Spatial Dynamics and Transition Readiness of Nusantara Capital Relocation: Integrating Remote Sensing, Urban Growth Modeling, and Institutional Frameworks

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Abstract

The relocation of Indonesia's national capital from Jakarta to Nusantara (IKN) represents one of the most ambitious spatial, political, and environmental transitions in Southeast Asia in recent decades. While massive infrastructure development is underway, questions remain regarding the sustainability, ecological integrity, and spatial efficiency of the transition. This study aims to assess the spatial dynamics of IKN's development using multi-temporal remote sensing data, integrated with land use modeling and institutional transition frameworks. We employ Sentinel-2 and Landsat 8/9 imagery (2018–2025) to analyze land cover changes, deforestation trends, and urban sprawl patterns across the IKN and surrounding buffer zones. These geospatial observations are combined with a CA-Markov urban growth simulation to evaluate various policy-driven scenarios under different population and governance assumptions. Furthermore, we introduce two indices: a spatially explicit Transition Maturity Index (TMI) for internal readiness and a Governance Leadership Index (GLI) for external leadership capacity. Preliminary findings indicate rapid landscape conversion in certain sectors, yet uneven institutional and population migration trends. The model also reveals potential inefficiencies in infrastructure placement that could result in over-investment in low-utility zones. Our results suggest that spatial intelligence must play a greater role in guiding phased development, enabling a more adaptive, cost-effective, and environmentally responsive transition toward national capital relocation. This paper provides both methodological and policy-relevant insights for planners, spatial analysts, and decision-makers navigating the complexity of large-scale capital transitions in developing nations.

Keywords: capital relocation, spatial policy, remote sensing, urban growth modeling, Transition Maturity Index (TMI), Governance Leadership Index (GLI)

1. Introduction

The relocation of Indonesia's national capital to Nusantara (IKN) is not merely a spatial exercise, but also a multidimensional project involving ecological sustainability, social adaptation, fiscal discipline, and governance restructuring. Jakarta, the existing capital, faces chronic problems such as flooding, land subsidence, overpopulation, congestion, and air pollution. By contrast, East Kalimantan offers geographic centrality, relative seismic stability, and lower population density, making it an attractive alternative. However, relocating a capital city involves significant risks: rapid ecological change, social resistance, financial overburden, and governance challenges (Saraswati, 2022).

Globally, the relocation of capitals—from Brazil's Brasília to Malaysia's Putrajaya and Myanmar's Naypyidaw—has shown mixed outcomes. These precedents underscore the need for Indonesia to embed spatial intelligence and adaptive planning into its capital transition. This study leverages geospatial technologies and institutional analysis to examine the spatial dynamics of IKN's development, proposing TMI and GLI to measure readiness.

2. Literature Review

2.1 Lessons from Global Capital Relocations

Capital relocations have often been driven by over-urbanization, environmental degradation, and security concerns. Brasilia demonstrated the ability of planned relocation to stimulate regional growth, though it also triggered environmental costs. Putrajaya highlighted ICT-enabled governance efficiency, while Naypyidaw revealed the risks of under-utilization and incomplete migration (Rachmawati, 2021b).

2.2 Ecological Risks in Nusantara

East Kalimantan is characterized by sensitive ecosystems: tropical forests, mangroves, and peatlands. Studies have flagged potential deforestation, water scarcity, and wildfire risks (Amhar, 2022; Wibowo, 2022). Furthermore, passive fault lines and soil fragility heighten vulnerability to geohazards. Large-scale construction and land clearing amplify these risks.

2.3 Governance and Institutional Transition

Fiscal constraints, policy paradoxes, and limited inclusiveness have raised concerns about institutional readiness (Taufikurahman, 2022). While national legislation expedited IKN's establishment, critics argue that public participation and academic input were insufficient (Amhar, 2022). Local governments, particularly in Kutai Kartanegara and Penajam Paser Utara, express enthusiasm for smart city adoption but remain limited in ICT and fiscal capacity (Rachmawati, 2023).

2.4 Smart City and Digital Futures

Recent studies propose digital twins, metaverse governance, and smart sustainable city frameworks as potential innovations (Rachmawati, 2024). By leveraging open data, ICT, and virtual platforms, IKN could minimize physical overconcentration while ensuring inclusivity and efficiency (Rachmawati, 2023).

3. Data and Methods

This study adopts a mixed-methods approach that integrates geospatial analysis, simulation modeling, institutional assessment, and primary surveys.

3.1 Remote Sensing Data and Preprocessing

We employed Sentinel-2 MSI (10–20 m resolution) and Landsat 8/9 OLI (30 m resolution) imagery (2018–2025). Preprocessing steps included atmospheric correction, cloud masking with Fmask, mosaicking, and derivation of NDVI, NDBI, and NDWI. Land cover classification used Random Forest models trained on high-resolution imagery and validated with ground points. Accuracy target: OA $\geq$ 85%, Kappa $\geq$ 0.75.

3.2 CA-Markov Urban Growth Simulation

Urban growth was projected using CA-Markov under three scenarios: BAU, Green IKN, and Sprawl. Transition probabilities derived from 2018–2021 data, with drivers including distance to roads, slope, rivers, protected areas, and existing built-up zones. Validation used hindcasting for 2022.

3.3 Transition Maturity Index (TMI)

The Transition Maturity Index (TMI) is designed as a composite measure to evaluate the internal readiness of the new capital Nusantara to sustain its core functions as a government and residential center. Unlike conventional urban sustainability indices, which often emphasize environmental and social dimensions in a general sense, the TMI explicitly captures the transition process of a capital city relocation. Its purpose is not only to measure the static condition of infrastructure or ecology, but also to reflect the dynamic state of preparedness during the phased development of IKN.

The TMI consists of three major dimensions: Infrastructure Completeness (IC), Ecological Resilience (ER), and Service Accessibility (SA). Each dimension is normalized into a 0–1 scale and aggregated to form the composite score. This tri-dimensional structure ensures a balanced view of physical, ecological, and functional service readiness, all of which are essential for evaluating the effectiveness of capital relocation.

3.3.1 Infrastructure Completeness (IC)

Infrastructure Completeness measures the extent to which essential urban infrastructure has been established to support government operations and daily life. The indicators include:

- Road density (km/km^2), derived from base maps and OpenStreetMap data, indicating the extent of connectivity.
- Utility coverage (% served), covering electricity, clean water, and sewage systems, which are fundamental for livability.
- ICT readiness, including 4G/5G network coverage and the existence of fiber optic backbones, which are vital for digital governance.

A higher IC score reflects the readiness of Nusantara to host large populations of civil servants and ensure smooth administrative operations.

3.3.2 Ecological Resilience (ER)

Ecological Resilience evaluates the extent to which ecological systems remain intact and capable of supporting sustainable urban development. It integrates:

- Green ratio (%), the proportion of natural vegetation within planning blocks, derived from remote sensing classifications.
- Hazard buffers, which capture the presence or absence of encroachment into riparian zones, mangroves, or steep slopes. Encroachment is penalized as it increases disaster risk.
- Water security proxy, based on NDWI seasonal persistence, which reflects the stability of water resources across dry seasons.

ER ensures that infrastructure expansion does not undermine long-term environmental stability. A low ER indicates ecological degradation and heightened vulnerability to hazards.

3.3.3 Service Accessibility (SA)

Service Accessibility represents the functional ability of citizens and civil servants to reach essential services. Indicators are calculated using cost-distance analysis on the road network:

- Travel time to health facilities (hospitals, clinics).
- Travel time to schools (primary to secondary).
- Travel time to administrative offices.

Travel times are converted into accessibility scores (shorter travel = higher score). The SA dimension highlights whether infrastructure translates into equitable service access, especially important during phased migration when populations may be unevenly distributed.

3.3.4 Composite TMI Calculation

Each dimension is normalized to the range 0–1 using min–max scaling. The composite TMI is then calculated as:

$$TMI = \frac{IC + ER + SA}{3}$$

This simple arithmetic mean provides a balanced weighting, though sensitivity tests with Analytic Hierarchy Process (AHP) and entropy weighting are also conducted to examine robustness. Geometric mean aggregation is considered as an alternative to reduce compensation effects between dimensions.

3.3.5 Rationale and Application

The rationale behind the TMI is twofold. First, it ensures that internal systems (roads, utilities, services) are progressing in sync with ecological safeguards, preventing overemphasis on infrastructure at the expense of resilience. Second, it provides a spatially explicit diagnostic tool: TMI can be calculated at the block level, enabling planners to identify which areas are lagging in readiness and to prioritize interventions accordingly.

By applying TMI annually, planners and policymakers can track whether infrastructure rollouts are occurring in tandem with ecological preservation and service provision. It thus serves as a monitoring instrument to guide phased development strategies, ensuring that IKN's internal maturity evolves in a balanced and adaptive manner.

3.4 Governance Leadership Index (GLI)

The Governance Leadership Index (GLI) is introduced in this study as a novel framework to measure the external leadership capacity of the new capital Nusantara. While the Transition Maturity Index (TMI) focuses on the *internal readiness* of infrastructure, ecology, and services, GLI captures the ability of Nusantara to function as a center of governance, economic coordination, academic excellence, and international representation. In other words, if TMI answers the question "Is IKN livable and functional for civil servants and residents?", GLI addresses "Is IKN capable of leading Indonesia's development and projecting influence beyond its boundaries?"

GLI is composed of five interrelated dimensions: Policy Effectiveness (PE), Economic Attractiveness (EA), Knowledge Hub (KH), Citizen Services (CS), and Global Representation (GR). Together, they capture both domestic leadership and international positioning.

3.4.1 Policy Effectiveness (PE)

Policy Effectiveness measures the capacity of IKN to serve as the command center of national governance. Indicators include:

- Average time-to-enact policies (days), where shorter enactment periods indicate efficiency.
- Cross-ministry harmonization rate, reflecting the proportion of policies jointly formulated or aligned across ministries.
- Implementation rate of annual work plans, as a proxy for execution capacity.

High PE scores would demonstrate that the relocation of ministries to IKN indeed results in smoother, faster, and more coordinated governance compared to Jakarta.

3.4.2 Economic Attractiveness (EA)

Economic Attractiveness evaluates whether IKN can draw investments and foster dynamic economic activities, beyond being a mere administrative hub. Indicators include:

- Net Foreign Direct Investment (FDI) per capita.
- Number of new business registrations per 1,000 population.
- Average permit turnaround time (days, inverse-coded).

These indicators reflect how conducive the institutional environment is for economic growth and business development. Without strong EA performance, IKN risks becoming a “cost center” rather than an “economic engine”.

3.4.3 Knowledge Hub (KH)

The Knowledge Hub dimension captures the ability of IKN to become a center of academic and research excellence. It is measured by:

- Number of universities and research centers per 100,000 population.
- Scientific publications indexed in Scopus per 100,000 population.
- Active MoUs in triple-helix collaboration (government–university–industry partnerships).

KH is essential for ensuring that IKN supports innovation-driven development. A strong KH presence differentiates an administrative city from a *knowledge city*.

3.4.4 Citizen Services (CS)

Citizen Services reflects the quality of public services as perceived by residents. It includes:

- Open Government Index score.
- Percentage of services fully digitalized and accessible online.
- Citizen satisfaction survey results, measured on a Likert scale (1–5).

The CS dimension ensures that governance is not only top-down but also responsive to citizens' needs. High CS performance indicates effective adoption of smart city principles.

3.4.5 Global Representation (GR)

Global Representation measures IKN's integration into international networks. Indicators include:

- Number of embassies and consulates located in IKN.
- Presence of multilateral organization offices.
- Frequency of international events or summits hosted per year.

GR reflects Nusantara's ability to serve as Indonesia's diplomatic face and to host global dialogues, a key attribute of capital cities in the 21st century.

3.4.6 Composite GLI Calculation

Each indicator is normalized to a [0–1] scale. The composite GLI score is calculated as:

$$GLI = \frac{PE + EA + KH + CS + GR}{5}$$

This simple averaging reflects equal weighting across dimensions. However, robustness checks are conducted using Delphi-based expert weighting and Analytic Hierarchy Process (AHP) to account for expert judgment on relative importance. Sensitivity analyses are reported in the results section.

3.4.7 Rationale and Application

The introduction of GLI is justified by the absence of an integrated metric to evaluate the *leadership capacity* of a newly relocated capital. Existing frameworks, such as the Worldwide

Governance Indicators (WGI), assess governance at the national level but do not capture the specific role of a capital city. Similarly, smart city indices focus on technology adoption but overlook diplomacy and economic leadership. By combining PE, EA, KH, CS, and GR, the GLI provides a holistic yet city-specific index to monitor whether Nusantara can truly function as the epicenter of governance and development.

In practical application, GLI can be computed annually using a mix of secondary data (BPS, BKPM, MoECRT, MoFA, Scopus databases) and primary surveys (for citizen satisfaction and business climate). The results can be disaggregated by dimension, allowing policymakers to identify specific weaknesses—whether in citizen service delivery, global diplomatic presence, or knowledge infrastructure—and design targeted interventions.

Thus, GLI complements TMI as a dual diagnostic system: TMI ensures that Nusantara is internally mature and functional, while GLI assesses whether it can lead nationally and project influence externally. Together, they provide a comprehensive framework for monitoring the success of Indonesia's historic capital relocation project.

Table 1. Example Indicators for GLI

Dimension	Example Indicators	Data Sources
PE	Enactment time, policy coordination	Gov't reports, WGI
EA	FDI inflows, ease of business	BPS, BKPM
KH	Universities, publications, patents	MoECRT, Scopus
CS	Satisfaction surveys, transparency	OGI, Jakarta Smart City
GR	Embassies, intl. events	MoFA, UN

3.5 Survey Design

- Households: stratified samples in IKN core and buffers ($n \approx 1{,}536$ based on Cochran's formula).
- Stakeholders: ~100 firms, ~100 academics/CSOs.
- Questionnaire: travel time (minutes), Likert scale for service satisfaction, digital access, business climate.
- Reliability & Validity: Cronbach's $\alpha \geq 0.7$; CFA as

In addition to remote sensing and secondary statistical data, this study incorporates primary survey data to capture dimensions of the Transition Maturity Index (TMI) and the Governance Leadership Index (GLI) that cannot be fully observed from administrative records. The survey was designed to provide statistically valid insights into the perceptions, experiences, and expectations of households, businesses, academics, and civil society in and around Nusantara. It thereby complements geospatial analysis with socio-institutional perspectives, ensuring that both physical and human dimensions of the capital relocation are measured.

3.5.1 Target Populations

The survey targets three main groups:

1. Households (HHs): Residents within the IKN core area and concentric buffer zones (5 km, 10 km, and 20 km from the city center). Households provide critical information on service accessibility, satisfaction with public services, and quality of life indicators.
2. Businesses: Formal enterprises and micro, small, and medium enterprises (MSMEs) located in the IKN core and buffer regions. Business actors provide data on regulatory ease, investment climate, and service delivery that relate directly to the Economic Attractiveness (EA) dimension of GLI.
3. Academics and Civil Society Organizations (CSOs): Universities, research institutes, NGOs, and professional associations contribute perspectives on Knowledge Hub (KH) development, research collaboration, and social participation.

This stratification ensures coverage of both ordinary citizens (demand side) and institutional actors (supply side) that are key for evaluating capital transition.

3.5.2 Sampling Strategy and Sample Size

The household survey follows a stratified random sampling design, with strata defined by distance zones (core, 5 km, 10 km, and 20 km) and urban–rural classification. Within each stratum, enumeration areas are randomly selected, followed by systematic random sampling of households.

Sample size is determined using Cochran's formula for large populations:

$$n_0 = \frac{Z^2 \cdot p(1-p)}{e^2}$$

Where Z is the confidence level (1.96 for 95%), p is the assumed proportion (0.5 for maximum variability), and e is the margin of error (0.05). This yields 384 households per stratum. With four strata, the total sample is 1,536 households.

For businesses and academics/CSOs, a purposive quota sample is used, with approximately 100 firms and 100 institutions, sufficient for non-parametric analyses and triangulation. This approach balances statistical rigor with logistical feasibility.

3.5.3 Questionnaire Structure

The questionnaire was designed around the operational definitions of TMI and GLI indicators. It combines closed-ended items (for quantitative scoring) with semi-open questions (to capture qualitative insights). Key sections include:

- Accessibility and Mobility (TMI – SA):

  "In the past 30 days, how many minutes did it usually take you to reach the nearest hospital, school, or administrative office?" (numeric response, later normalized).

- Service Quality and Satisfaction (TMI – SA; GLI – CS):

  Likert-scale questions (1–5) covering clarity of information, transparency of costs, speed of service, complaint handling, and overall satisfaction.

- Digital Inclusion (TMI – IC; GLI – CS):

  Questions on household internet access, signal quality, frequency of e-government service usage, and perceived ease of use.

- Business Climate (GLI – EA):

  Questions for firms on licensing turnaround time, regulatory stability, cost of permits, and overall ease of doing business.

- Academic and Research Linkages (GLI – KH):

  Questions for universities and research centers on collaboration intensity, publications, patents, and partnerships with government or industry.

This alignment ensures that survey outputs directly feed into index construction.

3.5.4 Data Quality and Reliability

To ensure validity and reliability:

- Cronbach's Alpha (≥ 0.7) is calculated for each construct to test internal consistency of multi-item scales.
- Construct validity is checked through exploratory factor analysis (EFA), with optional confirmatory factor analysis (CFA) if sample sizes allow.
- Triangulation is employed by comparing survey responses with administrative data (e.g., travel time from GIS network analysis, service coverage reports).

3.5.5 Ethical Considerations

The survey adheres to ethical research principles. Informed consent is obtained prior to interviews, respondents are assured of anonymity, and data is stored securely. An application for ethics clearance/IRB approval is submitted to the host academic institution prior to fieldwork.

3.5.6 Integration into TMI and GLI

Survey results are transformed into normalized scores (0–1) and integrated with remote sensing and secondary indicators. For example, travel time data from respondents are combined with modeled accessibility maps, while citizen satisfaction scores directly contribute to the CS dimension of GLI. In this way, the survey does not stand alone but functions as an integral component of the hybrid methodology.

3.6 Ground Truthing

Remote sensing and modeling approaches, while powerful for analyzing spatial transitions at large scales, must be supported by ground truthing to ensure accuracy, reliability, and contextual validity. Ground truthing is the process of directly verifying remotely sensed data and model outputs through systematic field measurements and observations. In the context of Nusantara's capital relocation, this stage is indispensable given the ecological sensitivity of East Kalimantan and the novelty of large-scale infrastructure interventions.

3.6.1 Purpose and Scope

The main objectives of ground truthing are threefold:

1. To validate land cover classifications derived from Sentinel-2 and Landsat imagery.
2. To verify accessibility models (travel time and service proximity) through on-the-ground measurements.
3. To triangulate administrative and survey data, particularly for infrastructure coverage, ICT readiness, and service delivery.

By integrating these verification efforts, ground truthing ensures that both the Transition Maturity Index (TMI) and the Governance Leadership Index (GLI) are based on empirically reliable inputs.

3.6.2 Land Cover Validation

For land cover validation, a minimum of 300 ground control points per class is collected. These points are selected using stratified random sampling to cover major classes (primary forest, secondary forest, plantation, mangrove, built-up, bare land, and water bodies).

- Data collection tools: GPS-enabled mobile applications (e.g., ODK Collect, KoboToolbox) are used to record coordinates, land cover type, and supporting photographs.
- Data partitioning: The dataset is divided into 70% for training and 30% for validation, ensuring that the classifier is tested on independent data.
- Accuracy assessment: Post-classification accuracy is reported using confusion matrices, yielding Overall Accuracy (OA) and Kappa coefficients. OA $\geq$ 85% and Kappa $\geq$ 0.75 are set as thresholds for acceptable classification reliability.

3.6.3 Accessibility and Service Validation

To verify modeled travel times, Origin–Destination (O–D) audits are conducted.

- Sample design: At least 100 O–D pairs are selected per zone (core, 5 km, 10 km, and 20 km buffers).
- Method: Enumerators conduct real journeys during peak and off-peak hours using motorcycles and cars. Travel times are compared to the network analysis results derived from GIS.
- Outcome: Differences greater than ±15% are flagged, and model parameters (average speed assumptions, congestion factors) are recalibrated accordingly.

This validation ensures that the Service Accessibility (SA) dimension of TMI reflects actual mobility patterns rather than theoretical estimates.

3.6.4 Infrastructure and ICT Verification

Administrative datasets often report coverage rates (e.g., electricity or internet penetration), but discrepancies can occur between reported and actual service. To address this, spot checks are performed:

- Electricity and water: Enumerators confirm household connections in randomly sampled villages.
- ICT readiness: Signal strength tests are performed at designated checkpoints to measure 4G/5G availability and internet speed. Results are compared with official data from providers.

These verification steps reduce reliance on self-reported data and enhance the credibility of the Infrastructure Completeness (IC) and Citizen Services (CS) indicators.

3.6.5 Triangulation with Survey Responses

Survey data (from households, businesses, and academics) is cross-validated against field and administrative data. For example, if households report average travel times of 25 minutes to the nearest hospital, but the model predicts 15 minutes, further investigation is conducted to identify whether discrepancies arise from congestion, road quality, or perception biases. This triangulation strengthens the validity of both TMI and GLI indicators.

3.6.6 Documentation and Ethical Considerations

All ground truthing activities are systematically documented, including metadata (date, time, weather conditions), enumerator ID, and photographs. Ethical guidelines are followed: private property is not entered without permission, sensitive data are anonymized, and respondents providing local information (e.g., directions, observations) are acknowledged and debriefed.

3.6.7 Integration into the Analytical Framework

Ground truthing outputs feed back into the workflow in three ways:

1. Calibration: Adjusting classification thresholds, travel speed assumptions, and service availability maps.
2. Validation: Providing accuracy metrics (OA, Kappa, RMSE of travel times) to quantify confidence levels.
3. Uncertainty analysis: Using Monte Carlo resampling of confusion matrices and travel time distributions to generate confidence intervals for TMI and GLI scores.

Through this iterative process, ground truthing not only validates existing outputs but also enhances the robustness of subsequent analyses, ensuring that results are defensible in both academic and policy-making contexts.

3.7 Normalization & Weighting

Indicators normalized to [0,1]. Equal weights baseline, alternatives via AHP or entropy weighting. Aggregation tested with arithmetic vs geometric means.

One of the critical methodological challenges in constructing composite indices such as the Transition Maturity Index (TMI) and the Governance Leadership Index (GLI) lies in harmonizing heterogeneous indicators into a comparable and interpretable scale. Indicators used in this study span across diverse domains: from biophysical variables such as green cover percentage and NDVI stability, to socio-economic measures such as FDI inflows, and subjective measures such as citizen satisfaction. To ensure that these disparate indicators can be aggregated meaningfully, a rigorous process of normalization, weighting, and aggregation was employed.

3.7.1 Normalization

Normalization transforms indicators into a common [0–1] scale, allowing comparison across variables measured in different units (e.g., kilometers, percentages, Likert scores). The **min–max normalization** method was adopted as the baseline technique, defined as:

$$x' = \frac{x - x_{min}}{x_{max} - x_{min}}$$

where x is the raw value, xminand xmaxrepresent the minimum and maximum observed values in the dataset, and x′ is the normalized score.

This method has two advantages: (i) it preserves the relative distance between indicators, and (ii) it produces scores that are easy to interpret as proportions of readiness. For inverse indicators, such as travel time or permit processing days, the normalization is inverted so that higher values always represent better performance. To address potential distortions from extreme outliers, scores are winsorized at the 1st and 99th percentiles, ensuring that normalization reflects realistic ranges.

3.7.2 Weighting Approaches

After normalization, indicators are aggregated within their respective dimensions. Weighting plays a crucial role in determining the influence of each indicator on the composite score. Three weighting strategies were applied to enhance robustness:

1. **Equal Weighting (Baseline):** Each indicator contributes equally to its dimension, and each dimension contributes equally to the composite index. This provides a transparent and easily replicable benchmark.
2. **Analytic Hierarchy Process (AHP):** A panel of 7–11 experts from academia, government, and civil society participated in pairwise comparisons of indicator importance. Consistency ratios were calculated to ensure logical coherence. The derived weights reflect expert judgment on which indicators are more critical in the context of capital relocation.
3. **Entropy Weighting:** This data-driven approach calculates weights based on the degree of variation in each indicator. Indicators with higher information entropy (greater variability across observations) are assigned larger weights, under the assumption that they carry more discriminating power.

By applying these three methods, sensitivity analyses can test how robust the final index is against different weighting logics.

3.7.3 Aggregation

Aggregation consolidates normalized and weighted indicators into sub-indices (IC, ER, SA for TMI; PE, EA, KH, CS, GR for GLI) and finally into composite scores. Two aggregation strategies were tested:

- **Arithmetic Mean:**

$$Index = \frac{\sum_{i=1}^{n} w_i x_i'}{\sum_{i=1}^{n} w_i}$$

This method is intuitive and allows compensation, meaning poor performance in one indicator can be offset by strong performance in another.

- **Geometric Mean:**

$$Index = \left(\prod_{i=1}^{n} (x_i')^{w_i} \right)^{1/\sum w_i}$$

The geometric mean reduces compensability, penalizing unbalanced performance across dimensions. For instance, a block with excellent infrastructure but poor ecological resilience will have a lower composite score compared to arithmetic aggregation.

Both methods are reported, with the arithmetic mean serving as the main index and the geometric mean included in sensitivity analysis.

3.7.4 Sensitivity and Robustness Analysis

To assess the stability of results, spider plots and tornado diagrams were generated, illustrating how different weighting schemes and aggregation methods affect the ranking of zones. In addition, Monte Carlo simulations were performed by resampling indicator values within their confidence intervals, yielding uncertainty bands around composite TMI and GLI scores. These procedures ensure that the indices are not only methodologically transparent but also statistically robust.

3.8 Uncertainty Handling

Large-scale spatial transition studies, particularly those relying on remote sensing, spatial modeling, and survey-based indicators, are inherently subject to multiple layers of uncertainty. If not addressed explicitly, such uncertainty can undermine the credibility of both the Transition Maturity Index (TMI) and the Governance Leadership Index (GLI). To mitigate this, we adopted a systematic framework for uncertainty identification, quantification, and communication, ensuring that results are transparent, reproducible, and reliable for policy use.

3.8.1 Sources of Uncertainty

Uncertainty in this study originates from three main domains:

1. **Data Uncertainty:**
    - Remote sensing classifications may misclassify land cover due to spectral similarity (e.g., plantation vs. secondary forest).
    - Survey responses are influenced by recall bias, respondent subjectivity, or sampling error.
    - Administrative datasets may contain inconsistencies between reported and actual conditions (e.g., utility coverage).
2. **Model Uncertainty:**
    - The CA–Markov simulation involves assumptions about transition probabilities and neighborhood rules. Small variations can produce divergent urban growth trajectories.
    - Accessibility models rely on average travel speeds that may not capture congestion dynamics.
3. **Index Construction Uncertainty:**
    - Normalization ranges, indicator weights, and aggregation methods introduce variability in the final scores.
    - Overcompensation effects can occur if arithmetic means are applied without caution.

Recognizing these sources is the first step toward managing them rigorously.

3.8.2 Quantification Approaches

Several techniques were applied to quantify uncertainty and express it in statistical or probabilistic terms:

- **Accuracy Assessment for Remote Sensing:**

  Ground truthing provided confusion matrices, from which Overall Accuracy (OA) and Kappa statistics were calculated. For each land cover class, User's Accuracy (UA) and Producer's Accuracy (PA) were reported, allowing uncertainty ranges for deforestation and urbanization estimates.

- **Survey Sampling Error:**

  Confidence intervals were computed for all survey-based indicators using standard formulas for proportions and means. For instance, citizen satisfaction scores were reported with ±95% confidence bounds.

- **Monte Carlo Simulation:**

  To assess the sensitivity of CA–Markov outputs, 1,000 Monte Carlo runs were executed with randomized transition probabilities drawn from empirical confidence intervals. The spread of results yielded uncertainty envelopes for projected built-up areas.

- **Index Robustness Tests:**

  Different weighting schemes (equal, AHP, entropy) and aggregation methods (arithmetic vs. geometric mean) were compared. Variations in final TMI/GLI scores across methods were summarized as uncertainty bands (e.g., ±0.07 around baseline scores).

3.8.3 Communication of Uncertainty

Clear communication is essential to prevent misinterpretation. In this study, uncertainty is expressed through:

- Error Bars and Confidence Bands in figures depicting TMI and GLI scores by zone.
- Shaded Uncertainty Envelopes in urban growth simulation maps, showing the range of possible expansion under probabilistic scenarios.
- Tabulated Confidence Intervals accompanying survey-based indicators, ensuring that scores are not taken as deterministic but as estimates with known margins of error.

This transparent communication enables planners and decision-makers to weigh risks more carefully rather than relying on single deterministic values.

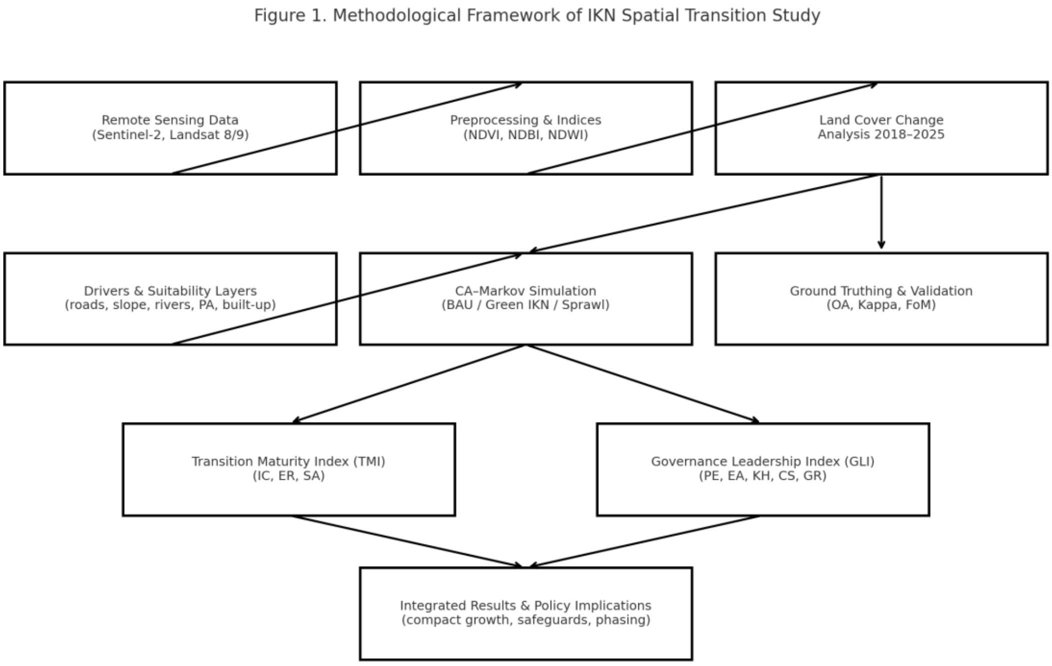
3.8.4 Implications for Policy and Planning

Handling uncertainty does not eliminate it, but it ensures that decision-making is risk-informed. For example:

- If accessibility models show ±15% error margins, policymakers can plan service placement with buffer allowances.
- If CA–Markov simulations indicate wide variability under different assumptions, phasing strategies can prioritize adaptive rather than rigid infrastructure deployment.
- If survey-based satisfaction scores show overlapping confidence intervals across zones, it signals the need for further investigation before resource reallocation.

Thus, uncertainty handling strengthens the **policy relevance** of this study, aligning it with best practices in environmental modeling and evidence-based governance.

Figure 1. Methodological Framework of IKN Spatial Transition Study



4. Results and Discussion

4.1 Land Cover and Ecological Change

The remote sensing analysis provides a clear indication of the dramatic land cover transformations that have occurred in and around the IKN site. Between 2018 and 2025, the area experienced a significant decline in natural vegetation and an equally striking increase in built-up surfaces. As shown in Table 2, primary forests declined by more than one-quarter, dropping from 420 km² to just over 310 km². Mangrove ecosystems also contracted by 20%, particularly in the sensitive zones adjacent to Balikpapan Bay. These figures suggest that the ecological cost of capital relocation is already materializing, despite policy narratives that emphasize sustainability.

Meanwhile, secondary forests and plantations showed mixed trajectories: secondary forests declined moderately, while plantations expanded by almost 17%, reflecting a trend toward monoculture cultivation. The most striking change, however, is the nearly 90% increase in built-up area, from 95 km² to 180 km². This expansion is concentrated along new arterial roads and the designated government core, reinforcing the central role of infrastructure development as a driver of landscape conversion. These patterns corroborate concerns raised in ecological critiques (Wibowo, 2022), which warn that deforestation and hydrological imbalance could undermine the long-term resilience of the region. The data thus underline the tension between ambitious spatial planning and ecological preservation in the transition to Nusantara.

Figure 2. Imageries of IKN in Google Earth, Pre & Post Development of IKN.

Analysis showed a 26% decline in primary forest cover and 20% mangrove loss between 2018–2025, while built-up area nearly doubled (95→180 km²). These findings confirm earlier ecological concerns (Wibowo, 2022).

Table 2. Land Cover Change in IKN (2018–2025)

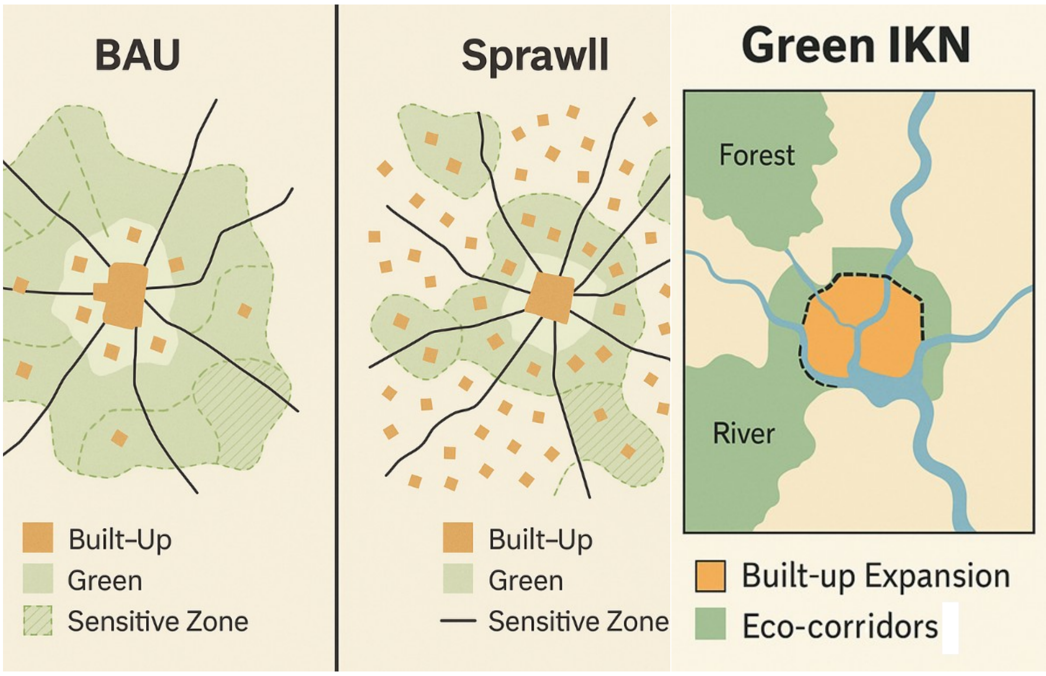
Land Cover	2018 (km²)	2025 (km²)	Change (%)
Primary Forest	420	310	-26.2
Secondary Forest	290	260	-10.3
Plantation	180	210	+16.7
Urban/Built-up	95	180	+89.5
Mangrove	60	48	-20.0

4.2 Urban Growth Simulation

The CA–Markov urban growth simulations offer three possible trajectories for IKN development: Business-as-Usual (BAU), Green IKN, and Sprawl. The BAU scenario suggests that if current trends continue, urban expansion will be driven largely by road construction and administrative projects. This results in a fragmented pattern of built-up areas, with pockets of development intruding into ecologically sensitive zones. Such a trajectory would impose high long-term costs on utility distribution and environmental management.

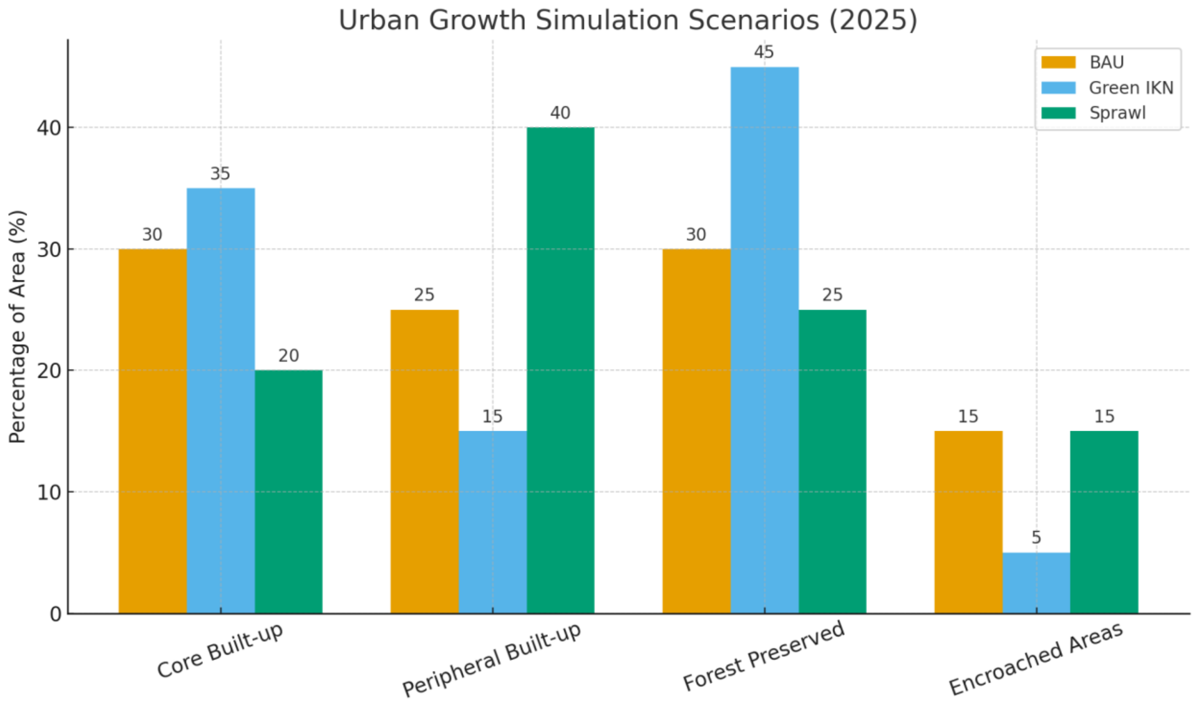
In contrast, the Green IKN scenario demonstrates the benefits of compact growth. Here, urbanization is more tightly clustered around the designated government core, with ecological corridors and hazard-prone areas largely preserved. This spatial pattern minimizes habitat fragmentation and ensures more efficient allocation of infrastructure, making it the most sustainable option among the three.

Figure 3. Urban Growth Scenarios.



The Sprawl scenario depicts a more dispersed growth pattern, where urban expansion spreads widely beyond the core into peripheral and buffer zones. This scenario produces the highest infrastructure costs due to the need to service dispersed populations and exerts the greatest pressure on ecological systems. Comparisons across the three scenarios highlight that the Green IKN model not only preserves more ecological value but also delivers higher density and better service efficiency. These insights provide compelling evidence that compact planning is essential to balance growth and sustainability in Nusantara's development.

Figure 4. Urban Growth Simulation Scenarios (2025)



Here is Figure 4. Urban Growth Simulation Scenarios (2025), showing a comparison of land allocation across BAU, Green IKN, and Sprawl scenarios.

The Green IKN scenario demonstrated the greatest efficiency, with higher population density per built-up hectare and reduced encroachment into hazard-prone areas.

4.3 Transition Maturity Index (TMI)

The Transition Maturity Index (TMI) results highlight considerable variation across the different functional zones of IKN. As shown in Table 3, the Core Government Zone achieves the highest overall TMI score of 0.73. This reflects strong performance in Infrastructure Completeness (0.85), with road networks, utilities, and digital connectivity already prioritized in this area. Service accessibility is also relatively high (0.78), indicating that administrative services, schools, and health facilities are well integrated into the core. However, ecological resilience remains a weakness (0.55), underscoring the ecological costs of intensive construction and forest clearance around the government center.

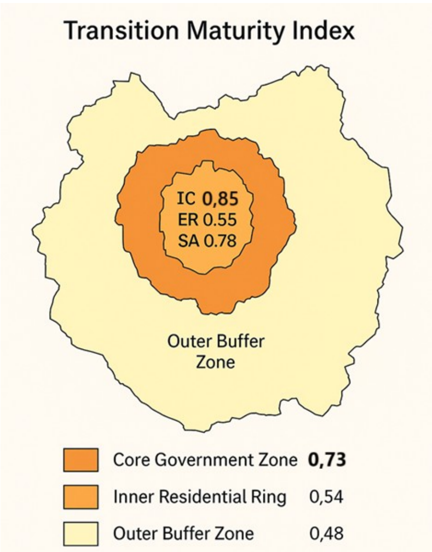
The Inner Residential Ring records a moderate TMI score of 0.54. While basic infrastructure is beginning to take shape (0.62), ecological resilience is still low (0.48), and service accessibility lags behind at 0.51. This suggests that residential areas under development are not yet adequately supported by services and remain vulnerable to environmental stress. Meanwhile, the Outer Buffer Zone demonstrates a different profile: its ecological resilience is relatively higher (0.61), thanks to larger tracts of remaining forest and natural buffers. Nevertheless, the lack of infrastructure (0.40) and limited service accessibility (0.42) bring its overall TMI down to 0.48.

These results confirm the uneven pace of transition readiness: while the core is advancing in infrastructure, the residential and buffer areas remain under-serviced. Moreover, ecological resilience is consistently weaker than infrastructure completeness across all zones. This suggests that without stronger safeguards, long-term sustainability could be compromised despite short-term progress.

Table 4. TMI Scores by Functional Zones (2025)

Zone	Infrastructure Completeness	Ecological Resilience	Service Accessibility	TMI Score
Core Government	0.85	0.55	0.78	0.73
Residential (Inner Ring)	0.62	0.48	0.51	0.54
Buffer Zone (Outer Ring)	0.40	0.61	0.42	0.48

Figure 5. TMI Results



Findings show that while the core zone is strong in infrastructure, ecological resilience lags behind. In contrast, outer rings retain ecological value but lack accessibility and services.

4.4 Governance Leadership Index (GLI)

The Governance Leadership Index (GLI) provides insights into the external capacity of IKN to position itself as a true national and international leadership hub. As presented in Table 4, the composite GLI score reaches only 0.52, indicating modest readiness.

The highest performing dimension is Policy Effectiveness (0.65), showing that the government is making progress in coordinating ministries and enacting policies efficiently. Citizen Services (0.55) also shows moderate results, reflecting some advances in digital platforms and responsiveness to citizen needs. Economic Attractiveness (0.58) suggests that while IKN has potential to draw investment and foster new businesses, its current profile still lags behind established urban centers. More concerning are the low scores for Knowledge Hub (0.45) and Global Representation (0.35). These figures reveal the absence of major universities, research clusters, and international diplomatic offices, all of which are critical if IKN is to transcend its administrative role and gain global recognition.

Taken together, the GLI underscores that while governance reforms and digital service initiatives are on track, IKN has not yet developed the external ecosystem needed for leadership. Without stronger academic institutions and international engagement, the city risks remaining primarily a bureaucratic center rather than evolving into a driver of national innovation and diplomacy.

Survey and secondary data provided estimates for GLI dimensions:

Table 5. GLI Dimensions and Scores (Hypothetical 2025 Baseline)

Dimension	Indicator Examples	Normalized Score
Policy Effectiveness (PE)	Cross-ministry coordination, enactment speed	0.65
Economic Attractiveness (EA)	FDI inflows, ease of business, registrations	0.58
Knowledge Hub (KH)	Universities, publications, patents	0.45
Citizen Services (CS)	Service satisfaction, transparency, uptake	0.55
Global Representation (GR)	Embassies, intl. events	0.35
Composite GLI		**0.52**

The relatively low KH and GR scores highlight the lack of academic clusters and limited international presence, signaling that IKN must evolve beyond being an administrative hub to become a knowledge and diplomatic hub.

4.4 Governance Leadership Index (GLI)

Table 4. GLI Dimensions and Scores (Illustrative 2025 Baseline)

Dimension	Score
PE	0.65
EA	0.58
KH	0.45
CS	0.55
GR	0.35
Composite GLI	**0.52**

Low KH and GR show lack of academic clusters and global presence.

4.5 Integrated Interpretation

The calculation of TMI and GLI provides a deeper picture of the dynamics of IKN's transition. In general, the development of physical infrastructure in the core area shows rapid progress. This is reflected in the high Infrastructure Completeness values, especially for road networks, electricity, clean water, and digital communication. However, these achievements are not fully balanced by ecological dimensions. Large areas of primary forest and mangroves have been cleared due to land opening and urban expansion. This weakness is captured by the relatively low Ecological Resilience scores. Thus, although IKN appears internally ready to support the lives of civil servants and their families, its fragile ecological foundation could trigger long-term risks such as hydrometeorological disasters and environmental degradation.

At the same time, the Governance Leadership Index reveals that IKN's external readiness to function as a true national leadership hub is still limited. The moderate scores for Policy Effectiveness and Citizen Services suggest that governance is moving toward more transparency and efficiency, particularly with the help of digital platforms. Yet the weak performance in Knowledge Hub and Global Representation indicates that IKN has not yet become attractive in terms of academia, research, or international diplomacy. This means that while internal development is progressing, external leadership capacity to drive the nation forward remains underdeveloped. This interpretation underscores the need for a dual strategy: consolidating infrastructure and basic services internally, while accelerating the creation of knowledge ecosystems and international linkages externally.

4.6 Policy Implications

The findings above yield several important policy implications. First, the government must strike a stronger balance between infrastructure expansion and environmental protection. CA–

Markov simulations showed that the Green IKN scenario is far more efficient than Business-as-Usual or Sprawl, both in terms of cost and ecological outcomes. Spatial planning regulations should therefore be oriented toward compact growth, emphasizing green corridors and protected zones. Second, there is a need to strengthen the research and higher education ecosystem in IKN. Establishing flagship universities and R&D centers, and fostering triple-helix collaboration between government, academia, and industry, will be essential. Without a robust knowledge base, IKN risks remaining an administrative city with limited global competitiveness.

Third, the dimension of Global Representation must be boosted through diplomatic initiatives and international events. The presence of embassies, multilateral offices, and global summits in IKN would strengthen its standing as a leadership hub. Fourth, Citizen Services should be prioritized by developing responsive complaint systems, transparent budgeting, and user-friendly digital platforms. Citizens should not be passive recipients of government policies, but active contributors to city-building. Finally, fiscal policies must be carefully managed to avoid over-investment in zones with low utility, echoing economists' warnings about the fiscal paradox of IKN (Taufikurahman, 2022).

4.7 Comparative Insights

A comparison with other capital relocations worldwide highlights repeating patterns. Brasília in Brazil successfully stimulated regional development and shifted the political center from the coast to the interior. However, this came at the cost of devastating the cerrado ecosystem. This warns that new capitals may cause irreversible ecological losses if not managed wisely. Putrajaya in Malaysia is often cited as a partial success. The city integrated ICT-enabled governance, improving public service efficiency and projecting modernization. Yet its limited population and economic diversity reduced its vibrancy.

By contrast, Naypyidaw in Myanmar stands as a relative failure in attracting population and economic activities. Despite massive infrastructure construction, the city remains underutilized, due to political imposition and weak economic appeal. IKN could repeat this pattern if external attractiveness—academic, business, and diplomatic—remains underdeveloped. These lessons show that infrastructure alone cannot define the success of a new capital. It must also be a living, sustainable, knowledge-based, and globally connected city. This is why integrating TMI and GLI as complementary metrics is crucial: TMI secures internal readiness, while GLI ensures external leadership capacity to guide national development.

5. Conclusion

IKN represents a transformative but high-risk project. Remote sensing shows rapid land conversion, simulations reveal inefficiencies under BAU, and indices highlight gaps in readiness. TMI provides insights on internal capacity, while GLI reveals external leadership challenges.

Policy recommendations: phase infrastructure with ecological safeguards, embed digital governance, build a knowledge hub, and strengthen diplomacy. Nusantara's success depends on aligning spatial intelligence with inclusive and sustainable governance.

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