrastructure management in Manokwari Regency is strongly influenced by pavement condition performance, infrastructure resilience capacity, environmental vulnerability, maintenance governance, and adaptive asset management systems. Integrating Provincial/Kabupaten Road Management System (PKRMS) indicators with climate resilience and green infrastructure principles reveals substantial disparities in transportation sustainability across districts. Districts with relatively stronger pavement functionality and moderate rehabilitation priorities, such as Manokwari Barat and Sidey, generally demonstrate more stable transportation governance and adaptive infrastructure performance. Lower PKRMS scores generally indicate that infrastructure systems remain functional and require less intensive rehabilitation interventions. According to Huda and Hartatik (2025), effective PKRMS implementation supports sustainable transportation systems through predictive maintenance planning, lifecycle infrastructure management, and optimized rehabilitation prioritization. Conversely, districts with severe pavement deterioration, poor accessibility, and high PKRMS priority levels, including Manokwari Utara and Manokwari Selatan, show low climate resilience and limited infrastructure adaptive capacity (Table 11). High PKRMS ratings indicate that pavement conditions have progressed beyond preventative maintenance norms, necessitating extensive rehabilitation or reconstruction to restore transportation functionality and adaptive infrastructure capacity. Moreover, broad road networks, such as those in Masni, complicate maintenance and pose infrastructure management challenges, as larger transportation corridors require substantial rehabilitation resources and ongoing asset management. Radwan et al. (2024) emphasized that degraded pavement conditions significantly increase fuel consumption, greenhouse gas emissions, lifecycle infrastructure costs, and environmental pressures, thereby diminishing transportation sustainability and climate resilience. Furthermore, Ojo (2024), resilient infrastructure systems

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require integrated governance frameworks that combine maintenance management, climate adaptation, environmental sustainability, and long-term infrastructure planning to strengthen transportation resilience to climate-induced pressures. These priority estimates do not independently measure governance quality or climate resilience.

Table 11. PKRMS per district in Manokwari Regency

District	Estimated research priority score	Classification status
Manokwari Barat	45 – 55	Moderate
Sidey	50 – 58	Moderate
Warmare	58 – 65	Moderate–High
Prafi	60 – 68	Moderate–High
Masni	70 – 80	High
Manokwari Timur	72 – 82	High
Manokwari Selatan	80 – 90	Very High
Manokwari Utara	90 – 100	Critical

Source: Primary data (2025)

The discussion also highlights that these systems play a critical role in improving long-term transportation sustainability and reducing environmental vulnerability. Districts characterized by extensive transportation corridors, particularly Masni and Prafi, require adaptive asset management strategies because larger road networks substantially increase maintenance complexity, rehabilitation costs, and infrastructure governance challenges. Predictive maintenance systems integrated into PKRMS frameworks may support lifecycle cost control and transportation performance, subject to local evaluation. According to Radwan et al. (2024), deteriorated pavement conditions significantly increase fuel consumption, greenhouse gas emissions, and infrastructure lifecycle expenses due to increased rolling resistance and transportation inefficiency. Consequently, sustainable asset management systems are essential to improve pavement durability, reduce environmental impacts, and strengthen adaptive transportation systems. From a green infrastructure perspective, climate-responsive rehabilitation strategies represent a fundamental component of sustainable transportation governance in Manokwari Regency. Districts categorized as highly vulnerable require integrated rehabilitation interventions emphasizing low-carbon pavement technologies, ecosystem-based drainage systems, permeable roadside infrastructure, bio-retention systems, and climate-adaptive pavement materials. Green drainage systems are particularly important within tropical coastal regions because high rainfall intensity and hydrological instability accelerate pavement deterioration and runoff accumulation. Alhjouj et al. (2022) emphasized that sustainable transportation infrastructure management should integrate environmental sustainability, resilience-oriented adaptation, and lifecycle infrastructure efficiency to strengthen long-term infrastructure performance and ecological resilience. Therefore, adaptive rehabilitation systems should prioritize environmentally sustainable pavement technologies that reduce greenhouse gas emissions, improve drainage efficiency, and strengthen climate resilience.

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STUDY LIMITATIONS AND FUTURE RESEARCH

Several limitations should be considered when interpreting the findings. First, the assessment uses district-level road-condition data, which may conceal substantial differences among individual road segments. District-level aggregation limits the identification of localized pavement deterioration, accessibility constraints, and infrastructure exposure to environmental hazards. Future studies should apply segment-level spatial analysis to improve the accuracy of road-condition assessment and maintenance prioritization.

Second, the estimated IRI, SDI, and PCI values require further validation through standardized field measurements. IRI should be obtained using calibrated profilometers or validated measurement systems, while SDI and PCI require systematic pavement distress surveys following the applicable Indonesian Bina Marga and ASTM D6433 procedures. Using estimated ranges limits the precision of cross-indicator comparisons and prevents definitive conclusions about the actual pavement condition of individual road sections.

Third, the study uses district-level comparisons and available climatic information but does not yet establish causal relationships between climate variables and pavement deterioration. Future investigations should integrate long-term rainfall records, flood inventories, slope characteristics, hydrological data, and road-segment exposure information. Multi-temporal monitoring would help determine how climatic variability affects pavement deterioration and infrastructure maintenance requirements.

Finally, the proposed maintenance priorities require validation using detailed traffic volumes, road functional classifications, construction costs, budget allocations, and official PKRMS programming outputs. Future studies should integrate life-cycle cost assessment, greenhouse gas emissions, material durability, and ecosystem-based drainage performance to evaluate the environmental and economic implications of alternative rehabilitation strategies.

These improvements would strengthen the framework's transferability to other tropical road networks in eastern Indonesia and comparable developing regions. The dependence between RCI and IDR, overlapping inputs in RRC, and the exact offset between the reported SAI and EI scores also limit interpretation. Weight sensitivity cannot validate undocumented component measurements.

CONCLUSION

This study developed an integrated green infrastructure assessment framework to evaluate transportation sustainability, infrastructure resilience, environmental vulnerability, and adaptive infrastructure governance

across district road networks in Manokwari Regency. The first research contribution was demonstrating that the integration of multiple pavement sustainability indicators, including Road Condition Index (RCI), Infrastructure Damage Ratio (IDR), Road Resilience Coefficient (RRC), International Roughness Index (IRI), Surface Distress Index (SDI), and Pavement Condition Index (PCI), provides a comprehensive multidimensional framework for assessing transportation infrastructure performance within tropical developing regions.

The integrated assessment revealed substantial disparities in pavement functionality, transportation accessibility, infrastructure resilience, and environmental sustainability across districts. Districts such as Manokwari Barat and Sidey showed stronger green infrastructure performance, with better pavement conditions, improved accessibility, and greater resilience, whereas Manokwari Utara, Manokwari Selatan, and Manokwari Timur had lower serviceable road shares and require further assessment of damaged segments.

The second research objective was successfully achieved by identifying spatial disparities in green infrastructure performance and environmental vulnerability through comparative district-based sustainability analysis of the Green Infrastructure Performance Index (GIPI). The spatial analysis showed that transportation sustainability and adaptive infrastructure capacity are unevenly distributed across Manokwari Regency because of variations in pavement deterioration, accessibility performance, climate exposure, and maintenance capacity. Districts categorized as highly vulnerable generally showed low RCI, PCI, and RRC values alongside high IDR, IRI, and SDI values, indicating severe pavement roughness, surface distress, declining accessibility, and weak climate resilience.

Conversely, districts with moderate-to-high sustainability performance demonstrated comparatively stronger transportation functionality and lower environmental pressures. The findings further revealed that high rainfall intensity, hydrological instability, flooding, and tropical climatic variability associated with the Pacific Ocean significantly accelerate pavement deterioration and environmental vulnerability. Dimnet (2022) emphasized that transportation infrastructure within tropical regions requires resilience-oriented infrastructure management because climate variability substantially increases infrastructure vulnerability and maintenance complexity. Because the reported SAI and EI scores offset one another, the current GIPI ranking duplicates RCI and cannot yet establish an independent green infrastructure ranking.

The third research objective demonstrated substantial spatial variation in road infrastructure sustainability across the eight districts of Manokwari Regency, requiring differentiated technical interventions. Manokwari Utara and Manokwari Selatan require priority structural rehabilitation, drainage improvements, erosion control, and moisture-resistant pavement materials because of their poor road conditions. Masni and Prafi require phased rehabilitation, corridor-based maintenance, and systematic pavement monitoring to address deterioration across their extensive road networks.

Manokwari Timur requires targeted pavement strengthening and improved drainage, while Warmare should focus on periodic maintenance and preventive rehabilitation. In contrast, Manokwari Barat and Sidey should prioritize routine maintenance, pavement preservation, and drainage management to sustain existing road performance. These interventions should incorporate periodic assessments of IRI, SDI, and PCI, as well as PKRMS-based maintenance planning, to improve investment efficiency and strengthen long-term infrastructure resilience under tropical climatic conditions.

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APPENDIXES

Appendix Table A1. District road-network inventory and basic geometric characteristics

District	Road sections (n)	Road length (km)	Mean width (m)	Minimum width (m)	Maximum width (m)
Manokwari Barat	68	74.812	4.18	3.00	7.00
Manokwari Selatan	37	59.172	3.93	3.00	6.00
Manokwari Timur	13	16.413	3.35	3.00	5.50
Manokwari Utara	3	6.338	3.33	3.00	4.00
Masni	43	189.344	3.50	3.00	5.00
Prafi	40	121.376	3.69	3.00	5.00
Sidey	10	58.277	3.90	3.00	5.50
Warmare	13	57.339	4.04	3.00	5.50
Total / overall	227	583.071	—	—	—

Source: Primary Data (2025)

Appendix Table A2. Road-condition distribution and derived network-condition indicators by district

District	Total length (km)	Good (km)	Moderate (km)	Lightly damaged (km)	Heavily damaged (km)
Manokwari Barat	74.812	32.806	5.440	11.943	24.623
Manokwari Selatan	59.172	15.147	3.810	4.129	36.086
Manokwari Timur	16.413	4.763	0.605	2.039	9.006
Manokwari Utara	6.338	1.210	0.000	0.000	5.128
Masni	189.344	65.262	4.252	5.038	114.792
Prafi	121.376	41.575	7.176	8.485	64.140
Sidey	58.277	25.930	1.190	0.000	31.157
Warmare	57.339	20.063	4.805	4.260	28.211
Total / overall	583.071	206.756	27.278	35.894	313.143

Source: Primary Data (2025)

Appendix Table A3. Pavement-type composition of the district road network

District	Hot-mix (km)	Lapen/Makadam (km)	Concrete (km)	Telford/gravel (km)	Earth/unopened (km)	Recorded pavement total (km)
Manokwari Barat	34.418	0.380	16.885	11.247	11.882	74.812
Manokwari Selatan	18.033	0.588	6.488	14.096	19.967	59.172

District	Hot-mix (km)	Lapen/Makadam (km)	Concrete (km)	Telford/gravel (km)	Earth/unopened (km)	Recorded pavement total (km)
Manokwari Timur	5.851	0.140	1.988	1.561	6.873	16.413
Manokwari Utara	1.210	0.000	0.000	0.828	4.300	6.338
Masni	76.522	0.770	5.568	92.238	15.016	190.114
Prafi	46.587	2.500	9.169	49.267	13.853	121.376
Sidey	26.730	0.000	0.890	29.972	0.685	58.277
Warmare	29.703	0.220	1.000	19.856	6.560	57.339
Total	239.054	4.598	41.988	219.065	79.136	583.841

Source: Primary Data (2025)

Appendix Table A4. District GIPI components and calculation using the reported SAI and EI

District	RCI	SAI	EI
Manokwari Barat	51.12	65.00	37.24
Manokwari Selatan	32.04	36.00	28.08
Manokwari Timur	32.71	38.00	27.42
Manokwari Utara	19.09	24.00	14.18
Masni	36.71	42.00	31.42
Prafi	40.17	48.00	32.34
Sidey	46.54	43.00	50.08
Warmare	43.37	46.00	40.74

Source: Primary Data (2025)

Appendix Table A5. Source-data validation and reconciliation

Check	Worksheet result	Recalculated result	Implication
Number of road sections	227 district records	227 records	Consistent
Total road length	Worksheet aggregate row: 1,166.142 km	Sum of eight district subtotals: 583.071 km	Aggregate row is exactly double the district total; use district-level sum pending verification
Condition-class total	Good 206.756; Moderate 27.278; Light damage 35.894; Heavy damage 313.143 km	Sum = 583.071 km	Condition classes reconcile with district road length
Pavement-type total	Hot-mix 239.054; Lapen/Makadam 4.598; Concrete 41.988; Telford/gravel 219.065; Earth/unopened 79.136 km	Sum = 583.841 km	Exceeds road length by 0.770 km; verify category overlap or entry errors

Source: Primary Data (2025)

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Appendix Table A6. Conditional sensitivity of GIPI to selected weights

District	Baseline	Equal weights	Access emphasis	Environment emphasis	Rank in all scenarios
Manokwari Barat	51.12	51.12	53.90	48.34	1
Sidey	46.54	46.54	45.83	47.25	2
Warmare	43.37	43.37	43.90	42.84	3
Prafi	40.17	40.17	43.74	38.60	4
Masni	36.71	36.71	37.77	35.65	5
Manokwari Timur	32.71	32.71	33.77	31.65	6
Manokwari Selatan	32.04	32.04	32.83	31.25	7
Manokwari Utara	19.09	19.09	20.07	18.11	8