An AI-Assisted Multi-Spectral Remote Sensing Framework for Change Detection and Road Damage Index (RDI) in Flood-Prone Regions

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Keywords: Road Damage Index (RDI), Flood Vulnerability, Remote Sensing, Infrastructure Resilience, Soil Moisture

Abstract

Road infrastructure in flood-prone regions is highly vulnerable to degradation driven by environmental, hydrological, and climatic stressors. However, quantitative and spatially explicit assessments of such vulnerabilities remain limited, particularly for rural and intercity road networks. This study introduces a comprehensive Road Damage Index (RDI) framework that integrates multi-source satellite observations, meteorological records, and soil-related parameters to quantify road susceptibility in West Azerbaijan Province, Iran. All geospatial layers were preprocessed, normalized to a common scale, and weighted according to their relative contribution to road degradation. The resulting RDI was computed through pixel-wise aggregation, generating a spatially continuous map of road damage potential. Quantitative analysis indicates that over 95% of the 3,652.99 km road network falls within Moderate to Very High vulnerability levels, including 59.3% Moderate, 23.2% High, and 12.5% Very High, while only a small fraction (5.0%) exhibits low susceptibility. Spatial variability analysis reveals that northern and western counties show higher RDI values due to unfavorable soil and hydrological conditions, while southern and central regions demonstrate relatively lower vulnerability. The proposed framework provides a scalable, cost-effective, and reproducible methodology for regional road monitoring, integrating multi-dimensional environmental factors into a single decision-support index. Overall, the RDI framework enhances the capacity for data-driven infrastructure planning, targeted maintenance prioritization, and disaster preparedness, offering a transferable tool for improving road resilience under current and projected climate variability.

1. Introduction

Road networks are critical infrastructure that supports economic activities, emergency response, and daily transportation (Smith et al., 2020; Zhao et al., 2022). In regions prone to extreme weather events, such as heavy rainfall and flooding, asphalt roads are particularly vulnerable to surface degradation, rutting, and waterlogging, which can compromise safety and increase maintenance costs (Li et al., 2019; Rahman et al., 2021). In Iran, West Azerbaijan Province frequently experiences seasonal floods and extreme precipitation, making timely monitoring of road conditions essential for disaster preparedness and resilience planning.

Traditional methods for road condition assessment, such as field surveys and visual inspections, provide accurate information but are limited by high labor costs, time constraints, and spatial coverage (Chen et al., 2018). Remote sensing (RS) technologies offer a scalable alternative. Optical satellites such as Sentinel-2 provide multi-spectral data for vegetation and surface moisture analysis, while radar satellites such as Sentinel-1 enable monitoring of surface deformation and water content, even under cloudy conditions (Ghorbanzadeh et al., 2023; Mahdavi et al., 2024).

Previous studies have predominantly concentrated on monitoring urban infrastructure or mapping flood-affected areas (Houmma et al., 2025; Notarangelo et al., 2025), often neglecting the direct assessment of road asphalt conditions, which are highly vulnerable to hydrological and meteorological hazards. Moreover, existing approaches typically rely on single-source satellite data or individual indices, limiting their ability to capture the complex interactions between surface moisture, vegetation cover, and waterlogging that contribute to asphalt deterioration. Few studies have attempted to integrate multiple environmental and remote sensing datasets into a unified framework that quantitatively identifies potentially damaged road sections, highlighting a critical research gap that the present study aims to address.

In this study, we propose a comprehensive geospatial framework for assessing road asphalt damage and vulnerability using multi-source environmental and remote sensing data. The framework integrates diverse spatial datasets—including vegetation, moisture, climate, soil, and erosion-related information—to construct an Enhanced Road Damage Index (RDI) that quantitatively identifies potentially damaged or high-risk road sections. A case study in West Azerbaijan demonstrates the framework's applicability, offering a low-cost, scalable, and operationally feasible approach for regional road monitoring, infrastructure management, and disaster preparedness.

2. Materials and Methods

2.1 Study Area

The study area encompasses several counties in West Azerbaijan Province, Iran, including Takab, Shahin Dezh, Bukan, Mahabad, Sardasht, Piranshahr, Naqadeh, Oshnavieh, Urmia, Salmas, and Khoy (Figure 1). This region is characterized by a diverse topography, ranging from mountainous terrain in the south and west to relatively flat plains in the north and east, which significantly influences surface runoff and flood dynamics. West Azerbaijan experiences a semi-arid to temperate climate, with annual precipitation varying between 300 and 700 mm, predominantly occurring in winter and spring. Seasonal rainfall combined with snowmelt in the highlands frequently leads to flash floods and localized waterlogging, which can severely impact road

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infrastructure. The road network in these counties consists of both primary highways and secondary rural roads, many of which traverse flood-prone areas and agricultural lands.

The selection of these counties is based on their high vulnerability to hydrological hazards and the strategic importance of the transportation network for local communities. By focusing on multiple counties, the study aims to demonstrate the scalability and applicability of the proposed AI-assisted multi-spectral remote sensing framework for assessing road damage across varying topographic and climatic conditions.

Satellite imagery from Sentinel-2 (B2–B12) is used to capture multi-spectral information across the study area, enabling the calculation of NDVI, NDMI, and NDWI indices, which serve as inputs for the proposed Road Damage Index (RDI). This case study provides a practical demonstration of remote sensing-based, scalable monitoring of asphalt degradation in flood-prone regions.

Figure 1. Location of the Study area.

2.2 Satellite-Based Earth Observation Framework

The proposed AI-assisted Multi-Spectral Remote Sensing Framework for Road Damage Index (RDI) integrates multi-source satellite imagery, meteorological data, and environmental indices to quantitatively evaluate potential road damage in flood-prone regions. The framework is designed to provide a scalable, low-cost, and operationally feasible solution for monitoring asphalt deterioration and water-related hazards along road networks.

2.2.1 Data Integration

The framework utilizes ten key layers reflecting surface conditions, hydrological stress, and environmental factors:

Optical Remote Sensing Indices: NDVI, NDMI, and NDWI derived from Sentinel-2 imagery capture vegetation cover, surface moisture, and water accumulation, which directly influence asphalt integrity.

Meteorological Data: Rainfall, Rainfall Deficit Index (RDI), snowfall averages, and humidity (both relative and absolute) provide temporal context regarding precipitation, flood risk, and moisture retention on asphalt surfaces.

Soil and Environmental Indices: Soil Moisture Deficit Index (SMDI), Soil Moisture Index (SMI), Composite Dust Vulnerability Index (CDVI), and Wind Erosion Index (WEI) represent soil stress, wind and dust exposure, which can exacerbate road degradation.

All layers are resampled to a common spatial resolution and reprojected to a unified coordinate reference system to ensure spatial consistency for pixel-wise analysis.

2.2.2 Road Damage Index (RDI) Computation

Normalization: Each raster layer is normalized to a 0–1 scale based on its physical range (Low–High) to ensure comparability.

Weighting and Aggregation:

All raster layers were preprocessed to ensure spatial alignment, including resampling to a uniform resolution and reprojection to a common coordinate reference system. Each dataset was then normalized to a 0–1 scale according to its physical range (Table 1), allowing pixel-wise comparability across different measurement units. Based on their relative contribution to road degradation, higher weights were assigned to key variables such as NDVI, NDMI, NDWI, Rainfall, RDI, SMDI, and SMI, while secondary factors including WEI and CDVI received lower weights. The Enhanced Road Damage Index (RDI) was calculated as a weighted sum of the ten normalized layers, representing the integrated influence of environmental, meteorological, and soil parameters on road vulnerability. The entire process was automated through Python-based scripts to ensure consistency, scalability, and reproducibility across large geographic areas.

$$i^{L} . i^{w} \sum_{i=1}^{n} = \text{Enhanced RDI} \tag{1}$$

Where i^{w} is the assigned weight of layer i^{L}. The resulting index ranges from 0 (no damage) to 1 (maximum potential damage).

2.2.3 Output and Visualization

The proposed framework generates a continuous raster map of Enhanced RDI across the study area, offering a spatially explicit depiction of potential road damage. For analytical purposes, the raster can be classified into discrete damage categories—such as low, medium, and high—or visualized using continuous color gradients to emphasize vulnerable road sections. Additionally, by intersecting the RDI raster with road vector datasets, it is possible to quantify the length and spatial distribution of roads under varying damage risk levels, thereby supporting targeted infrastructure maintenance, risk assessment, and disaster preparedness planning.

2.2.4 Advantages

The framework offers several key benefits: it integrates multi-source remote sensing and meteorological data, enabling a comprehensive assessment of both hydrological and environmental stressors affecting road infrastructure. Its automated and scalable processing reduces dependency onlabor-intensive field surveys, facilitating operational monitoring across large and inaccessible areas. Furthermore, by considering multiple environmental and climatic factors simultaneously, the framework enhances sensitivity to flood-induced and moisture-related road damage, providing a robust tool for risk-informed decision-making in flood-prone regions.

To provide a clear overview of the study workflow, Figure 2 presents a conceptual flowchart of the methodology. The diagram illustrates the integration of multi-source remote sensing, meteorological, and environmental data, followed by preprocessing, normalization, and weighted aggregation to construct the Enhanced Road Damage Index (RDI). This approach enables a spatially explicit assessment of road vulnerability, highlighting the sequential process from raw data acquisition to the generation of actionable road vulnerability maps.

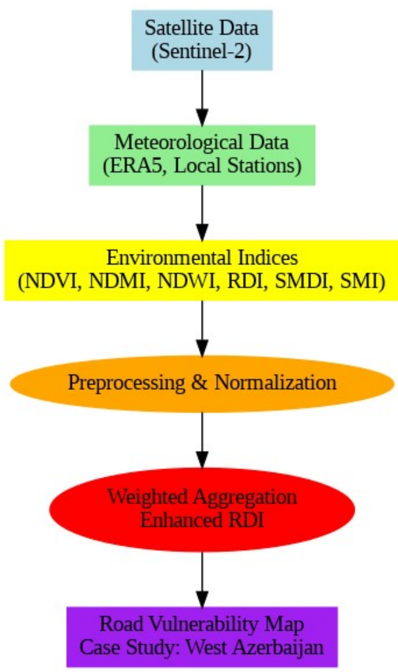

Figure 2. Workflow for computing the Enhanced Road Damage Index (RDI).

2.3 Remote Sensing Spatial Determinants

This study leverages a comprehensive suite of recent, multi-source geospatial datasets (2024–2025) that serve as spatial determinants of road damage susceptibility in flood-prone regions. A summary of all datasets, their sources, and their corresponding impacts is presented in Table 1. These datasets integrate satellite-based Earth observation, up-to-date meteorological measurements, and environmental indices, enabling a quantitative and spatially explicit assessment. NDVI, NDMI, and NDWI were derived from recent Sentinel-2 multispectral imagery, with NDVI quantifying vegetation cover near roads, influencing runoff and drainage efficiency, while NDMI and NDWI capture surface moisture and water accumulation patterns, serving as direct proxies for flood-induced asphalt deterioration. Daily rainfall, Rainfall Deficit Index (RDI), snowfall averages, and relative and absolute humidity were obtained from current ground weather stations and global reanalysis products (ERA5, CHIRPS), characterizing precipitation intensity, soil wetness, and moisture retention, which collectively control waterlogging and surface softening of asphalt. Soil Moisture Deficit Index (SMDI) and Soil Moisture Index (SMI) were derived from up-to-date remote sensing soil moisture products such as SMAP and ERA5-Land, representing soil stress and dryness/softening potential that indirectly influence road stability, while Wind Erosion Index (WEI) and Composite Dust Vulnerability Index (CDVI) integrate recent remote sensing and climate-derived wind and dust exposure metrics, capturing environmental stressors that can accelerate surface degradation.

Although explicit elevation and slope layers were not directly included, their effects are implicitly captured through the spatial variability of moisture, runoff, and flood-related indices, which reflect terrain-controlled hydrological processes

. All raster layers were resampled to a common spatial resolution, reprojected to a unified coordinate reference system, and harmonized for pixel-wise analysis. Collectively, these spatial determinants form the foundation of the Road Damage Index (RDI), enabling the integration of hydrological hazards and environmental stressors into a robust, operational, and reproducible geospatial framework for road infrastructure assessment and disaster preparedness.

Factor	Explanation & Source	Impact
NDVI	Vegetation cover near roads from Sentinel-2 imagery; affects runoff and drainage efficiency (Ghorbanzadeh et al., 2023)	Low vegetation → higher waterlogging and asphalt damage
NDMI	Surface moisture derived from Sentinel-2 B8/B11 bands (Mahdavi et al., 2024)	Low NDMI → higher flood-induced weakening
NDWI	Water accumulation from Sentinel-2 B3/B11 bands (Houmma et al., 2025)	High NDWI → potential asphalt softening
Rainfall	Daily precipitation from ground stations and ERA5/CHIRPS (Li et al., 2019)	Heavy rainfall → water accumulation and asphalt softening
Rainfall Deficit Index (RDI)	Wet/dry anomalies from ERA5/TRMM data (Rahman et al., 2021)	High deficit → increased road stress
Snowfall Avg	Snow accumulation and melt from local stations and ERA5 (Zhao et al., 2022)	Contributes to flooding and surface moisture
Humidity / Absolute Humidity	Moisture retention on asphalt from ERA5/local weather (Smith et al., 2020)	Low humidity → faster drying, potential cracking
SMDI	Soil moisture stress from SMAP/ERA5-Land (Chen et al., 2018)	High deficit → soil-induced road weakening

SMI	Soil Moisture Index from ERA5-Land/local soil sensors (Muñoz-Sabater, J et al., 2021)	Low SMI → high dryness → cracking risk; High SMI → potential softening and subsidence
WEI	Wind exposure from ECMWF/local wind stations (Notarangelo et al., 2025)	Accelerates dust deposition and minor surface erosion
CDVI	Dust vulnerability from MODIS and local dust monitoring (Houmma et al., 2025)	Dust deposition → surface degradation

Table 1. Key Remote Sensing and Environmental Layers.

3. Results

To assess road damage susceptibility across the study area, we developed a comprehensive spatial model integrating multiple environmental and hydrometeorological factors (Figure 3). Raster layers representing vegetation cover, surface moisture, rainfall patterns, soil moisture, wind exposure, and dust vulnerability were preprocessed, normalized, and combined into the Enhanced Road Damage Index (RDI). Each factor was weighted according to its relative influence on road degradation, allowing a pixel-wise assessment of potential damage. The resulting map provides a detailed, spatially explicit representation of vulnerability, highlighting areas that are more likely to experience asphalt deterioration under current environmental conditions.

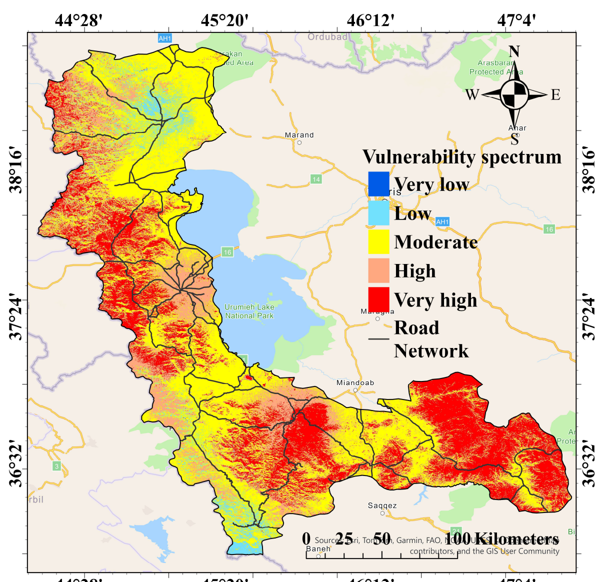

Figure 3. Spatial distribution of the Enhanced Road Damage Index (RDI).

The spatial distribution of road damage susceptibility reveals distinct patterns across the study area. Northern and western regions exhibit higher RDI values, corresponding to increased vulnerability due to low vegetation cover, drier soil conditions, and greater exposure to flooding. In contrast, areas with moderate soil moisture and denser vegetation show lower RDI values, indicating reduced susceptibility. The associated pie chart visually summarizes the distribution of road segments across susceptibility classes, showing that the majority of roads fall into the Moderate category (59.28%), followed by High (23.15%), Very High (12.53%), Low (5.02%), and Very Low (0.02%) (Figure 4).

These spatial patterns and proportional distributions provide actionable insights for targeted road maintenance, prioritization of infrastructure investments, and disaster preparedness, demonstrating the practical utility of the multi-factor Enhanced Road Damage Index (RDI) framework for regional road management.

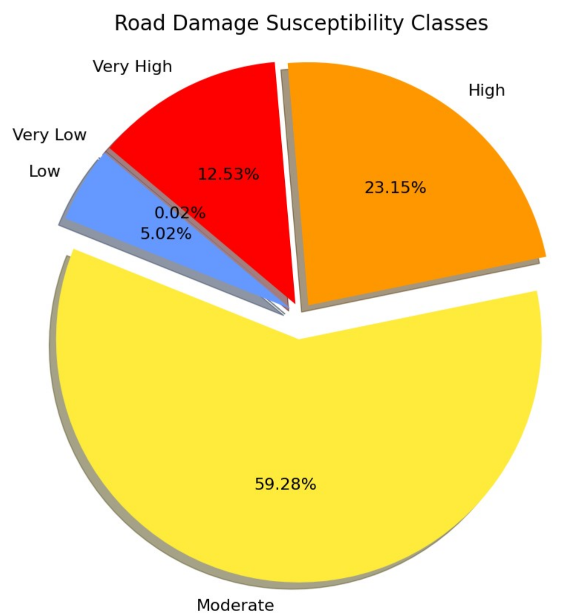

Figure 4. Percentage of area by damage susceptibility class.

3.1 Multiscale Road Damage Susceptibility Analysis

The results indicate that out of the total 3,652.991 km of the road network analyzed, the majority of roads fall within the Moderate vulnerability class, accounting for 2,164.257 km (59.28%). This is followed by the High vulnerability class with 846.968 km (23.15%) and the Very High vulnerability class with 457.686 km (12.53%), representing a significant portion of the network. In contrast, roads with lower vulnerability are minimal, with only 183.244 km (5.02%) classified as Low and less than one kilometer (0.836 km; 0.02%) classified as Very Low.

Collectively, over 95% of the total road length falls within the Moderate to Very High vulnerability categories, underscoring the widespread exposure of the regional road network to environmental and hydrological stressors. (Table 2).

RDI Class	Road Length (km)	Percent
Very Low	0.836	0.02%
Low	183.244	5.02%
Moderate	2164.257	59.28%
High	846.968	23.15%
Very High	457.686	12.53%
SUM	3652.991	100%

Table 2. Road Vulnerability Distribution by RDI Class.

The table presents the distribution of road segments across five vulnerability classes—Very Low, Low, Moderate, High, and Very High—based on the Road Damage Index (RDI) for each county in West Azerbaijan (Table 3). The RDI is a composite indicator derived from multiple environmental, meteorological, and soil-related factors, including vegetation cover (NDVI), surface moisture (NDMI, NDWI), rainfall, soil moisture indices (SMDI, SMI), wind exposure (WEI), and dust vulnerability (CDVI). These factors, represented in spatial layers, were aggregated to identify sections of the road network that are more susceptible to damage.

County-level observations:

Bukan exhibits a majority of roads in the Moderate class (72.57%), with a smaller fraction in Low (14.14%) and High (7.86%), reflecting generally average vegetation cover, moderate soil moisture, and moderate exposure to flooding and wind erosion. Only a negligible portion falls under Very Low (0.08%) and Very High (5.35%).

Khoy shows an even higher proportion of roads in the Moderate class (79.42%), suggesting widespread conditions favorable to average vulnerability: moderate NDVI and NDWI values, as well as relatively stable soil moisture. Very High vulnerability is minimal (0.15%), indicating limited areas of extreme stress.

Mahabad displays a more distributed pattern, with substantial portions in Moderate (39.87%) and High (35%), highlighting the presence of regions with higher flood exposure or drier soils. The relatively elevated Very High fraction (9.26%) suggests localized hotspots of critical road stress.

Orumiiyh stands out with a significant High (23.87%) and Very High (16.54%) vulnerability, likely related to lower vegetation cover and drier soils in some sub-regions, combined with terrain-induced waterlogging from rainfall accumulation.

Oshnavieh and Piranshahr are dominated by the Moderate class (76–77%), indicating fairly uniform environmental conditions across their road networks, with minor portions in High and Very High.

Salmas has a strikingly high proportion in the Moderate class (96.18%), reflecting relatively stable soil moisture, low wind/dust stress, and moderate vegetation cover, resulting in a more resilient road network.

Sardasht and Shahindezh show substantial Moderate and High fractions, with very low percentages in Very High, suggesting that while most roads are moderately vulnerable, extreme risk areas are limited.

Takab is notable for having the largest proportion of Very High vulnerability (44.27%), corresponding to regions with poor drainage, high soil dryness, and exposure to environmental stressors, making it a key priority for maintenance.

Naqadeh predominantly falls in Moderate (89.9%), with very low fractions in High or Very High, reflecting relatively favorable environmental conditions for road stability.

Regional and environmental implications:

The spatial distribution of vulnerability mirrors underlying environmental patterns captured by the RDI components: counties with lower vegetation cover, higher surface dryness, greater water accumulation potential, or higher wind/dust exposure tend to have larger fractions in the High and Very High classes. Conversely, areas with moderate soil moisture, denser vegetation, and lower exposure to hydro meteorological hazards are dominated by Moderate or Low vulnerability.

Relation to RDI maps and planning:

These results correspond closely with the previously generated RDI maps, where northern and western regions, such as Takab and Orumiiyh, appear as hotspots of vulnerability, whereas Salmas, Naqadeh, and parts of Bukan show more resilient conditions. The table quantitatively summarizes these spatial patterns, offering a clear guide for prioritizing road maintenance, allocating resources, and implementing disaster preparedness measures based on relative vulnerability.

Total network perspective:

The Total_Road_km column shows the extent of the road network in each county, allowing the assessment of vulnerability both in relative (percent) and absolute (km) terms. For example, while Takab has a smaller total road length (376.57 km) compared to Orumiiyh (604.77 km), the high fraction of Very High vulnerability highlights the critical nature of its road network. This combination of spatial and quantitative information enables data-driven decision-making for regional road management.

Name	VL (%)	L (%)	M (%)	H (%)	VH (%)	Km
Bukan	0.08	14.14	72.57	7.86	5.35	565
Khoy	0.10	12.73	79.42	7.60	0.15	446
Mahabad	0.12	15.75	39.87	35.00	9.26	381
Orumiiyh	0.08	0.80	58.71	23.87	16.54	604
Oshnavieh	0.32	4.67	76.69	9.66	8.66	141
Piranshahr	0.21	7.70	77.20	10.64	4.25	213
Salmas	0.18	0.46	96.18	1.46	1.72	248
Sardasht	0.19	24.41	69.43	5.44	0.53	238
Shahindezh	0.17	23.44	63.53	10.73	2.13	261
Takab	0.12	0.18	40.87	14.36	44.27	376
Naqadeh	0.26	1.30	89.90	8.14	0.40	174

Table 3. County-level road damage susceptibility (%).

4. Discussion

4.1 Spatial Distribution and Regional Variability of Road Damage Susceptibility

The Enhanced Road Damage Index (RDI) map highlights pronounced spatial heterogeneity in road vulnerability across West Azerbaijan Province. More than 95% of the analyzed road network is classified within moderate to very high vulnerability levels, reflecting the region's complex interplay of environmental and hydrological conditions. The southern and western mountainous counties, such as Sardasht and Piranshahr, exhibit elevated vulnerability due to steep slopes, rapid runoff, and increased erosive forces, which compromise road substructures. In contrast, flatter northern and eastern counties, including Urmia and Naqadeh, experience significant vulnerability primarily driven by waterlogging and prolonged soil saturation, leading to asphalt softening and subgrade instability.

This pronounced spatial heterogeneity underscores the importance of a location-specific assessment. Uniform mitigation strategies would be insufficient, as counties are influenced by distinct combinations of factors. For example, Oshnavieh and other western regions are affected by high precipitation interacting with dense vegetation, which modulates surface moisture retention. Eastern counties, such as Khoy and Salmas, are more susceptible to wind erosion and dust deposition due to their proximity to the Urmia Lake basin and relatively arid conditions. The multi-factor RDI framework

https://doi.org/10.5194/isprs-annals-X-4-W8-2025-819-2026 |

captures these spatially varying interactions, providing a nuanced understanding beyond traditional single-index assessments.

4.2 Advancements over Previous Approaches

Prior studies have largely focused on either urban infrastructure monitoring or flood-affected area mapping (Houmma et al., 2025; Notarangelo et al., 2025), often overlooking proactive evaluation of rural and intercity road networks. Conventional approaches relying on individual spectral indices or single-source satellite datasets are limited in capturing the multifactorial drivers of road degradation, such as the interaction between soil moisture, vegetation cover, and climatic stressors.

The present study extends beyond these limitations by integrating multiple remote sensing datasets, meteorological variables, and specialized indices, including the Soil Moisture Deficit Index (SMDI) and Composite Dust Vulnerability Index (CDVI). This multi-source integration enables a comprehensive assessment of hydrological and environmental stressors on road infrastructure. The framework further incorporates expert-driven weighting to quantify the relative importance of each factor, enhancing the physical interpretability and predictive performance of the model.

4.3 Implications for Infrastructure Management and Resilience

The RDI framework provides a robust, spatially explicit tool for regional road maintenance and disaster preparedness. Roads identified as “very high” vulnerability can be prioritized for inspection, reinforcement, or early warning measures before periods of elevated hydrological risk.
The integration of environmental, meteorological, and soil-related layers facilitates evidence-based allocation of limited maintenance resources
, ensuring strategic intervention where it is most needed.
Moreover, the methodology is adaptable and scalable. Integration with platforms such as Google Earth Engine allows dynamic updates with new satellite imagery and climate data, supporting long-term resilience planning under future climate scenarios. This capability enables forecasting of evolving road vulnerabilities and adaptive management strategies, overcoming the constraints of traditional field-based assessments.

4.4 Limitations and Future Directions

While robust, the framework has inherent limitations. The RDI’s accuracy depends on input data resolution, which may not fully capture localized damage such as small cracks or potholes. The expert-based weighting scheme could benefit from quantitative refinement using approaches like the Analytical Hierarchy Process (AHP) combined with sensitivity analysis.
Future research should incorporate high-resolution satellite or UAV imagery to improve local-scale validation
, incorporation of traffic volume to assess functional vulnerability, and temporal analyses using multi-year datasets to evaluate degradation trends and the impacts of specific extreme weather events. Such refinements would strengthen both the operational utility and predictive accuracy of the RDI framework for regional road management.

5. Conclusion

This study presents a comprehensive assessment of road damage susceptibility in West Azerbaijan using a multi-factor Road Damage Index (RDI) framework. By integrating environmental, hydrological, and soil-related indicators, the analysis quantitatively identifies sections of road with varying vulnerability levels. Results indicate that moderate to very high susceptibility classes cover the majority of the regional road network, with 59.3% of roads classified as Moderate, 23.2% as High, and 12.5% as Very High, emphasizing significant exposure to surface moisture, soil dryness, and hydrological hazards. County-level analysis further highlights spatial heterogeneity, where northern and western counties exhibit higher proportions of High and Very High risk roads due to the combined effects of dry soil conditions, low vegetation cover, and increased flood potential.
The RDI maps provide a spatially explicit tool for prioritizing maintenance, allocating resources, and supporting disaster preparedness, offering a replicable methodology for regional road management. The integration of multi-source satellite, meteorological, and soil datasets demonstrates the robustness of the approach, ensuring that both environmental stressors and local conditions are accounted for. Overall, this framework enables evidence-based decision-making and sets the stage for future temporal analyses to monitor evolving vulnerability patterns and optimize infrastructure resilience.

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