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A Spatio-Temporal Evaluation of Water Resilience and Urban Metabolism in Informal Settlements using Remote Sensing

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Abstract

Informal settlements face layered challenges of environmental degradation, governance fragmentation, and infrastructure inequity. This study aims to evaluate the spatial-temporal dynamics of environmental and hydrological stress within these settlements to inform targeted upgrading strategies. Utilizing Google Earth Engine and QGIS, multi-temporal and multi-spectral satellite imagery from Landsat 8/9 and Sentinel-2 (2015–2024) was processed to map ecological stress and urban expansion in Makassar, Indonesia. The methodological approach includes the calculation and zonal statistics extraction of key indices: Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), Land Surface Temperature (LST), and Moisture Stress Index (MSI). The findings reveal a severe ecological gradient characterized by a continuous downward trend in vegetation (NDVI < 0.2) and a corresponding escalation of surface impermeability in informal zones. This urban densification directly driven thermal intensification, with LST peaking above 34°C, and extreme moisture stress exceeding critical resilience thresholds (MSI > 0.9). Ultimately, this integrated geospatial diagnostic empowers the SLAIS Framework to transition landscape architecture into an operable, evidence-based discipline capable of targeting interventions where metabolic pathology is greatest.

Keywords: Urban Metabolism, Informal Settlements, Remote Sensing, Landscape Resilience, NDVI/NDBI/LST/MSI

I. INTRODUCTION

Informal settlement expansion in rapidly expanding cities has emerged as a key challenge to landscape architects, policymakers, and planners (Tsenkova, 2012). The settlements, characterized by uncontrolled land use, inadequate infrastructure, and exposure to the environment, emerge under conditions of socio-economic exclusion and spatial marginalization (Wekesa et al., 2011). While urban populations grow, they bear a disproportionate brunt of climate-related hazards, such as flooding in urban centers, heat stress, and water scarcity, hazards that are intensified by poor drainage, sparse cover of vegetation, and greater growth of impervious surfaces (Soja, 2013).

In Indonesia, such weaknesses are exacerbated by inefficient urban metabolism where the conversion of water, waste, and energy resources is disorderly because of uncontrolled growth and inefficient systems of governance (Kennedy et al., 2011). For example, cities like Makassar experience compounded hazards from high rainfall variability, and poor wastewater infrastructure, leading to contamination of water bodies, reduced infiltration into the ground, and severe public health impacts (Tjandraatmadja et al., 2012).

Although these issues are urgent, traditional landscape architecture and urban planning systems do not take advantage of the potential of geospatial and remote sensing technologies (Chatrabhuj et al., 2024). These technologies provide systematic and scalable data on landscape change, hydrological process, and vegetation stress, the issues at the heart of urban resilience building

(Fletcher et al., 2013). By spatial-temporal change in vegetation (NDVI), urban density (NDBI), thermal flux (LST), and ecological water stress (MSI), remote sensing gives a diagnostic window through which planners can measure risk, set priorities, and monitor outcomes (Zhao et al., 2025).

This research addresses these critical gaps by developing an integrated remote sensing and cloud-based geospatial framework to systematically measure and map urban metabolic inefficiencies within the informal settlements of Makassar. By pairing multi-temporal satellite observations from Landsat 8/9 and Sentinel-2 across a nine-year trajectory (2015–2024), this study evaluates the spatial-temporal dynamics of structural densification and its direct consequence on localized environmental stress. The methodological approach utilizes the calculation and zonal statistics extraction of key biophysical indices, specifically NDVI, NDBI, LST, and MSI, to uncover the exact spatial signatures where surface sealing, vegetation degradation, microclimatic thermal intensification, and moisture deficits overlap. Ultimately, this integrated geospatial diagnostic aims to transition landscape architecture into an operable, evidence-based discipline. By establishing a highly replicable, data-driven framework, this study provides planners, policymakers, and designers with the precise spatial insights necessary to target localized Water-Sensitive Urban Design (WSUD) retrofits and climate adaptation strategies directly where environmental vulnerability and metabolic pathology are greatest

II. METHODOLOGY

II.1. Study Design and Spatial Context

This study utilizes a mixed-methods research design that integrates cloud-based geospatial analysis and remote sensing to investigate macro-level spatial transformations and environmental degradation within informal settlements in Makassar, Indonesia. This approach quantifies how structural density directly alters ecological variables, specifically hydrological stress, vegetative fragmentation, and thermal exposure.

II.2. Research site

The research is conducted in Makassar City, the capital of South Sulawesi Province, Indonesia. As a rapidly urbanizing coastal city, Makassar faces significant environmental and infrastructural challenges, including unregulated informal settlement growth, flood risks, and limited sanitation infrastructure (Ismail et al., 2025). Informal settlements are concentrated in low-lying and peri-urban zones, often near canals and rivers (Asmal et al., 2025). This geographic and socio-ecological context makes Makassar a representative case for evaluating urban metabolism and resilience through remote sensing.

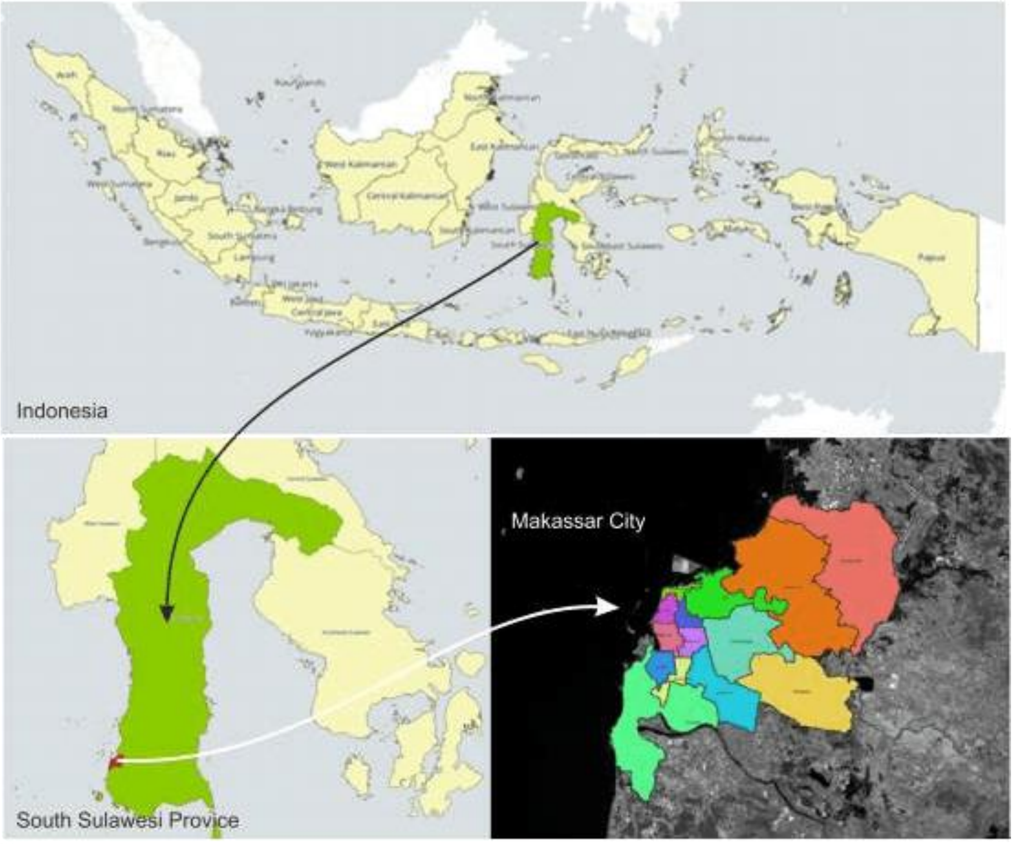

Figure 1. Research Location
Source: Modified by Author

II.3. Data Acquisition and Preprocessing

To ensure consistency and capture a decade of rapid urbanization, multispectral satellite observations were acquired for three distinct temporal snapshots: 2015, 2020, and 2024. Surface Reflectance products were obtained from open-access Earth observation constellations: Landsat 8/9 Operational Land Imager (OLI/TIRS) (30 m spatial resolution) and Sentinel-2 MultiSpectral Instrument (MSI) (10–20 m spatial resolution). To minimize atmospheric interference, imagery was filtered for a cloud cover threshold of <10% during the peak dry season months (July to October) to capture maximum thermal and moisture stress profiles. Image collection filtering, cloud-masking, and index calculations were executed programmatically using JavaScript API within Google Earth Engine (GEE), minimizing local computing constraints and standardizing atmospheric correction.

II.4. Remote Sensing Indices

Four environmental indicator variables were calculated within GEE to map metabolic inefficiencies. The operational math and band designations are structured as follows:

1. Normalized Difference Vegetation Index (NDVI).
   NDVI is used to evaluates vegetation density and health (Mehmood et al., 2024).
   $$NDVI = \frac{NIR - RED}{NIR + RED} \qquad (1)$$
   Where NIR is Band 5 (Landsat 8/9) / Band 8 (Sentinel-2), and RED is Band 4 (Landsat 8/9 / Sentinel-2) (Sparf, 2024).
2. Normalized Difference Built-up Index (NDBI)
   NDBI is retrieved by quantifying surface impermeability and urban expansion (Wahid &

Mushref, 2026).

$$NDBI = \frac{SWIR_1 - NIR}{SWIR_1 + NIR} \qquad (2)$$

Where $SWIR_1$ is Short-Wave Infrared Band 6 (Landsat 8/9) / Band 11 (Sentinel-2).

3. Land Surface Temperature (LST)
   LST estimates microclimatic thermal flux and urban heat island (UHI) intensity (Singh & Grover, 2014). Derived from the Thermal Infrared Sensor (TIRS) Band 10 (Landsat 8/9) by converting Top of Atmosphere (TOA) spectral radiance to brightness temperature, subsequently corrected for surface emissivity (e) based on fractional vegetation cover (P_v).
4. Moisture Stress Index (MSI)
   MSI serves as an inverted proxy for canopy and soil moisture deficits. Higher values indicate severe moisture deprivation (Adak et al., 2023).

$$MSI = \frac{SWIR_1}{NIR} \qquad (3)$$

II.5. Analytical Workflow and Geospatial Processing

Once computed in GEE, the localized raster datasets were exported to QGIS 3.34 for advanced spatial statistical extraction. The sequential analytical workflow was conducted as follows:

- Vector boundary shapefiles delineating the official informal settlement zones of Makassar were overlaid onto the raster datasets. All calculated indices were clipped tightly to these specific administrative polygons.
- Using the Zonal Statistics toolset in QGIS, the underlying pixel data within the informal settlement boundaries were extracted. This step resolved numeric values for mean, range, and standard deviation for every snapshot year, establishing a quantitative baseline for each settlement.
- Multi-temporal trend analysis was conducted by generating raster cell frequency histograms across 2015, 2020, and 2024 to trace the statistical distribution shift of environmental degradation over time.
- Overlay and Heatmap Generation: Spatial overlay techniques integrated road networks, drainage canals, and historical maps with the index layers. Differential heatmaps were constructed by subtracting earlier raster arrays from later ones to isolate areas of maximum environmental degradation and prioritize them for Water-Sensitive Urban Design (WSUD) interventions.

II.6. Analytical Contribution

This research design enables a spatially anchored and temporally dynamic evaluation of metabolic inefficiencies in informal urban contexts. By permitting the visualization of vegetation loss, built-up pressure, and climatic stress, the technique feeds directly into SLAIS interventions such as WSUD strategies, green infrastructure retrofitting, and participatory spatial planning. The integration of remote sensing hence renders landscape architecture an operable diagnostic and design-oriented discipline

III. RESEARCH RESULT

This part offers the spatial and temporal results of the geospatial analysis conducted over Makassar's informal settlement territories. Through the utilization of remote sensing indices, NDVI, NDBI, LST, and MSI, along with infrastructural and historical overlays, the analysis provides valid information on landscape transformation, environmental suffering, and city metabolic pathology.

III.1. Historical Landscape Change

The historic Makassar map, contrasted with contemporary land use, illustrates a dramatic change in spatial pattern and environmental integrity. That which was previously rural or low-density areas, typically typified by high vegetation and permeable land, is now high-density informal settlements. These transformations are highly localized along secondary roads and canal networks, reflective of an uncontrolled peri-urban sprawl pattern. Loss of green corridors and degradation of riparian buffers compound a central narrative: that landscape transformation in Makassar occurred without infrastructural adaptation at the system level or environmental conservation.

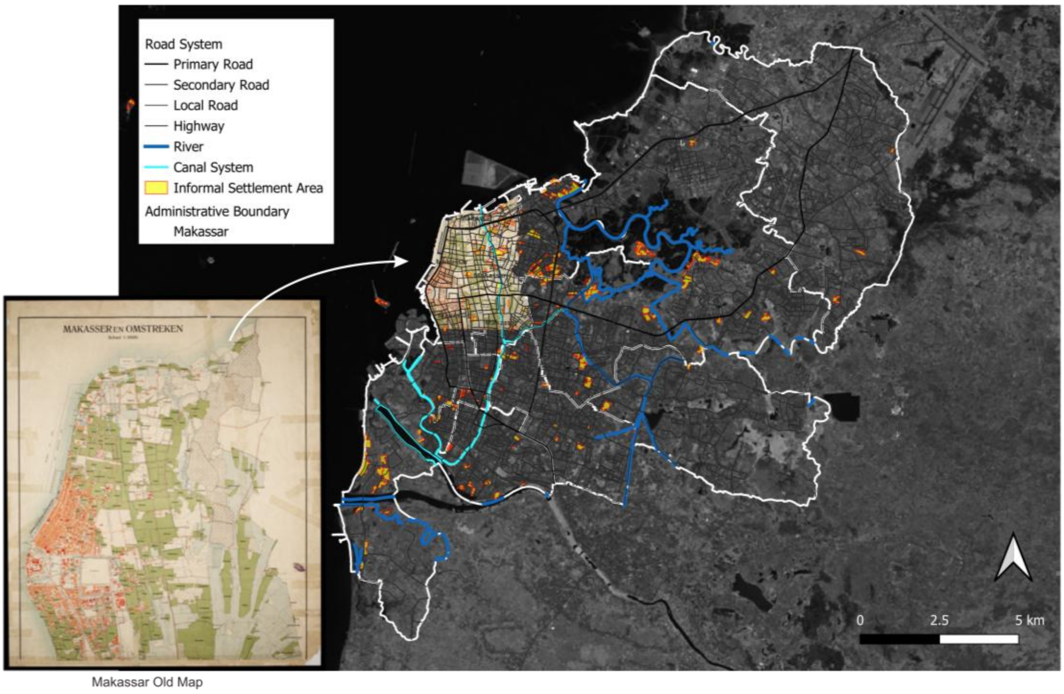

Figure 2. Historical mapping of Makassar City overlaid with informal settlement
Source, Modified by Author

III.2. Urban Expansion through NDBI Zonal Statistics

Normalised Difference Built-up Index (NDBI) in 2024 as shown in Figure 3 clearly delineates high urbanization across Makassar's core and western corridors. Red-colored zones on the map are linked with developed surfaces that are highly impervious, such as concrete rooftops, roads, and high-density housing units. Interestingly, informal settlements typically take place in these areas, revealing a straight relationship between unorganized development and metabolic inefficiency within the urban hydrologic cycle. Increase in impervious surface reduces

infiltration, increases surface run-off, and overwhelms drainage capacity. These are spatial signatures which validate the need for targeted Water-Sensitive Urban Design (WSUD) treatments such as permeable pavers, stormwater detention, and bioswales, to construct back resilience in these dense areas.

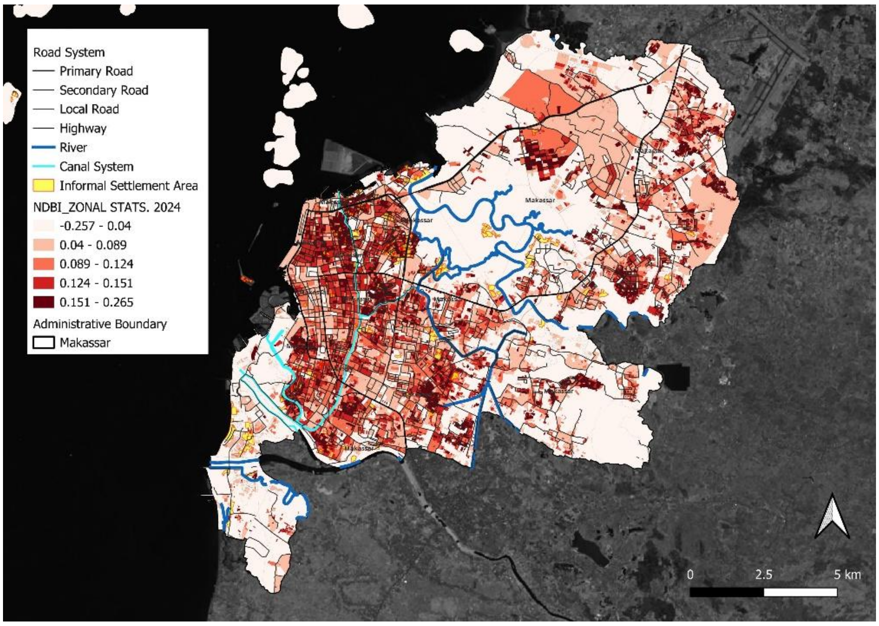

Figure 3. Normalized Difference Built-up Index (NDBI) – Zonal Statistics
Source: Modified by Author

III.3. Vegetative Cover Assessment via NDVI Zonal Statistics

The NDVI zonal analysis shows of vegetation cover over the settlement environment. Locations with low NDVI values (typically <0.2) denote lost or degraded vegetation, which are typically seen in central Makassar and informal settlement areas. Meanwhile, the periphery is relatively healthier vegetation with NDVI >0.4. NDVI distribution highlights an extreme ecological gradient where the informal settlements lack any access to green cover areas and face high microclimatic stress. Spatial inequality has profound implications for thermal control, flood defense, and community health. SLAIS applies the knowledge to advocate for the incorporation of ecological systems in settlement upgrading plans through green infrastructure retrofitting.

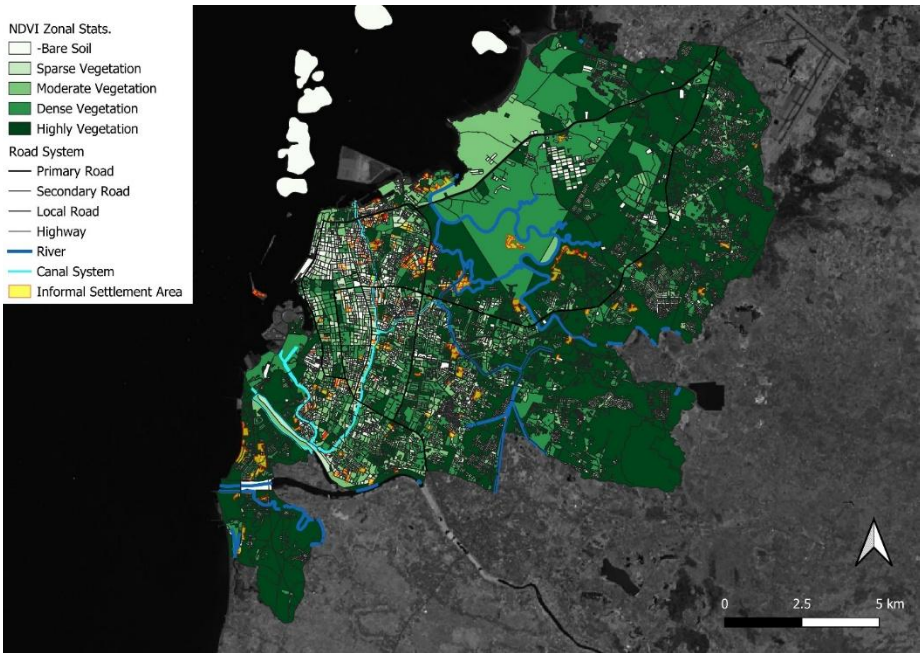

Figure 4. Normalized Difference Vegetation Index (NDVI)- Zonal Statistics
Source: Modified by Author

III.4. Temporal Trends in Vegetation Cover (NDVI: 2015–2024)

The temporal NDVI time series tracks a continuous downward trend in vegetation over the course of nine years. The NDVI histograms from 2015 to 2024 tend towards lower values, representing the compounding effects of infill urbanization, soil sealing, and green infrastructure loss. This trend of deterioration is geo-spatially related to informal expansion, especially near water courses and transportation corridors. This degradation does not only undermine the urban ecological metabolism but also increases exposure to surface flooding, heat islands, and socio-spatial inequalities.

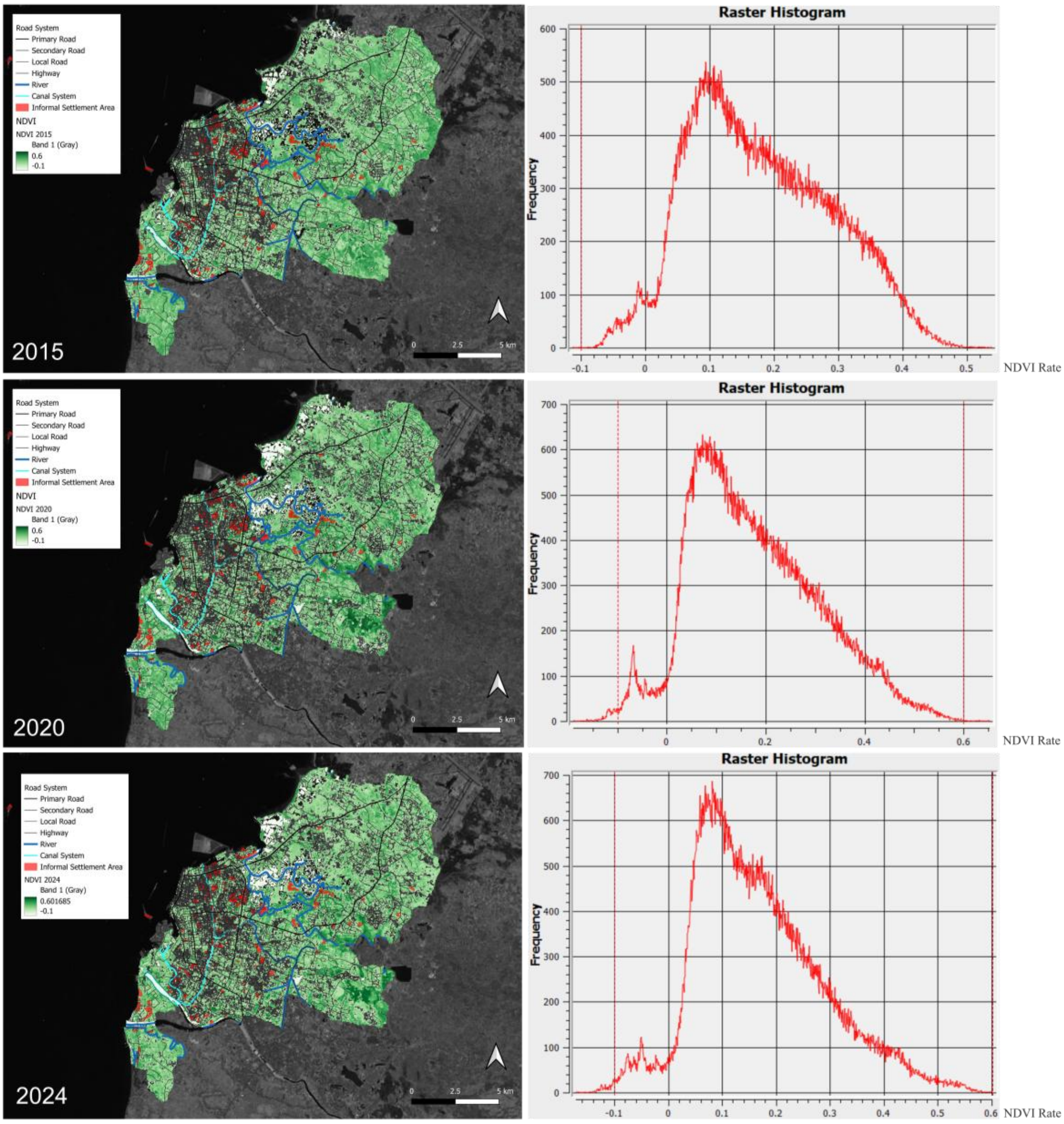

Figure 5. Temporal Trends in Vegetation Cover (NDVI: 2015–2024)
Source: Modified by Author

III.5. Thermal Stress Dynamics via Land Surface Temperature (LST)

The LST time maps of 2015, 2020, and 2024 show the enhancement of urban heat island (UHI) effects within Makassar. Central and eastern parts show a uniform rise in temperature up to a peak of more than 34°C in 2024. Such thermal hotspots exactly correspond to high NDBI and low NDVI regions, validating the fact that vegetation degradation and urban densification are major heat stress causes. Informal settlements—typically lacking thermal buffers like trees and open spaces—are most exposed. Elevated LST increases health risks, reduces habitability, and raises cooling energy demand.

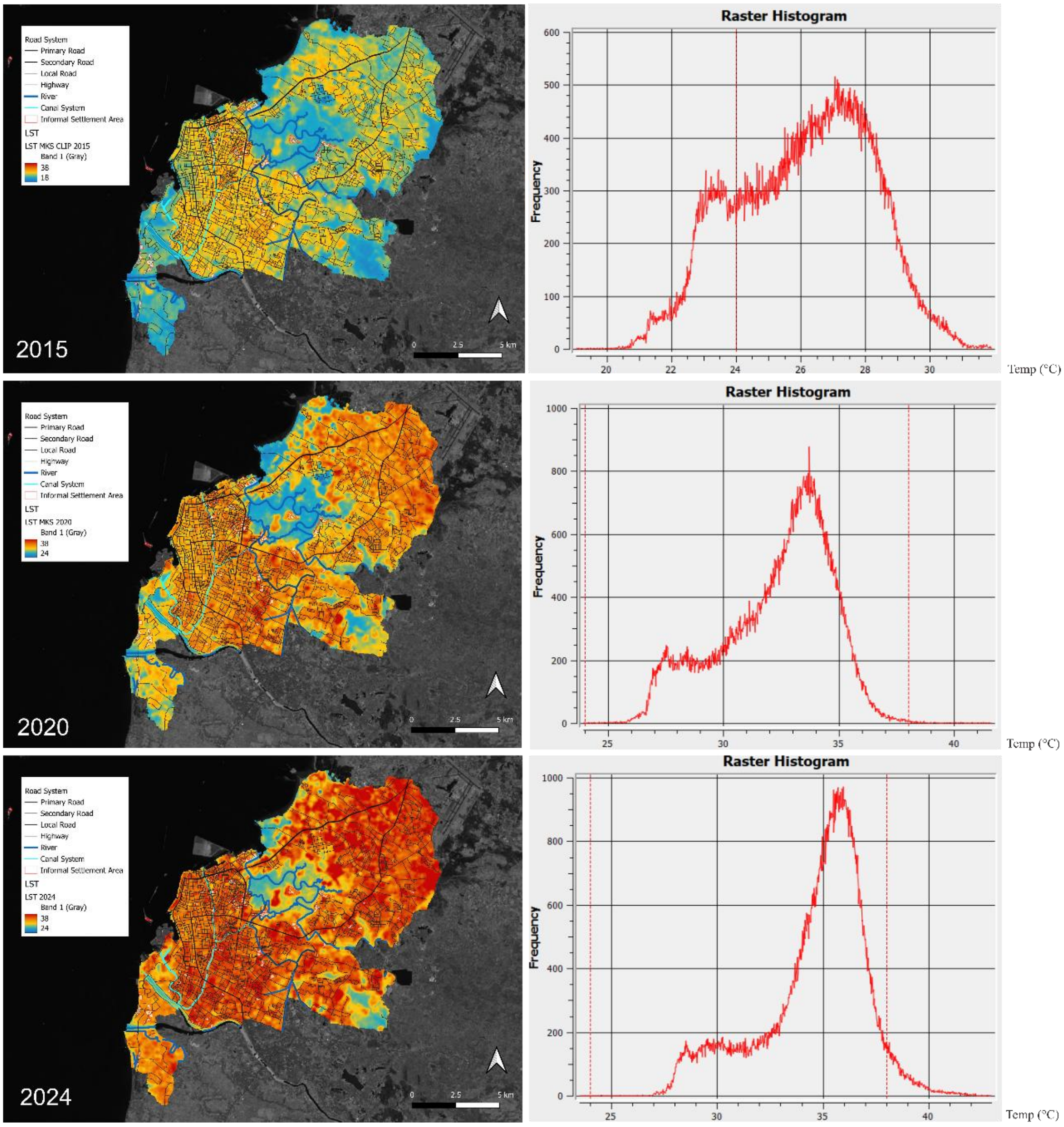

Figure 6. Thermal Stress Dynamics via Land Surface Temperature
Source: Modified by Author

III.6. Ecological Water Stress via Moisture Stress Index (MSI)

MSI values across Makassar show an intense rise in vegetation water stress, with almost all locations exceeding thresholds (>0.9) of extreme ecological degradation. Informal settlements have very high MSI values due to the double effect of vegetation removal and dispersion of impervious surfaces. MSI maps thus serve as a proxy for ecological resilience failure, pointing to areas where water retention, evapotranspiration, and subsurface recharge are drastically impaired.

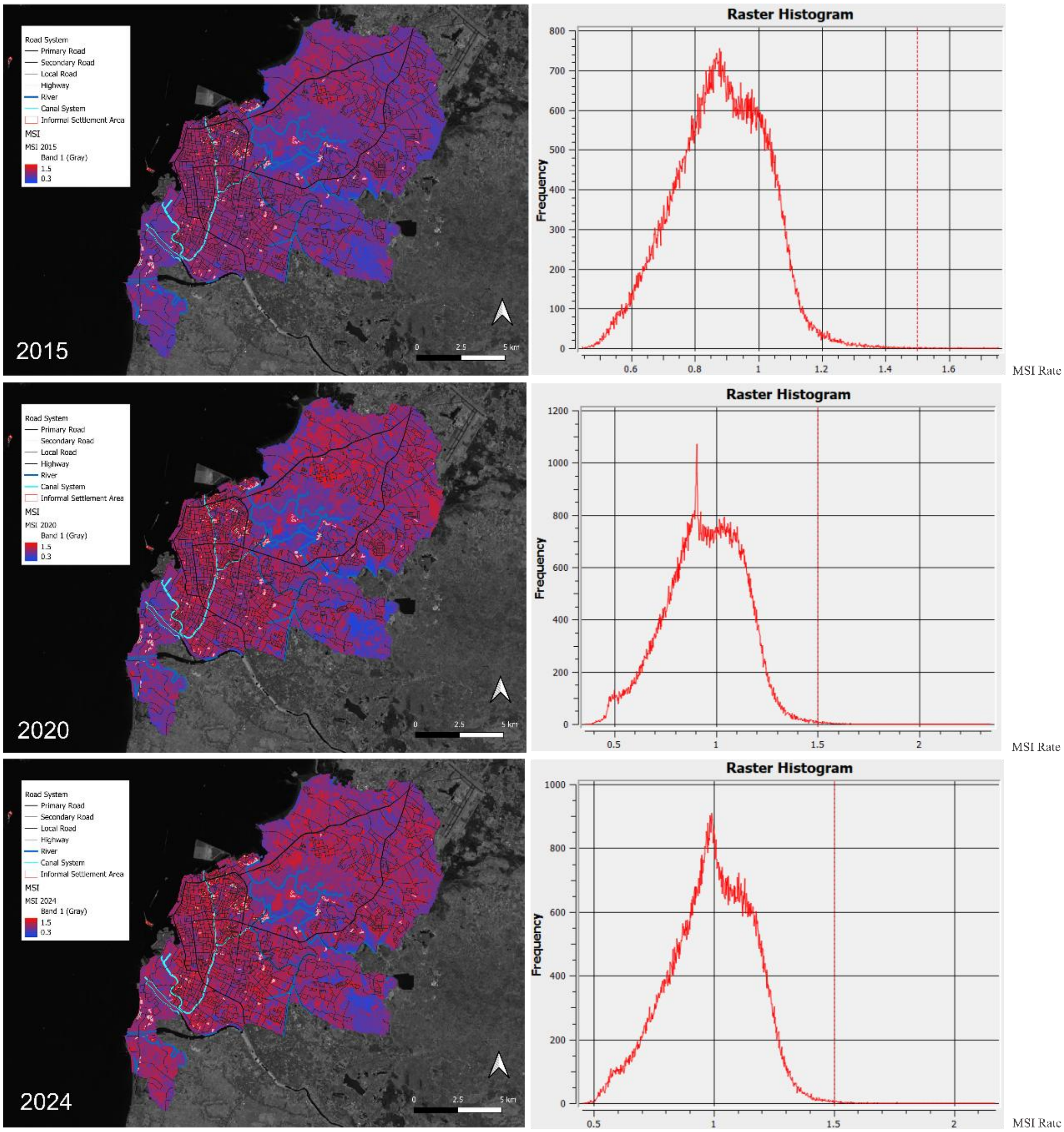

Figure 7. Ecological Water Stress via Moisture Stress Index (MSI) in Makassar City
Source: Modified by Author

IV. CONCLUSION

This research has demonstrated the operational necessity of remote sensing in diagnosing environmental and infrastructural vulnerabilities within informal settlements, using Makassar, Indonesia, as a critical case study. By integrating spatial-temporal analysis, this study has

generated a stratified, empirical understanding of how urban metabolic inefficiencies manifest across both time and space.
The integration of satellite-based indices, NDVI, NDBI, LST, and MSI, yielded specific, quantifiable insights into the settlement environments:

- NDBI zonal statistics for 2024 map a direct structural correlation between uncontrolled peri-urban sprawl along canals and roads and high surface impermeability.
- Temporal NDVI analysis tracked a continuous, nine-year downward trajectory , with informal core zones exhibiting critically low values (NDVI < 0.2), proving severe green infrastructure loss.
- Microclimatic thermal fluxes directly mirrored this ecological degradation, with Land Surface Temperature (LST) maps revealing a uniform rise that peaked above 34°C in 2024 within highly densified settlement zones.
- MSI values across the settlement territories conclusively exceeded extreme ecological degradation thresholds (>0.9) , serving as a spatial proxy for subsurface recharge and evapotranspiration failure.

These findings yield profound implications for both the theory and practice of sustainable urban planning and landscape architecture.

Practically, this research transitions landscape architecture from a purely aesthetic discipline into an operable diagnostic tool. The spatial overlap of severe thermal stress (LST >34°C) and moisture deficit (MSI >0.9) provides planners with a precision targeting mechanism. Instead of applying generalized municipal upgrades, cities can utilize these exact geospatial signatures to deploy localized Water-Sensitive Urban Design (WSUD) retrofits—such as permeable pavers, bioswales, and community-controlled green-blue corridors—directly where metabolic stress is highest.

Theoretically, these results prove that informal settlement vulnerability is not merely a socioeconomic condition, but a spatially anchored environmental failure. By capturing a decade of ecological decline, this methodology provides a highly replicable, data-driven framework for climate adaptation planning in rapidly urbanizing, data-scarce coastal cities across the Global South. Ultimately, it establishes an empirical pathway toward spatial justice, balancing target ecological restoration with physical urban interventions to protect vulnerable populations from climate extremes.

IV.1. Research Limitations

This study acknowledges several limitations. First, the use of medium-resolution satellite imagery (10–30 m) restricts the detection of fine-scale urban features. Second, the temporal analysis was limited to three time points, which may not fully capture seasonal or annual environmental fluctuations. Third, ground-truthing of remote sensing data was constrained by limited field access, affecting the validation of vegetation and moisture indices. Finally, while the study focuses on spatial-environmental dynamics, it does not yet integrate detailed socioeconomic or governance data, which are essential for a comprehensive assessment of informal settlement upgrading.

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