An Integrated Remote Sensing and GIS Road Condition Assessment Framework

Applying Geospatial Techniques to Improve Pavement Condition Analysis

Tshepo Marang El Nthaga
Department of Civil Engineering, Pan African University-Institute for Basic Sciences, Technology and Innovation (PAUSTI), Nairobi, Kenya
tshepoelnthaga@gmail.com (corresponding author)

Timothy Nyomboi
Kenya Urban Roads Authority (KURA), Nairobi, Kenya
tnyomboi@hotmail.com

Mercy Mwaniki
Department of Geomatics Engineering and Geospatial Information Systems (GEGIS), Jomo Kenyatta University of Agriculture and Technology (JKUAT), Juja, Kenya
mmwaniki@jkuat.ac.ke

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ABSTRACT

Road infrastructure is essential for supporting socio-economic activities but faces deterioration due to high traffic volumes, unpredictable weather, poor drainage, and inadequate maintenance. Traditional visual assessment methods are often time-consuming and subjective. In contrast, Geographic Information Systems (GIS) provide a more precise and efficient approach to road condition assessment, including drainage analysis. This study integrates Remote Sensing and GIS to develop an innovative virtual road condition assessment framework that combines pavement distress evaluation with drainage analysis. The research was conducted on selected roads within Jomo Kenyatta University of Agriculture and Technology (JKUAT). Using high-resolution drone imagery, field surveys, and GIS-based analysis, road conditions were assessed through pavement distress mapping, flow accumulation, curvature analysis, and road attribute evaluation. The results revealed that Innovation Street exhibited the most severe distresses, while Technology Street had predominantly minor to moderate deterioration. Commonly identified distresses included rutting, potholes, longitudinal and transverse cracking, weathering, and alligator cracking. The Quantum Pavement Condition Index (QPCI) effectively identified distress hotspots requiring urgent maintenance, demonstrating the framework's potential to enhance road maintenance planning and decision-making. This study highlights the value of integrating GIS and remote sensing for efficient, data-driven infrastructure management, offering a scalable and resource-efficient approach for improving road maintenance strategies.

Keywords-road condition assessment; drone data; GIS; pavement distress

I. INTRODUCTION

Roads play a fundamental role in a nation's social and economic development by facilitating the transportation of goods and people, enabling access to essential services, and supporting information exchange [1]. Pavement surfaces are crucial for ensuring comfort, safety, and cost-efficient vehicle operations. However, roads deteriorate over time and require regular maintenance to uphold durability, efficiency, and safety standards. According to [2], pavement deterioration can result from multiple factors, including heavy traffic loads, temperature fluctuations, inadequate shoulders, weak clayey subgrades, and poor drainage. Proper temperature control during construction is also essential to prevent pavement failure. In Kenya, road distress features such as rutting, potholes, and cracking are prevalent, exacerbated by excessive traffic and unpredictable weather conditions [3].

One of the most pressing challenges for authorities is prioritizing road maintenance while optimizing the use of limited funds. A systematic approach is essential for establishing effective maintenance guidelines. Thus, prioritizing road maintenance is critical, involving materials and processes designed to extend the lifespan of road infrastructure and preserve its condition [4]. Routine pavement inspections and condition ratings are necessary to identify defects, diagnose their causes, and determine cost-effective remediation strategies [5]. The primary goal of pavement evaluation is to assess both the structural and functional integrity of roadway segments, facilitating corrective measures and long-term monitoring. Identifying distress factors and material properties is crucial for successful rehabilitation strategies and efficient resource allocation [6]. Organizations categorize road conditions differently [7]. Traditional visual inspection techniques for road assessments present various challenges, including subjectivity and inconsistencies in distress detection and classification, as they rely on manual eye inspections [8]. Results often vary significantly among inspectors, reducing reliability.

Geographic Information Systems (GIS) and other spatial technologies offer robust solutions for integrating roadway data, enhancing analysis, and improving decision-making in highway management. By linking geographic and geometric objects and events, GIS provides a more efficient method for storing, accessing, and presenting transportation data compared to conventional paper-based records [9, 10]. Recent studies highlight the potential of integrating remote sensing and GIS for improved pavement condition assessments. For example, authors in [11] utilized GIS for pavement classification and mapping to enhance road maintenance management. However, while their spatial analysis revealed distress patterns, it did not consider drainage conditions. Similarly, in [12] authors developed an annual road deterioration record in Iraq using GIS and Micro PAVER software, while in [13] they analyzed road conditions in Nigeria using GIS and GPS data. Authors in [14], created a pavement surface index model using GIS and road survey data, providing a comprehensive classification of road conditions. However, this model primarily focused on pavement characteristics while overlooking hydrological factors such as water accumulation and drainage efficiency. GIS heat maps have also been employed to classify pavement deterioration severity, as demonstrated by authors in [15] in Nasiriya. Furthermore in [16, 17], Unmanned Aerial Vehicles (UAVs) have shown promise for capturing detailed 2D/3D road distress data through photogrammetry. The current study builds on such methodologies by proposing a more comprehensive approach that integrates pavement and drainage condition assessments. Drainage plays a critical role in preserving pavement integrity, as poor drainage accelerates water infiltration, leading to structural failures and faster pavement deterioration [18]. Cost-effective pavement management is a key priority in developing countries due to resource constraints. For instance, in [19] researchers developed a GIS-based decision-making model for road management, while in [20] authors emphasized GIS's role in sustainable road maintenance. GIS-based modeling has also demonstrated its potential in infrastructure monitoring. Authors in [21] applied GIS techniques to assess groundwater quality, a methodology similar to pavement and drainage studies. Additionally, satellite-based remote sensing technologies such as Synthetic Aperture Radar (SAR) offer large-scale, cost-effective monitoring solutions.

This study aims to address gaps in existing pavement evaluation methodologies by integrating drainage condition analysis with pavement assessments. It enhances the use of GIS and remote sensing for road condition monitoring, particularly in developing regions such as Africa. While previous research has demonstrated the benefits of GIS and remote sensing for pavement assessments, few studies have explored the impact of incorporating drainage analysis. This research seeks to bridge that gap by developing a comprehensive geospatial framework that combines pavement and drainage assessments, offering an innovative and holistic approach to road condition evaluation.

II. MATERIALS AND METHODS

A. Study Area

This study was conducted on selected roads within Jomo Kenyatta University of Agriculture and Technology (JKUAT), located in Juja, Kenya. The methodologies developed in this study were tested on Technology Street and Innovation Street , which were chosen due to their high levels of activity and diverse transportation modes. Figure 1 presents a map of the study area.

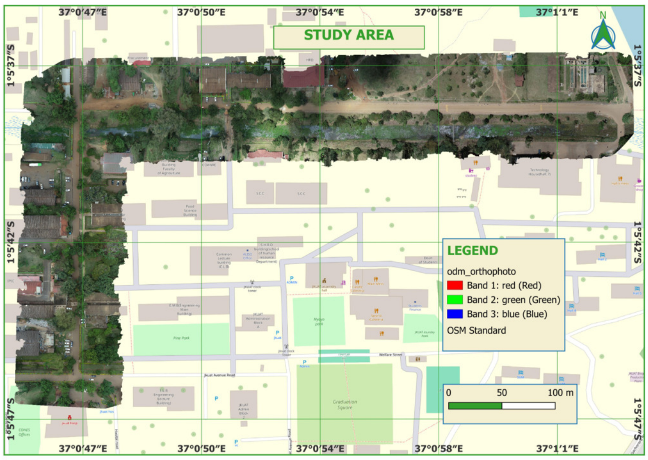

Fig. 1. Study area map.

B. Materials

This research utilized various advanced, open-source tools designed for precise geospatial analysis and data management:

- Open Drone Map (ODM): Used for generating high-resolution 3D models and maps from drone imagery.
- Quantum Geographic Information Systems (QGIS): Enabled in-depth spatial data creation, editing, and analysis.
- PostgreSQL: Provided a robust, SQL-compliant database for secure and efficient data storage.
- DJI Zenmuse: Captured high-resolution, real-time 3D data essential for structural assessments.
- GPS Map Camera: Facilitated accurate data validation through geo-tagged imagery.

The integration of these tools created a comprehensive system for structural and spatial evaluation, ensuring accurate and reliable analysis.

C. Methods

This study involved the collection and processing of both spatial and non-spatial data, as illustrated in Figure 2. A DJI EP800 Zenmuse drone, equipped with a 9 mm focal length camera, was deployed at an altitude of 1,575.373 m, capturing aerial imagery covering an 802 m span. Pavement condition assessment was conducted using QGIS tools, with verification performed through the Pavement Condition Index (PCI) survey following ASTM guidelines. Road attributes, including dimensions, surface types, and pavement IDs, were integrated into shapefiles for spatial analysis. A PostgreSQL database was developed to support geospatial analysis within QGIS. The database was structured using inputs such as pavement attributes, orthophotos, and digital surface models to ensure a comprehensive pavement evaluation. PgAdmin was used for database management, while the PostGIS extension enabled seamless integration with QGIS. To enhance pavement condition assessment, datasets on curvature, flow accumulation, and distress classification were combined to create the Quantum Pavement Condition Index (QPCI). This index provides a quantitative measure of pavement condition and aids in maintenance prioritization. Flow accumulation refers to the total volume of water entering each terrain cell, playing a crucial role in analyzing drainage efficiency [22]. Curvature, a fundamental surface characteristic, has long been recognized for its applications in hydrology and geomorphology [20].

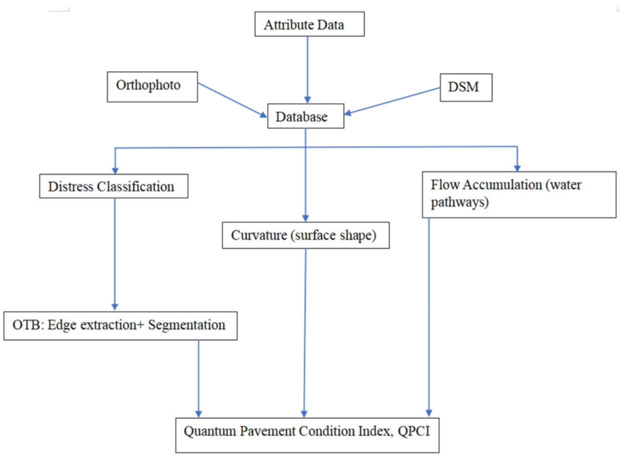

Fig. 2. Methodology.

1) Quantum Pavement Condition Index

The creation of the QPCI required three raster datasets: flow accumulation, curvature, and road distress data for Innovation Street and Technology Street. To compute the index, the input layer values for curvature, distress and flow were initially normalized and then combined using the raster calculator with the following expression:

$$("norm\ curv" \times 0.3) \times ("norm\ distress" \times 0.5) \times ("norm\ flow" \times 0.2)$$

2) Image Pre-Processing

Drone images were processed using Open Drone Map to produce an orthophoto (Figure 3) and Digital Surface Model (DSM) (Figure 4), facilitating pavement condition assessment. To enhance clarity by reducing noise and improving the visibility of road features, a median filter was applied to the orthophoto. The road segment was then clipped from the orthophoto to focus the analysis. Surface irregularities, including potholes and cracks, were detected using the Orfeo Toolbox (OTB) plugin in QGIS. The detection process involved edge extraction, followed by segmentation, which analyzed multiple spectral bands. Based on morphological characteristics, the segmented image was categorized into five classes: masked areas, drains, moderate distress, severe distress, and minor distress. The high resolution orthophoto provided a detailed view of the road surface, enabling precise identification of pavement distress.

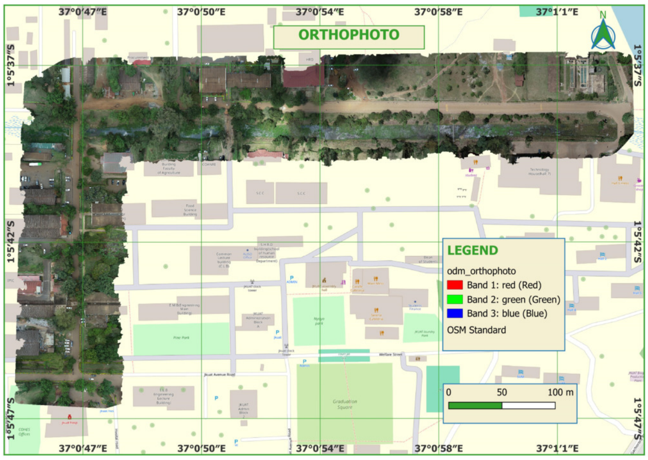

Fig. 3. True to scale high resolution orthophoto, with ground sampling distance of 0.0494 m.

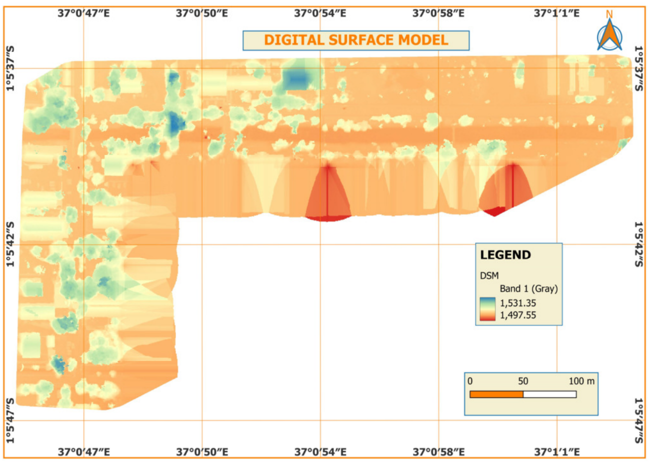

Fig. 4. High resolution DSM.

DSM (Figure 4) depicted elevation changes across the road surface, with values ranging from 1,497.55 m to 1,531.35 m. Low elevations, denoted by light blue, indicate depressions, which are prone to drainage issues and water pooling. The majority of the road surface is moderately elevated (orange color), representing relatively flat terrain with no significant peaks or depressions. Red highlights indicate high elevations. The DSM was used for hydrological analysis, specifically for mapping curvature and flow accumulation to assess drainage patterns and identify areas susceptible to water-related distress. The DSM accuracy was 5 cm per pixel, ensuring precise elevation measurements.

3) Hydrology Analysis

To examine road surface morphology and hydrology/drainage conditions, curvature and flow accumulation maps were generated (Figure 5). The DSM (5cm/pixel resolution) was processed for flow accumulation employing the following QGIS tools:

- Fill: Removed surface depressions to ensure accurate flow modeling.
- Flow Direction (D8 algorithm): Determined the direction of water movement.
- Flow Accumulation: Calculated flow intensity across the road surface.

To refine the results, minor flow values below 2,000 were filtered out using the Set Null tool, while significant flow paths were converted to vector format using the Raster to Polyline tool. For curvature analysis, the Curvature tool was utilized to perform a second derivative analysis of the DSM. This tool highlighted convex and concave regions, providing insights into surface undulations and potential drainage inefficiencies. The generated maps were instrumental in assessing drainage effectiveness and identifying areas susceptible to water-related distress, helping to pinpoint critical surface features and flow pathways.

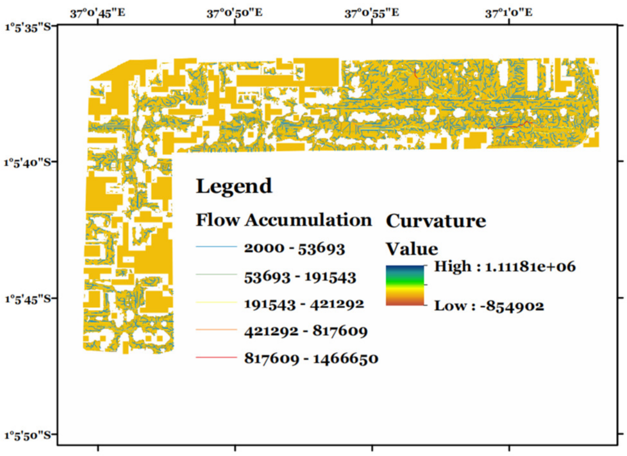

Fig. 5. Flow accumulation and curvature values with buildings and trees excluded.

4) Database Schema

A PostgreSQL database (Figure 6) was designed to efficiently store, retrieve and analyze various datasets, including road attributes, drone imagery, the DSM, and traffic data.

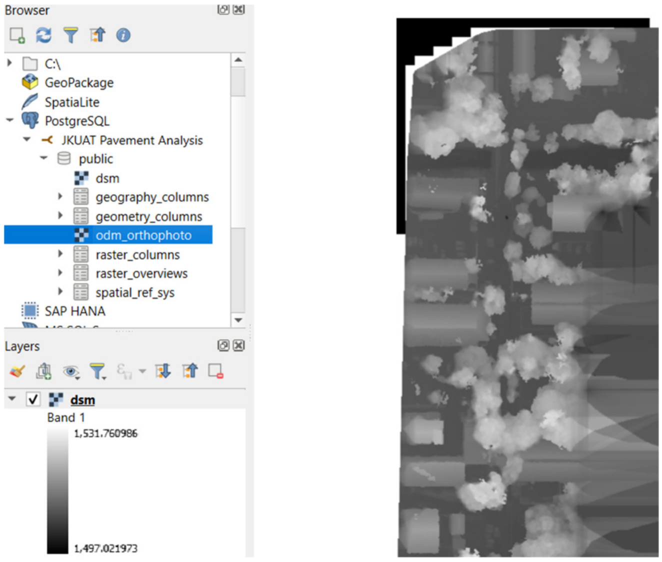

Fig. 6. PostgreSQL-QGIS connection screenshot.

A structured schema was implemented to seamlessly integrate spatial and non-spatial data, enabling efficient data management. This configuration allowed for fast querying and analysis, facilitating the extraction of relevant information for pavement quality assessment.

III. RESULTS AND DISCUSSION

A. Edge Detection and Distress Classification

The results are presented in two stages: edge detection maps (Figures 7-10), which define the boundaries used for the distress identification, and distress classification maps (Figures 11-14), which categorize pavement distress based on severity and type.

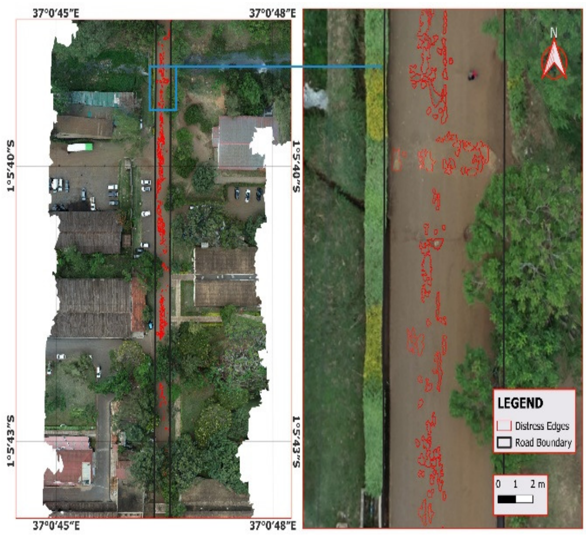

Fig. 7. Edge detection for Innovation-Street road distress condition (upper section of the road).

Fig. 8. Edge detection for Innovation-Street road distress condition (lower section of the road).

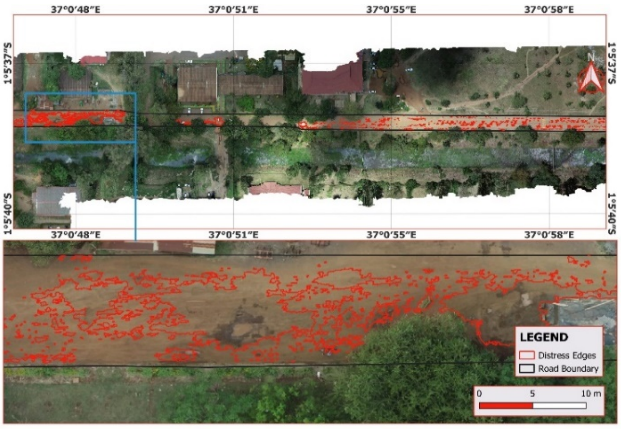

Fig. 9. Edge detection for Technology-Street road distress condition (left section of the road).

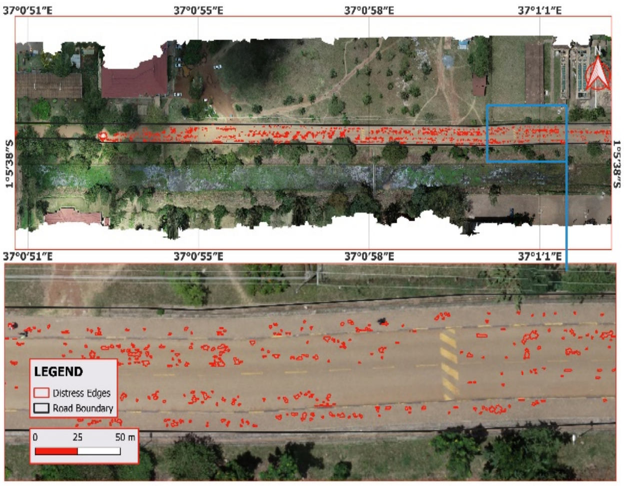

Fig. 10. Edge detection for Technology-Street road distress condition (right section of the road).

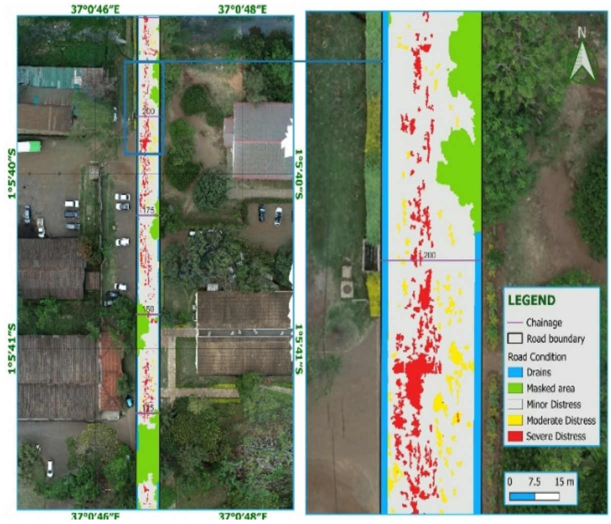

Fig. 11. Classified distress map of the upper section of the road (Innovation-Street) condition.

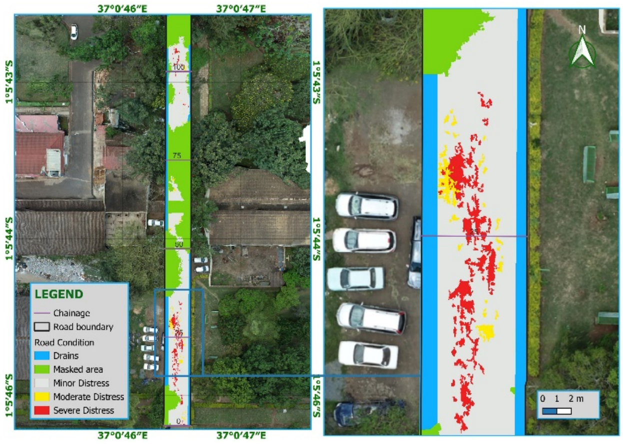

Fig. 12. Classified map of the lower section of the road (Innovation-Street) condition.

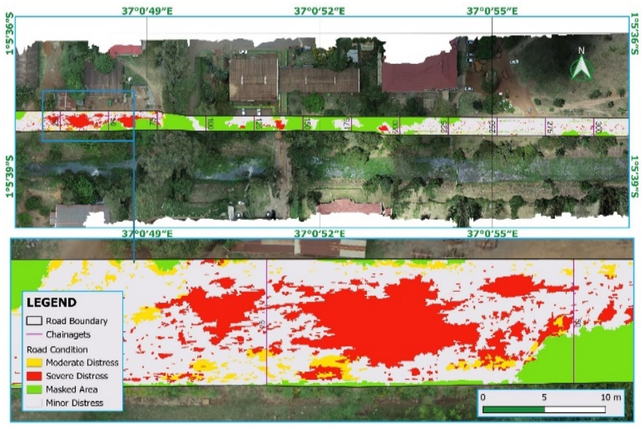

Fig. 13. Classified distress map of the left section of the road (Technology-Street) condition.

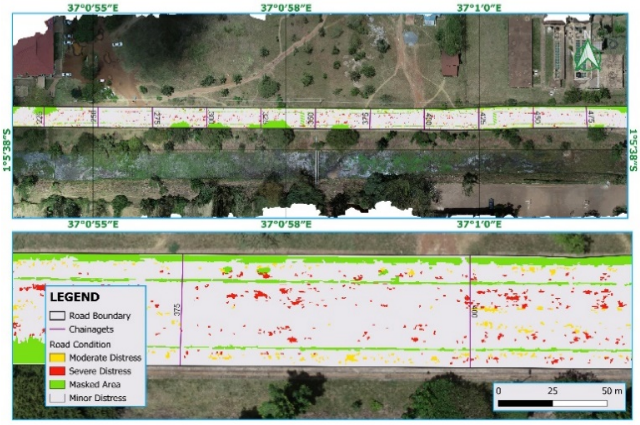

Fig. 14. Classified map of the right section of the road (Technology-Sstreet).

The blue rectangle highlights a zoomed-in view of the selected area, with the background image being the corresponding ODM orthophoto. Distresses were classified into three levels -minor, moderate, and severe- represented using color coding (Figures 11-14). To prevent misidentification of pavement distress, the masked area (green) includes trees, vehicles, and pedestrians, which were excluded from analysis. This ensured that only road surface defects were considered in distress identification.

- Minor Distress Analysis: This class was characterized by small cracks, hairline fractures, and minor surface deformations. While not immediately problematic, these distresses serve as early indicators of pavement deterioration, which, if left unaddressed, could escalate into more severe issues.
- Moderate Distress Analysis: Consisted of uneven surfaces, shallow potholes, and medium-sized cracks. These distresses were found predominantly near drainage outlets. Although they are not posing an immediate structural failure, these distresses have the potential to worsen over time, necessitating timely intervention.
- Severe Distress Analysis: Characterized by large potholes, deep cracks, and surface. These defects were observed in specific sections of the road and pose a direct risk to vehicle operation, increasing the likelihood of accidents and vehicle damage. The extent of the distress suggests potential damage to the underlying subgrade, which could compromise the road's structural integrity.

It is important to note that distress identification was limited to overall failure detection and did not differentiate between specific types of distress.

B. Pavement Condition Index

To validate the accuracy of the QGIS-based pavement assessment, a PCI survey was conducted on two road segments: Innovation Street and Technology Street. The results of this survey are presented in Tables I-III.

1) Branch 1: Innovation Street

Innovation Street, an asphalt-surfaced road classified under ASTM D6433-07 [23], spans 240.9 m and was divided into three sections, with seven randomly selected sample units analyzed. The survey identified various distresses, including longitudinal and transverse cracking, weathering/raveling, alligator cracking, potholes, block cracking, patching, utility cut patching, and edge cracking. The failed sections indicated that the road had reached the end of its service life, while serious sections, though not entirely collapsed, required immediate repairs.

TABLE I. BRANCH 1 PCI VALUES

Chainage	Section	Sample	Area (m^2)	PCI	Condition
0+025-0+050	1	2	150	8	Failed
0+075-0+100	1	4	150	0.9	Failed
0+125-0+150	2	6	150	20	Serious
0+150-0+175	2	7	150	0	Failed
0+175-0+200	2	8	150	20	Serious
0+200-0+225	3	9	150	0	Failed
0+225-0+240.9	3	10	150	0	Failed

2) Branch 2: Technology Street

Technology Street, with an asphalt surface in its first section, was assessed under ASTM D6433-07 [23] and spanned 191 m, divided into two sections with eight random sample units analyzed. Identified distresses included rutting, potholes, longitudinal and transverse cracking, weathering/ raveling, edge cracking, alligator cracking, swell, and block cracking. Failed sections showed severe deterioration requiring urgent repairs, while critical distresses were likely caused by a combination of high traffic volumes, environmental exposure, and aging materials. Some sections were classified as satisfactory, exhibiting fewer distresses, while others were in poor to very poor condition, characterized by surface irregularities, potholes, and extensive cracking. The survey highlighted significant variations in pavement conditions across Technology Street, with the first half predominantly exhibiting failed and very poor conditions, likely due to environmental degradation, insufficient maintenance, or heavy traffic loads, while a few sections remained in relatively better condition, possibly due to reduced exposure to damaging forces.

TABLE II. BRANCH 2 PCI VALUES

Chainage	Section	Sample	Area (m^2)	PCI	Condition
0+00-0+025	1	1	137.5	0	Failed
0+025-0+050	1	2	137.5	0	Failed
0+050-0+075	1	3	137.5	0	Failed
0+075-0+100	1	4	137.5	74	Satisfactory
0+100-0+125	2	5	137.5	40	Poor
0+125-0+150	2	6	137.5	30	Very Poor
0+150-0+175	2	7	137.5	14	Serious
0+175-0+191	2	8	137.5	28	Very Poor

3) Branch 3: Technology Street

The second section of Technology Street, surfaced with block paving and designated under ASTM E2840-11 (15), spans 326 m, with 13 randomly selected sample units analyzed.

The identified distresses included damaged pavers, faulting, excessive joint width, and heave. With PCI ratings ranging from 93 to 99, the survey results indicated a largely positive condition across all sample units, with the pavement found to be in excellent structural condition. The PCI results aligned with the QGIS distress classification (Figure 14), further confirming the accuracy of the geospatial pavement assessment.

TABLE III. BRANCH 3 PCI VALUES

Chainage	Section	Sample	Area (m^2)	PCI	Condition
0+00-0+025	1	1	150	93	Good
0+025-0+050	1	2	150	93	Good
0+050-0+075	1	3	150	96	Good
0+075-0+100	1	4	150	98	Good
0+100-0+125	1	5	150	98	Good
0+125-0+150	1	6	150	98	Good
0+150-0+175	1	7	150	98	Good
0+175-0+200	1	8	150	98	Good
0+200-0+225	1	9	150	99	Good
0+225-0+250	1	10	150	97	Good
0+250-0+275	1	11	150	98	Good
0+275-0+300	1	12	150	97	Good
0+300-0+325	1	13	150	99	Good

C. Flow Accumulation and Curvature

The flow accumulation and curvature maps provide valuable insights into the road's surface morphology and drainage characteristics. The predominant yellow coloration on the curvature map indicates that most of the road surface exhibits a neutral curvature, meaning it is neither highly convex nor concave. This suggests moderate water behavior, where accumulation is insufficient to cause significant pooling. Similarly, the flow accumulation map predominantly displays light blue, signifying that most of the road experiences low to moderate water flow accumulation. This indicates relatively efficient drainage, reducing the likelihood of severe water-related pavement distress.

D. Quantum Pavement Condition Index

The QPCI heatmap (Figure 15) provides a comprehensive assessment of pavement conditions across the study area, highlighting various levels of distress. The heatmap utilizes red color gradients to differentiate pavement distress severity, with darker shades indicating higher distress levels. Areas with high QPCI values (e.g., 3.4) correspond to locations with severe pavement distress, while lower values represent sections with minimal deterioration. This visualization allows strategic maintenance planning, prioritizing red zones that require immediate intervention while deferring maintenance in lighter red areas with minor distress. The analysis reveals that Innovation Street exhibits more deterioration, as indicated by its darker red shades, warranting a higher maintenance priority than Technology Street.

E. Validation

To verify the accuracy of the QGIS pavement assessment, validation points were overlaid on the orthophoto (Figure 16). These validation points align with the distress locations identified during the classification process, confirming the reliability of the geospatial analysis. Additionally, sample images of the distress, captured using GPS Map Camera, further corroborate the accuracy of the assessment, demonstrating that the QPCI method effectively identifies and classifies pavement distress levels.

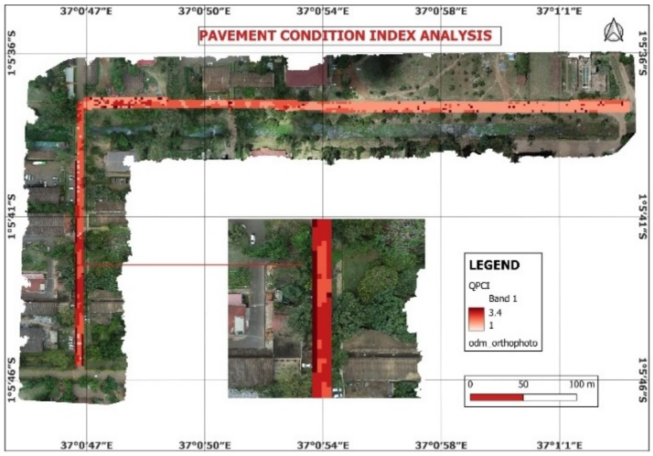

Fig. 15. Heatmap indicating the high and low priority distress areas through color coding.

(a)

(b)

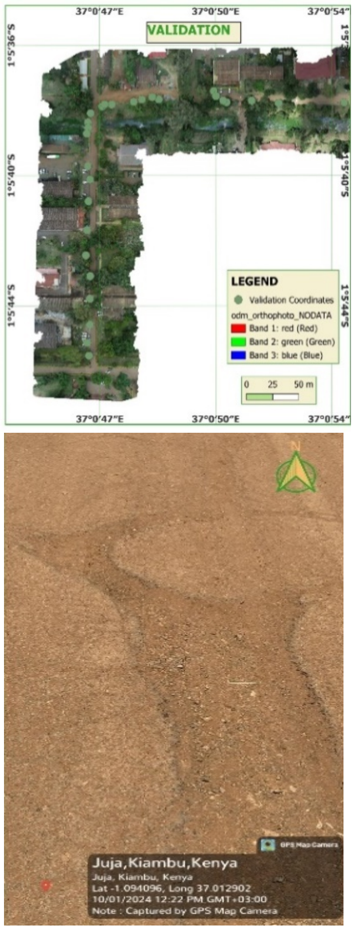

Fig. 16. (a) Orthophoto overlaid with validation coordinates, (b) Sample distress image captured using GPS Map Camera.

IV. CONCLUSION

This study presents a comprehensive framework that integrates GIS and Remote Sensing for road condition evaluation, with a unique emphasis on drainage analysis. By addressing limitations in conventional methods -such as subjective visual inspections and restricted implementation in developing regions- this research introduces a data-driven approach to pavement assessment. The Quantum Pavement Condition Index (QPCI), which synthesizes flow accumulation, curvature, and distress data, has proven effective in prioritizing maintenance needs. The findings validate the framework's effectiveness, identifying Innovation Street as a high-priority area requiring urgent intervention, while Technology Street exhibits moderate to severe distress in select sections. By bridging the gap between remote sensing advancements and practical implementation in Africa, this study significantly contributes to sustainable road maintenance practices. Moreover, the scalability and adaptability of this approach offer a pathway for global infrastructure management. By enabling proactive maintenance, optimizing resource allocation, and reducing long-term repair costs, this integrated method supports both economic efficiency and infrastructure resilience.

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