



Shifting shoreline: A four-decade analysis of coastal spatial transformation in an urban fishing settlement

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ABSTRACT

Background: Coastal cities across the Global South are experiencing rapid spatial transformation driven by urbanization, port expansion, and land reclamation. This study examines four decades (1988–2025) of coastal spatial transformation and identifies the critical period in which development trajectories changed structurally. **Methods:** A quantitative-spatial approach integrating multitemporal remote sensing and non-parametric time-series analysis was employed. Built-up areas were extracted from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI/TIRS imagery for 1988, 2000, 2015, and 2025 using the Normalized Difference Built-up Index (NDBI) with adaptive thresholding. Structural changes in the time series were detected using Pettitt's change-point test implemented in the pyhomogeneity module. **Findings:** Built-up land expanded from 26.43 ha in 1988 to 86.11 ha in 2025, representing a cumulative increase of 225.8%. Three phases of transformation were identified: organic settlement expansion (1988–2000), infrastructure-driven acceleration (2000–2015), and consolidation through densification and small-scale reclamation (2015–2025). The Pettitt test identified a statistically significant change point in 2015 ($p \approx 0.000$), after which mean built-up extent increased by 71.1%. Coastal spatial transformation is non-linear and shaped by the interaction of urbanization pressures, infrastructure development, reclamation, and planning policies. **Conclusion:** The findings highlight the need for socio-ecological safeguards in coastal planning to support Sustainable Development Goal 11 and balance urban growth with the protection of vulnerable coastal communities and ecosystems. **Novelty/Originality of this article:** This study provides the first statistically dated reconstruction of four-decade coastal spatial transformation by integrating multitemporal NDBI analysis with Pettitt change-point detection, offering a reproducible and low-resource framework for long-term coastal monitoring in data-scarce regions of the Global South.

KEYWORDS: built-up land; change-point detection; coastal cultural sustainability; NDBI; spatial transformation.

1. Introduction

Coastal zones concentrate a large share of the world's population, economic activity, and ecological risk, and they are transforming faster than almost any other class of terrestrial environment. More than a tenth of humanity now lives in the narrow low-elevation coastal belt, and the trajectory of settlement, infrastructure, and land conversion in this belt will largely determine the exposure of people and assets to flooding and sea-level rise over the coming decades (Neumann et al., 2015). In rapidly urbanising Asia, this pressure is intensified by the coupling of metropolitan expansion with port-led development, so that the shoreline itself becomes a contested surface reshaped by

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reclamation, embankment, and the outward march of built-up land. Understanding how these coastal spaces change, including when it happens, how quickly, and with what social and ecological consequences, has therefore become a central concern for urban studies, spatial planning, and coastal governance.

Nowhere in Indonesia are these dynamics clearer than on Jakarta's northern coast, and within it the fishing settlement of Kampung Nelayan Muara Angke offers a particularly clear case. For decades Muara Angke has functioned simultaneously as a residential space, a space of production, and a hub of fisheries-based economic activity. Since the 1980s, however, it has undergone marked land-use change as fishponds and wetlands have been converted into dense settlements, port and fishing facilities, and commercial zones. This physical change has been accompanied by shifts in the socio-economic structure of the fishing community, which has been progressively displaced by urban modernisation and the expansion of urban infrastructure (Noegroho & Ardiani, 2017). The area thus condenses, within a single small territory, the broader tension between metropolitan growth and the persistence of a coastal livelihood community.

Historically, Muara Angke developed from the colonial period as a traditional fishing port embedded in Jakarta's seafood distribution network. The construction of the Nizam Zachman Oceanic Fishing Port in the 1980s reinforced its role as a key node in national fisheries logistics, and subsequent interventions, including the fish auction market and successive rounds of port modernisation, intensified economic activity across the surrounding coast (Passas & Syaiful, 2022). Yet physical growth has coincided with mounting environmental stress, including tidal (rob) flooding, land subsidence, and coastal ecological degradation (Wurjanto et al., 2023). The conversion of fishponds and the erosion of mangrove and wetland buffers have further compromised the ecological functions on which the settlement depends (Yuliantri et al., 2024; Wibin & Jayanti, 2024).

These transformations carry direct consequences for the social life of the fishing community. Reclamation and embankment construction have progressively restricted access to the sea, while wetlands that formerly served as ecological space and flood buffers have diminished. Robin et al. (2017) show that fishers around Jakarta Bay confront declining catches and rising social vulnerability as the coastal environment changes. The shift in spatial function has, in turn, driven a transition in the character of the area from a community-based settlement toward an increasingly economically differentiated urban space. This is precisely the kind of change in the form, function, and structure of space that Yunus (2008) identifies as spatial transformation arising from the interaction of physical, social, and policy forces.

Read through a wider theoretical lens, this dynamic reflects a shift in the nature of space from a space of places toward a space of flows (Castells, 2004): flows of capital, investment, and infrastructure reorient the coast, so that the socio-cultural meanings embedded in the living spaces of coastal communities come under pressure. Relph (1976) describes the resulting loss of place identity as placelessness, that is, the growing sameness of spatial function under the pressure of modernisation. Against this backdrop, the empirical task of measuring, dating, and interpreting spatial transformation in Muara Angke acquires both scientific and policy significance.

Despite a substantial literature on tidal flooding, reclamation, fisher vulnerability, and shoreline change along the Jakarta coast, research on the spatial transformation of Muara Angke remains confined largely to short-term, thematic analyses. Spectral indices such as the NDBI can reliably map built-up surfaces, yet they have rarely been applied over multi-decadal horizons capable of tracing the full evolution of coastal space. Statistical approaches for objectively detecting structural change in development trajectories, notably the Pettitt change-point test, have likewise seen little application in the Indonesian coastal context. Moreover, the empirical relationship between the physical reworking of the area and the social dynamics of its fishing community has seldom been examined through a measurable, spatially explicit approach. A clear opportunity therefore exists to advance understanding of coastal spatial transformation on the Jakarta shoreline through a longer temporal lens and a more rigorous analytical design.

To situate this study, the following review draws together four related areas of research: coastal urban transformation and metropolitan coastal development; theories of spatial transformation; remote sensing and the NDBI for built-up mapping; and change-point detection in time-series analysis. It then locates the Indonesian coastal experience, and the specific case of Muara Angke, within these areas before stating the research gap that the study addresses.

Coastal urbanisation has become one of the defining spatial processes of the twenty-first century. Global assessments project that urban land will expand markedly by 2030, with much of this growth concentrated in biodiversity-rich and hazard-exposed coastal regions, generating direct impacts on ecological systems and carbon pools (Seto et al., 2012). The intersection of demographic concentration, economic agglomeration, and physical exposure makes coastal cities simultaneously engines of growth and sites of acute vulnerability, since the same low-lying land that attracts port and logistics investment is also most exposed to sea-level rise and coastal flooding (Neumann et al., 2015). Metropolitan coastal development is thus characterised by a structural tension between the economic logic that drives land conversion seaward and the ecological logic that would counsel restraint.

Empirical studies of Asian coastal cities consistently document a recurrent developmental sequence. Early phases of coastal urbanisation tend to proceed through linear, low-density expansion along existing transport corridors, before shifting toward cluster-based growth and, ultimately, densification and reclamation as accessible land becomes scarce (Yilmaz & Terzi, 2020; Zhao et al., 2017). Port construction is a particularly powerful driver of this sequence, reorganising land-use patterns in its hinterland and accelerating the conversion of ecological land into built-up surfaces (Yan et al., 2021; Ji et al., 2025). In the Chinese coastal context, long-run analyses of land-use/land-cover change reveal that built-up expansion systematically spreads into wetlands, tidal flats, and aquaculture ponds, producing measurable declines in ecological land and ecosystem service capacity (Wang et al., 2023; Chen et al., 2023; Ren et al., 2025). Comparative work on cities such as Xiamen and Antalya further shows that infrastructure investment and connectivity gains are among the strongest predictors of the pace and spatial configuration of coastal land conversion (Zhang et al., 2025; Yilmaz & Terzi, 2020). Collectively, this literature establishes that metropolitan coastal development is neither gradual nor spatially uniform, but tends to unfold through distinct phases marked by periods of accelerated, infrastructure-led change. This observation motivates the search, in the present study, for a statistically identifiable structural break.

Interpreting coastal land conversion requires more than descriptive measurement; it requires a theory of how and why space changes. Yunus (2008) conceptualises spatial transformation as change in the form, function, and structure of space produced by the interaction of physical, social, and policy factors. This definition is well suited to settlements, such as Muara Angke, where morphological change is inseparable from shifts in economic function and governance. Castell (2004) distinction between the space of places and the space of flows offers a complementary lens: as capital, investment, and infrastructure flows come to dominate, coastal space is turned away from its role as a container for community-based social life and toward its role as a medium for accumulation and circulation. Relph's (1976) notion of placelessness names the cultural cost of this shift, that is, the loss of place identity under the growing sameness brought by modernisation.

A political-ecology perspective situates these changes within relations of power, emphasising that coastal land-use transformation is mediated not only by market forces or natural dynamics but by institutional arrangements, regulatory decisions, and competing interests among the state, private capital, and local communities (Pelling, 2011; Anguelovski & Martínez Alier, 2014). Applied to Jakarta, this perspective illuminates how planning regulations, concession permits, and infrastructure investment have favoured large-scale port and commercial development over the subsistence needs of fishing communities, with reclamation shaped by an interplay of national development priorities, municipal revenue objectives, and speculative real-estate interests (Colven, 2017). The

socio-ecological systems (SES) framework (Ostrom, 2009) adds a systemic dimension, conceptualising the coast as a linked human and natural system in which change in one part, such as the physical expansion of built-up land, spreads to the social, economic, and ecological parts. The conversion of fishponds and wetlands, which function at once as productive resources, ecological buffers, and livelihood assets, therefore represents not a simple land-cover change but a disruption of an entire socio-ecological configuration, a pattern documented across Southeast Asian coastal communities where such disruption weakens collective resource governance and intensifies livelihood pressures (Armitage et al., 2017; Nunan, 2020). Finally, the concept of spatial justice (Soja, 2010; Harvey, 2008) highlights the question of distribution, namely who bears the costs and who gains the benefits of spatial change, and provides the basis for judging the social consequences of transformation in Muara Angke.

Remote sensing has become the main instrument for measuring urban and coastal land-cover change at scale, offering consistent, repeatable, and cost-effective observation across long time horizons. Among the many spectral indices developed for built-up mapping, the Normalized Difference Built-up Index (NDBI) proposed by Zha et al. (2003) remains one of the most widely adopted, owing to its simplicity, transferability, and reliance on the contrasting reflectance of impervious surfaces in the shortwave-infrared (SWIR) and near-infrared (NIR) regions. Zha et al. (2003) reported mapping accuracies as high as 92.6% and emphasised the index's capacity to reduce the subjectivity inherent in supervised classification. Comparative analyses by Xu (2007) confirmed that NDBI achieves consistent spectral separability between built-up land, vegetation, and water in varied urban settings, while Laosuwan & Sangpradit (2012) showed that combining NDBI with complementary indices such as NDVI and NDWI can sharpen land-cover discrimination and reduce spectral confusion in mixed coastal and wetland environments.

Subsequent applications have extended NDBI to diverse geographies and confirmed both its utility and its constraints. Karanam (2018) reported an overall accuracy of 92.8 % for NDBI-based built-up mapping, exceeding conventional supervised classification, and Wahid & Mushref (2026) showed that integrating NDBI with GIS-based spatial analysis enables accurate mapping of built-up land and quantitative characterisation of urbanisation gradients. At the same time, Oknisia & Nugraini (2025) caution that NDBI can misclassify dry, exposed soils as built-up surfaces where spectral similarity is high, underscoring the need for careful thresholding and ancillary interpretation in non-urban and coastal mosaics. These findings frame the methodological posture adopted here: NDBI is treated as a robust primary indicator of built-up development, but is combined with adaptive thresholding and visual interpretation to mitigate misclassification along fishpond edges and dense coastal margins. Crucially, although NDBI is frequently applied to single-date or short-interval imagery, its use in sustained multi-decadal monitoring of a single coastal settlement remains uncommon. The present study addresses this gap directly.

Measuring how much built-up land has changed is necessary but not sufficient; robust interpretation also requires identifying when the trajectory of change shifted. Development trends in coastal areas rarely follow smooth linear paths. Instead, they are interrupted by abrupt structural shifts triggered by policy interventions, infrastructure projects, and reclamation, producing time series that fluctuate, exhibit large inter-period differences, and may contain outliers (Wang et al., 2021). Detecting such shifts objectively calls for change-point methods that make minimal distributional assumptions. The non-parametric test introduced by Pettitt (1979) is well suited to this task: it evaluates every candidate breakpoint in a series, is insensitive to the underlying distribution, and is comparatively robust to outliers, making it a standard tool for detecting abrupt change in hydrological, climatic, and environmental series (Yue & Wang, 2004). Its application to remote-sensing-derived land-use series provides a statistical bridge between multitemporal mapping and interpretation, allowing the periodisation of spatial change to rest on an objective foundation rather than on visual inspection alone (Wang et al., 2021). Despite this suitability, the Pettitt test has rarely been used in the Indonesian coastal context, and almost

never in combination with a multi-decadal NDBI series, which is precisely the combination used here.

Indonesian coastal urbanisation is shaped by the interaction of rapid metropolitan growth, ambitious infrastructure programmes, and marked environmental fragility. Firman (2017) documents the emergence of mega-urban regions on Java, in which the outward expansion of the built environment increasingly integrates coastal peripheries into metropolitan economic networks. Along the northern coast, this integration has been accompanied by intense pressure on ecological land: Krisnanta et al. (2025) show that regional infrastructure development in the northern coastal region of Central Java accelerates urbanisation while degrading the coastal environment, and Kawata (2022) highlights the erosion of green infrastructure and the related weakening of flood resilience in the Jakarta megacity. The Jakarta coast, in particular, has become a clear example of the contradictions of infrastructure-led coastal development, where reclamation and sea-wall proposals are entangled with national development priorities, municipal finance, and real-estate speculation (Colven, 2017).

Within this setting, Muara Angke has attracted growing scholarly attention, though largely through thematic and sectoral lenses. Studies have examined the feasibility and economic rationale of modernising the Nizam Zachman fishing port (Wurjanto et al., 2023), the revitalisation of the fish-market area (Passas & Syaiful, 2022), the spatial and morphological logic of the settlement through space-syntax and everyday-architecture perspectives (Sunardi & Ariaji, 2022), the degradation of mangrove ecosystems and its consequences for wildlife habitat (Yuliantri et al., 2024), and strategies for restoring the area's identity through sustainable aquaculture (Wibin & Jayanti, 2024). Complementary work on Jakarta Bay documents the deteriorating status of fisheries habitat and the rising vulnerability of fishing livelihoods (Nugraha et al., 2020; Robin et al., 2017). This body of work establishes that Muara Angke is undergoing significant environmental and social change; what it has not yet provided is a quantitative, multi-decadal reconstruction of the settlement's built-up trajectory or a statistically grounded periodisation of its transformation.

Three gaps emerge from the foregoing review. First, although NDBI is an established tool for built-up mapping, it has rarely been applied continuously across a four-decade horizon to a single coastal settlement, leaving the long-run trajectory of coastal change under-measured. Second, change-point statistics, and the Pettitt test in particular, have seldom been used in the Indonesian coastal context to date structural shifts in urban expansion, so that existing periodisations rest largely on qualitative judgement. Third, the empirical relationship between the physical reworking of coastal space and the social dynamics of fishing communities has rarely been examined through a spatially explicit, quantitative design. The present study addresses these gaps by integrating multitemporal NDBI extraction (1988 to 2025) with Pettitt change-point detection to produce an objective, replicable periodisation of transformation in Muara Angke, and by interpreting that periodisation through the combined lenses of spatial-transformation theory, political ecology, and spatial justice. Its contribution is therefore both methodological, in that it shows a reproducible, low-resource workflow for long-term coastal monitoring suited to data-scarce settings in the Global South, and substantive, in that it provides the first statistically dated account of coastal spatial transformation in one of Jakarta's most representative fishing settlements and linking that account to questions of sustainable and inclusive coastal governance (Charles et al., 2020).

Against this background, the present study pursues two objectives. The first is to quantify the four-decade (1988 to 2025) trajectory of built-up land expansion in Muara Angke using multitemporal NDBI analysis. The second is to identify, in statistical terms, the critical period at which that trajectory changed structurally, using the Pettitt change-point test. The remainder of the paper is organised as follows. Section 2 sets out the methodology, covering the study area, the data, and the analytical procedures. Section 3 presents and discusses the results. Section 4 concludes with recommendations oriented toward Sustainable Development Goal 11.

2. Methods

2.1 Study area

The study area encompasses the coastal zone of the Pluit and Kapuk Muara sub-districts within Penjaringan District, North Jakarta, comprising the Kampung Nelayan Muara Angke fishing settlement, the Nizam Zachman Oceanic Fishing Port, remaining fishpond areas, and adjacent water zones. The area is bounded by Kapuk Muara to the west, Jakarta Bay to the east, and the densely urbanised fabric of North Jakarta to the south. Satellite imagery reveals a varied land-use mosaic of dense settlements, port facilities, residual fishponds, wetland open spaces, and the main access roads linking the coast to the city centre.

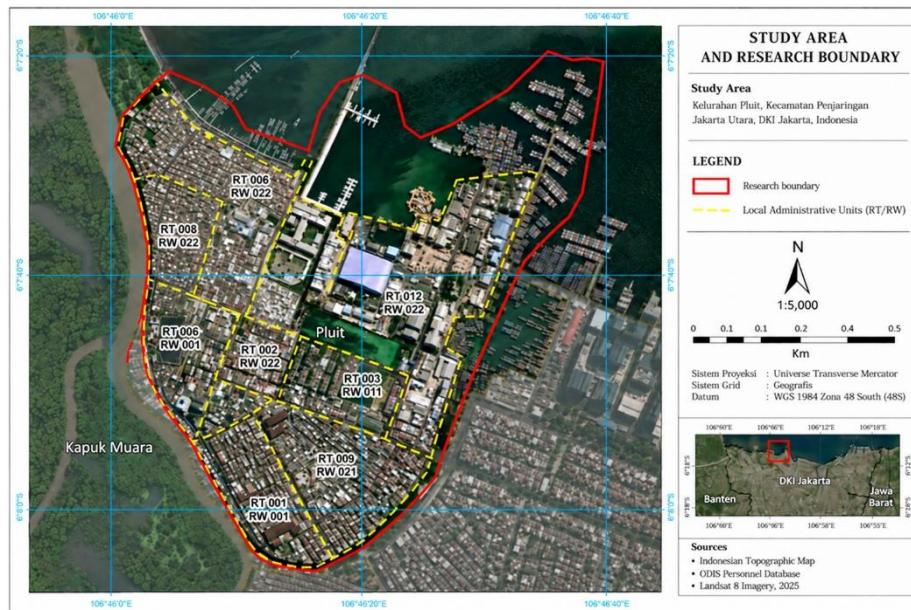


Fig. 1. Study area Muara Angke

Geomorphologically, Muara Angke is a low-lying coastal plain formed through estuarine sedimentation and the historical construction of fishponds, with elevations of only 0-1 m above sea level (Robin et al., 2017). Its morphology continues to change under the influence of reclamation and wetland conversion (Noegroho & Ardiani, 2017), producing an organic spatial pattern that follows former fishpond and canal alignments (Sunardi & Ariaji, 2022). The area also lies within one of the most severe land-subsidence zones in North Jakarta, which compounds the risk of tidal flooding and coastal ecological vulnerability (Wurjanto et al., 2023). These characteristics make Muara Angke a critical and information-rich case for examining coastal spatial transformation.

2.2 Data collection

The primary data comprise multitemporal optical satellite imagery from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI/TIRS, representing four reference years (1988, 2000, 2015, and 2025) selected to capture the early, middle, and current states of the settlement across the four-decade study period. All scenes were obtained from the United States Geological Survey (USGS) EarthExplorer platform at a spatial resolution of 30 m. To ensure temporal comparability, scenes were selected according to two criteria: cloud cover below 10 % over the study area, and acquisition during the dry season (May to October), which minimises the unwanted influence of atmospheric moisture on SWIR and NIR reflectance. Supporting datasets include the administrative boundary of Pluit sub-district (Bappeda DKI

Jakarta), the Indonesian base map (Rupabumi Indonesia), and high-resolution Google Satellite imagery used for visual verification and ground-truthing.

Consistent preprocessing across all four acquisition dates is fundamental to multitemporal analysis, because apparent changes in index values must reflect genuine land-cover transformation rather than artefacts of inter-scene radiometric or atmospheric variation. Preprocessing therefore comprised four sequential operations: radiometric calibration, atmospheric correction, cloud masking, and clipping.

First, raw digital numbers were converted to at-sensor spectral radiance and subsequently to top-of-atmosphere reflectance using the sensor-specific calibration coefficients supplied in the scene metadata, thereby harmonising values across the three Landsat sensors. Second, atmospheric correction was performed using the Dark Object Subtraction (DOS-1) method to retrieve surface reflectance. Although more advanced radiative-transfer algorithms, such as the Second Simulation of the Satellite Signal in the Solar Spectrum (6S), can offer small gains in absolute reflectance accuracy, DOS-1 has been shown to yield consistent relative reflectance values well suited to multitemporal comparative analysis (Chavez, 1988; Song et al., 2001), where inter-date consistency matters more than absolute calibration. Third, residual clouds and cloud shadows were identified and masked using the quality-assessment (QA) band and manual screening, and the affected pixels were excluded from index computation. Fourth, each corrected scene was clipped to the administrative boundary of the study area to constrain the analysis to the Muara Angke coastal zone and to reduce computational load. The consistency of this preprocessing chain across all four time points ensures that observed variation in NDBI reflects real land-cover change rather than processing artefacts.

2.3 Data analysis methods

2.3.1 Multitemporal NDBI-based built-up area extraction

The analysis of spatial transformation proceeded in three linked steps: extraction of built-up land using the NDBI, multitemporal comparison of the resulting classifications, and statistical detection of change points in the built-up time series. Each step is described below. Built-up land was extracted using the Normalized Difference Built-up Index (NDBI), which exploits the contrasting spectral response of impervious surfaces in the shortwave-infrared (SWIR) and near-infrared (NIR) regions. Zha et al. (2003) showed that built-up surfaces reflect more strongly in the SWIR than in the NIR, yielding positive index values, whereas vegetation and water bodies, which are dominated by NIR reflectance, yield negative values. The index is defined as follow the Equation 1.

$$\text{NDBI} = \frac{\text{SWIR} - \text{NIR}}{\text{SWIR} + \text{NIR}} \quad (\text{Eq. 1})$$

The SWIR denotes surface reflectance in the shortwave-infrared band (Landsat TM/ETM+ band 5; OLI band 6) and NIR denotes surface reflectance in the near-infrared band (Landsat TM/ETM+ band 4; OLI band 5). The index is bounded on the interval $[-1, +1]$. The spectral logic is straightforward: impervious materials such as concrete, asphalt, and rooftops exhibit relatively high SWIR reflectance and moderate NIR reflectance, so the numerator (SWIR – NIR) is positive; healthy vegetation reflects strongly in the NIR, driving the numerator negative; and open water absorbs across both bands, likewise yielding negative values. Positive NDBI values therefore serve as an effective discriminator of built-up land.

The main advantages of NDBI are its computational simplicity, its transferability across sensors and dates, and its reduced dependence on subjective training-sample selection relative to supervised classification, which together make it well suited to consistent multitemporal monitoring (Zha et al., 2003; Xu, 2007). Its main limitation is spectral confusion between built-up surfaces and dry, bare, or exposed soils, which share similar

SWIR and NIR behaviour and can inflate built-up estimates in mixed environments (Oknisia & Nugraini, 2025). A related constraint stems from the 30 m resolution of Landsat data, at which sub-pixel mixing between built-up surfaces, fishpond embankments, and narrow vegetated strips may introduce boundary uncertainties, which is a recognised limitation of all medium-resolution multitemporal urban mapping (Schneider et al., 2010). To address these limitations in a varied coastal mosaic of settlements, fishponds, embankments, and wetlands, NDBI values were classified using adaptive thresholding, meaning that the built-up and non-built-up cut-off was selected from the pixel-value distribution of each individual year rather than by imposing a single fixed threshold across all dates. This approach accommodates inter-date differences in illumination and surface moisture. For boundary-ambiguous zones such as fishpond edges and dense coastal settlement fringes, supplementary visual interpretation against high-resolution imagery was undertaken to refine the classification. The NDBI-derived built-up maps for 1988, 2000, 2015, and 2025 then served as the basis for multitemporal change analysis and as the primary input to the Pettitt change-point test.

2.3.2 Multitemporal spatial change analysis

Spatial change was quantified by comparing the NDBI classification maps for the four reference years using a post-classification comparison technique, in which classified maps from successive periods are overlaid to identify land-use transitions, namely settlement expansion, fishpond conversion, densification, and changes in coastal structure. The overlay was executed in QGIS 3.30 to generate a change matrix expressing the magnitude and direction of land conversion within each interval. The analysis additionally examined morphological indicators, namely shifts in the built-up boundary, the development of the road network, and the expansion of reclaimed land, to distinguish horizontal (areal) growth from vertical densification and to characterise the changing configuration of the coastal edge.

2.3.3 Change-point analysis using the pettitt test

To identify the period at which the built-up trajectory changed structurally, the non-parametric Pettitt (1979) change-point test was applied to the time series of built-up land extent. The method was selected because it detects a shift in the central tendency of a series without assuming any particular distribution. This is an important property for coastal land-use series that fluctuate under the influence of planning policy, infrastructure intervention, reclamation, and socio-economic dynamics, and that may therefore be non-normal, unevenly spaced, and outlier-prone. The Pettitt test is based on the Mann-Whitney statistic and evaluates every possible partition of the series to locate the single most probable change point. Formally, for a time series $x_1, x_2, \dots, x_n$ of length n , the Pettitt statistic U_t is computed at each candidate position t as the running sum of the signs of the pairwise differences between observations:

$$U_t = \sum_{i=1}^t \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (\text{Eq. 2})$$

where the sign function is defined as:

$$\text{sgn}(x_j - x_i) = \begin{cases} +1, & \text{if } x_j - x_i > 0 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 0 \end{cases} \quad (\text{Eq. 3})$$

The most probable change point corresponds to the position at which the absolute value of U_t attains its maximum over the series. The Pettitt test statistic K_t is therefore defined as:

$$K_t = \max_{1 \leq t \leq n} |U_t| \quad (\text{Eq. 4})$$

The statistical significance of the detected change point is then approximated by the associated probability:

$$p \approx 2 \exp\left(\frac{-6K^2}{n^3 + n^2}\right) \quad (\text{Eq. 5})$$

where U_t is the Pettitt test statistic at observation time t ; K_t is the maximum absolute value of U_t across all candidate positions, expressing the magnitude of the largest change in the series and identifying the location of the change point; t is the observation-time index ($t = 1, 2, \dots, n$); n is the total number of observations in the series; i and j are the first and second observation indices, respectively; x_i and x_j are the observed built-up land values at times i and j ; and $\text{sgn}(x_j - x_i)$ is the sign function used to compare the observations x_i and x_j . A change point is deemed statistically significant when $p \leq 0.05$, in which case the series is interpreted as containing a structural shift, that is, a phase of acceleration or slowing in built-up growth.

The interpretation is intuitive: because U_t accumulates the sign of every pairwise difference across a candidate split, it grows in magnitude wherever observations on one side of the split are systematically larger (or smaller) than those on the other; the position of maximum $|U_t|$ thus marks the point of greatest divergence between the two sub-periods. The Pettitt test is appropriate for the present study for three reasons: it requires no distributional assumptions and so accommodates the irregular, policy-driven character of coastal land-use series; it is comparatively robust to outliers, which are common where reclamation or infrastructure projects produce abrupt jumps; and it locates a single dominant change point, yielding an objective and replicable periodisation rather than one imposed by visual judgement. In this study, the input series comprised the built-up land extents derived from NDBI extraction for 1988, 2000, 2015, and 2025, and the statistics in Equations (2) to (5) were computed using the pyhomogeneity module in Python, which implements the Pettitt procedure and returns the change-point location, the K statistic, and the associated p -value. The change-point result thereby links the NDBI mapping to the multitemporal change analysis, grounding the periodisation of transformation in a transparent statistical foundation.

2.4 Verification and validation

Verification of the classification was conducted through visual inspection against high-resolution Google Satellite imagery for each reference year, assessing the spatial agreement between the mapped built-up class and the observable ground condition. Validation proceeded through cross-source triangulation, comparing the classification with spatial-planning maps, government technical reports, and published studies documenting shoreline and land-use change along the North Jakarta coast. This triangulation strengthens confidence that the land-change patterns detected from satellite imagery are consistent with the documented physical development of the area. Validation further included an assessment of temporal-trend consistency: the correspondence between the statistically identified change point and independently recorded episodes of faster construction, namely port modernisation, fishpond conversion, and built-up expansion, provides supporting evidence that the built-up time series has empirical validity.

With respect to quantitative accuracy assessment, a formal, sample-based confusion-matrix evaluation, which reports overall accuracy, producer's and user's accuracies, and the Cohen's kappa coefficient against an independent set of reference points, was not carried out for the NDBI classifications in this study, mainly because spatially and temporally

matched ground-reference data for the earlier acquisition dates (1988 and 2000) are unavailable, and retrospective field verification for those years is not feasible. For transparency, these values are not estimated or reported here, since doing so without an independent reference sample would misrepresent the evidence behind the classification. It should be emphasised that the accuracy figures cited earlier (for example, 92.6 % in Zha et al., 2003, and 92.8 % in Karanam, 2018) pertain to the general performance of the NDBI method reported in the literature and are not measures of the accuracy of the present classifications. The reliability of the classification here therefore rests on the qualitative and semi-quantitative procedures described above: adaptive, year-specific thresholding; cross-validation of boundary-ambiguity zones against high-resolution imagery; and confirmation of major land-cover transitions against historical aerial photography and official spatial-plan documents. These procedures confirm that the main transitions identified from NDBI mapping are consistent across independent sources. Future implementations of this framework should include a formal accuracy assessment for current dates by constructing a stratified random sample of reference points from very-high-resolution imagery or field survey and reporting overall accuracy and kappa, so as to attach clear confidence bounds to the built-up estimates and to strengthen the quantitative validation of long-term coastal change mapping.

3. Results and Discussion

3.1 Results

Results This section reports the empirical findings on built-up land dynamics derived from multitemporal NDBI processing and the associated change-point analysis, and then interprets them in relation to theory, the international literature, and coastal policy. Multitemporal NDBI analysis shows that the coastal landscape of Muara Angke underwent intensive physical transformation between 1988 and 2025. Total built-up land increased from 26.43 ha in 1988 to 86.11 ha in 2025, a cumulative rise of 225.8 %. This expansion reflects a fundamental shift in the dominant surface cover, from fishponds, swamps, and wetlands toward high-density built-up land. Figure 2 presents the NDBI-derived built-up classifications for the four reference years, and Table 1 summarises the decadal changes.

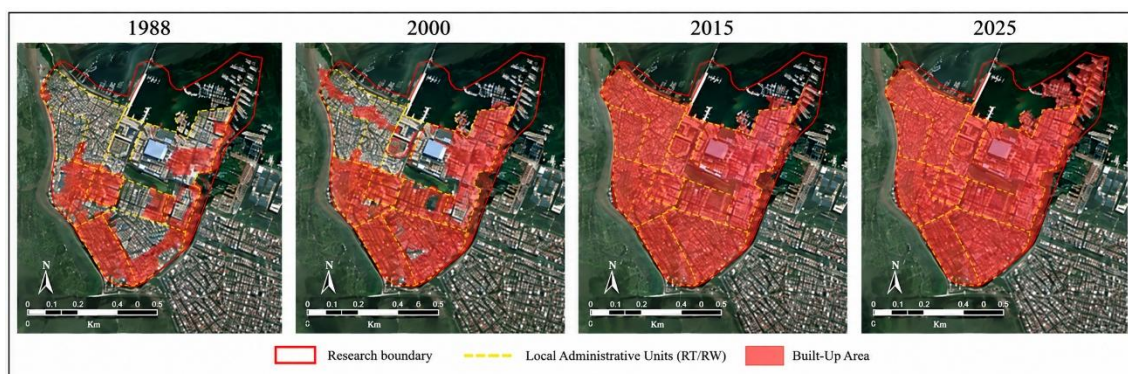


Fig. 2. Multitemporal NDBI-derived built-up land classifications for Muara Angke, 1988, 2000, 2015, and 2025

As Table 1 shows, the largest absolute and proportional expansion occurred during 2000 to 2015, when built-up land increased by 25.69 ha (52 % over the period). The interval 2015 to 2025 registered a smaller areal increase of 10.99 ha (15 %). Yet, as the spatial pattern below makes clear, this phase was marked by intensive densification rather than slowed transformation, with corresponding implications for the ecological quality of the coast. Taken together, the decadal figures indicate a shift in the developmental orientation of the area from subsistence-oriented activity toward more intensive commercial and infrastructural use.

Table 1. Changes in built-up land area per decade, Muara Angke, 1988 to 2025.

Year	Built-up land (ha)	Increase in period (ha)	Growth rate per period	Cumulative growth from base
1988	26.43	n/a	n/a	n/a
2000	49.43	23.00	87 %	87 %
2015	75.12	25.69	52 %	184 %
2025	86.11	10.99	15 %	226 %

The initial period (1988 to 2000) was marked by limited settlement growth that expanded linearly along the main road network in the southern part of the area. Such linear expansion is a common signature of early coastal urbanisation, preceding the shift toward cluster-based built-up growth induced by coastal economic pressure and rising port activity (Yılmaz & Terzi, 2020; Zhao et al., 2017). Throughout this phase, the northern and western portions of the area remained dominated by fishponds functioning simultaneously as ecological space and as space for fishing activity. The subsequent conversion of these fishponds and shallow-water zones into built-up land mirrors a pattern widely observed in Asian coastal cities experiencing the intensification of port and logistics functions (Yan et al., 2021; Ren et al., 2025).

During 2000 to 2015, fishpond conversion accelerated markedly, generating new built-up clusters in the central and north-eastern parts of the area. This development is consistent with the intensification of port activity and the expansion of coastal economic functions. As the literature on maturing coastal areas anticipates, growth in this phase began to shift from areal expansion toward densification and more structured spatial intervention, including small-scale reclamation, in response to land scarcity and mounting metropolitan urbanisation pressure (Ji et al., 2025; Zhang et al., 2025; Cutajar, 2022).

The most recent period (2015 to 2025) exhibits a qualitatively distinct character. Although the quantitative increase in built-up land was comparatively modest (10.99 ha), the emergent growth pattern is denser and more concentrated. Densification, together with expansion into shallow-water areas, signals the occurrence of small-scale reclamation and more structured development intervention along the coastal edge. In other words, the slowing of areal growth conceals an intensification of spatial and ecological pressure rather than a genuine deceleration of transformation.

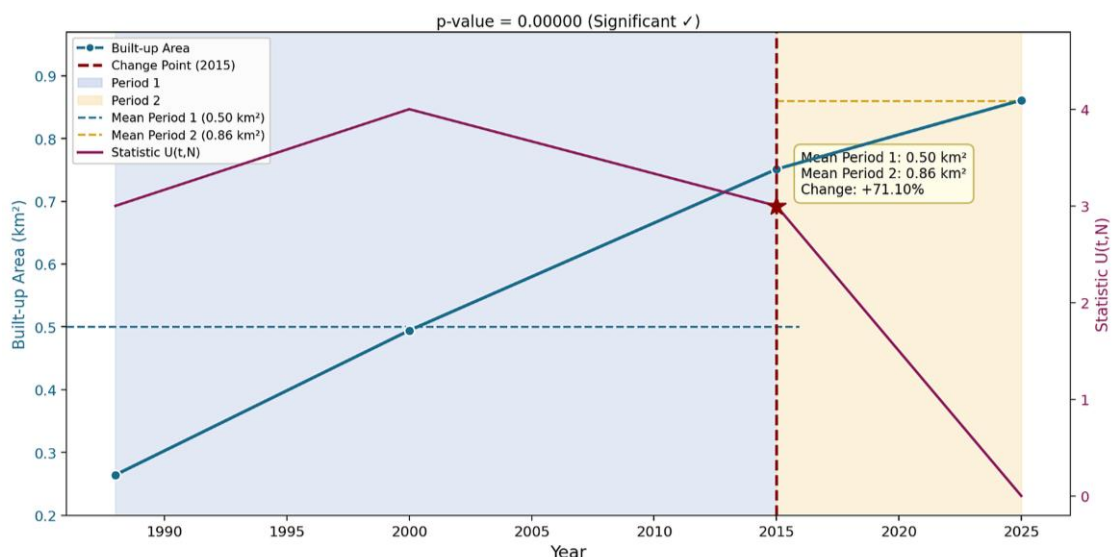


Fig. 3. Results of the Pettitt change-point detection test on the built-up land time series, with the structural break located in 2015

The Pettitt change-point test identifies the period at which the built-up growth trajectory changed structurally. The test locates a statistically significant break in 2015 ($p \approx 0.000$), marking the turning point of spatial development in Muara Angke, after which the

rate of built-up growth increased sharply (Figure 3). The mean built-up extent before 2015 was approximately 0.50 km², associated with gradual, organic development characteristic of the fishing settlement. After 2015, the mean extent rose to approximately 0.86 km², an increase of 71.1 % relative to the preceding period. This surge coincides with the start of several strategic infrastructure initiatives, including the modernisation of the fishing port, the construction of cold-storage facilities, and the expansion of the transport network along the North Jakarta coast.

The identification of 2015 as the structural change point indicates that the development of Muara Angke did not proceed gradually but underwent a relatively abrupt shift in its growth regime. This transitional phase was accompanied by intensifying urban-development pressure, changes in spatial function, and a simultaneous weakening of the ecological capacity of the North Jakarta coast. The statistical result thus provides an objective temporal anchor for the periodisation developed qualitatively above, and forms the empirical pivot for the discussion that follows.

3.2 Discussion

The results invite interpretation on four connected registers: the theoretical significance of the observed shift in the nature of coastal space; its ecological implications; its social consequences and their bearing on spatial justice; and the governance and policy context within which the 2015 change point is situated. Throughout, the findings are read against the international literature to establish where they concur with, and where they extend, existing knowledge.

The spatial transformation of Muara Angke reflects a fundamental transition from a space shaped through local community practice to one increasingly governed by economic and investment logic. In Castell (2004) terms, this is a movement from a space of places toward a space of flows, in which the coast functions less as a container for community-based social interaction and more as a medium for capital accumulation and the circulation of wider-scale economic activity. The pattern echoes the dynamics of coastal areas in many developing cities, where infrastructure intervention and investment become the primary drivers of spatial-structural change, particularly where coastal zones are integrated into regional and global economic networks (Seto et al., 2012; Krisnanta et al., 2025; Amalia, 2024). The temporal evidence reinforces this reading: before 2015, built-up growth still expressed the character of a fishing settlement bound to production functions and community activity, whereas after 2015 the acceleration of change was driven by infrastructure and coastal-industrial activity. This is consistent with findings that coastal infrastructure development frequently triggers structural land-use change and the intensification of urbanisation, especially where connectivity and large-scale investment increase (Neumann et al., 2015; Chen et al., 2023; Wahid & Mushref, 2026).

From an ecological standpoint, the marked decline in non-built-up land, which exceeds 30 % over the last two decades, points to a weakening of the area's capacity to absorb water and to buffer coastal flooding. The loss of traditional fishponds and coastal wetlands directly degrades ecosystem services (Yu et al., 2025), particularly the natural protection they afford against tidal flooding and seawater intrusion, and it interacts with the region's severe land subsidence to compound flood risk (Wurjanto et al., 2023; Kawata, 2022). The degradation of mangrove and wetland habitat further erodes the ecological integrity of the coast and its associated biodiversity (Yuliantri et al., 2024). The inverse relationship between built-up expansion and ecological function documented here is consistent with international coastal studies showing that unchecked coastal urbanisation tends to sacrifice wetlands and natural open space (Wang et al., 2023; Chen et al., 2023). In this respect the Muara Angke case concurs with, rather than departs from, the broad international evidence; its contribution is to date the ecological turning point precisely and to link it to an identifiable phase of infrastructure-led development.

The reshaping of spatial structure has also changed the relationship of the fishing community to its production and living space. Declining access to productive coastal space

has weakened the community's economic base and heightened its socio-economic vulnerability, producing a process of social and spatial dislocation in which physical change is not matched by any strengthening of local social capacity (Relph, 1976; Soja, 2010). Coastal research indicates that such dislocation frequently arises as an indirect consequence of infrastructure-based development and coastal industrialisation that privilege spatial efficiency over social sustainability (Chen et al., 2023). This vulnerability is evident in the livelihood literature: Saha et al. (2024) show that the livelihood vulnerability of coastal communities is governed by the combination of exposure to environmental hazards, sensitivity to changes in natural resources, and limited adaptive capacity. These conditions are closely mirrored in Muara Angke, where the reduction of productive space for fishers heightens structural livelihood risk. Consistent with Nugraha et al. (2020), the intensification of port and logistics activity around 2015 sharpened conflicts over coastal space and curtailed fishers' access to both production and living space.

These consequences are best understood through the lens of spatial justice (Soja, 2010; Harvey, 2008), which highlights both the distribution of socially valued resources across urban space and the meaningful participation of affected communities in decisions that shape it. In Muara Angke, the transformation documented here reflects a systematic spatial injustice: the households most exposed to the adverse effects of built-up expansion, that is, fishers whose livelihoods depend on the coastal environment, have been least involved in the planning processes that authorised that expansion. The displacement of fishponds and wetlands, the restriction of coastal access by port infrastructure, and densification without matching gains in ecological resilience together indicate a governance structure in which economic rationality has repeatedly taken precedence over social and ecological equity.

The temporal concentration of change around 2015 is particularly significant when read against the national policy environment. This period coincides not only with intensified infrastructure investment in North Jakarta but also with a broader political and economic context in which national development priorities, expressed through Indonesia's National Strategic Project/*Proyek Strategis Nasional* framework, accelerated investment in port, logistics, and coastal-industrial infrastructure across the archipelago (Firman, 2017). The alignment between this policy environment and the statistically identified change point suggests that local spatial dynamics in Muara Angke cannot be understood in isolation from national-scale regulatory and investment decisions. The development pathway also produced an uneven distribution of impacts across actors: the industrial and logistics sectors benefited from improved infrastructure and accessibility, while fishing communities faced shrinking production space, rising environmental risk, and constrained adaptation options. This asymmetry accords with the findings of Lautetu et al. (2022) and with international coastal research confirming that investment-driven coastal urbanisation tends to generate an uneven distribution of benefits across social groups (Krisnanta et al., 2025; Wang et al., 2023). Future research should trace the specific policy instruments and institutional channels through which national development priorities translate into localised spatial outcomes, with particular attention to their distributional consequences.

Theoretically, the Muara Angke case substantiates the proposition that coastal spatial transformation is non-linear and phase-structured rather than incremental, and it shows the analytical value of coupling spatial-transformation theory (Yunus, 2008; Castells, 2004) with a socio-ecological-systems reading (Ostrom, 2009) and a spatial-justice critique (Soja, 2010). The identification of a single dominant structural break lends empirical weight to the idea that infrastructure and policy act as triggering forces in coastal development. Practically, the findings caution that conventional monitoring focused on areal growth may misread periods of apparent slowdown, such as 2015 to 2025, that in fact hide intensifying densification and ecological pressure. Effective coastal planning must therefore attend not only to how much built-up land expands but to how its configuration and ecological footprint evolve. In sum, the physical transformation of Muara Angke cannot be separated from its social and ecological implications: the post-2015 structural shift represents a phase in which planning policy and infrastructure investment became the primary drivers of transformation while simultaneously repositioning coastal communities from primary

agents of space to an increasingly marginalised group. These findings affirm the need for a coastal planning approach oriented not solely toward physical growth but toward the socio-ecological sustainability of the area (Chen et al., 2023; Wang et al., 2023).

4. Conclusions

This study quantified the four-decade trajectory of built-up land expansion in Muara Angke from 1988 to 2025 and identified the period in which this trajectory underwent a structural shift. Built-up land increased from 26.43 ha to 86.11 ha, representing a 225.8% increase across three phases: organic settlement expansion (1988–2000), accelerated development associated with infrastructure and spatial intensification (2000–2015), and continued consolidation through densification and coastal spatial transformation (2015–2025). The Pettitt test identified 2015 as a statistically significant change point, after which mean built-up extent increased by 71.1%. These findings demonstrate that coastal spatial transformation in Muara Angke has been non-linear and phase-structured. The apparent reduction in the rate of areal expansion after 2015 should therefore not be interpreted as a decline in transformation, but rather as a shift toward greater densification within an increasingly constrained and environmentally vulnerable coastal space.

Viewed through the lens of Sustainable Development Goal 11, the observed pattern of growth raises significant concerns regarding the sustainability and resilience of current spatial development. The conversion of wetlands and fishponds, which historically functioned as natural flood buffers, has reduced the settlement's adaptive capacity in an area increasingly exposed to land subsidence and tidal flooding. At the same time, fishing households whose livelihoods are closely connected to the coastal environment have had limited influence in shaping the spatial changes affecting their settlement. Advancing SDG 11 in Muara Angke therefore requires spatial planning that limits further conversion of ecological land, protects and restores wetlands and fishponds through nature-based and green infrastructure, and strengthens the participation of fishing communities as active stakeholders in coastal planning. Methodologically, the reproducible NDBI–Pettitt workflow demonstrated in this study provides a relatively low-resource approach for identifying long-term spatial change and its structural turning points, offering a practical monitoring framework for coastal settlements where historical spatial data remain limited.

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Author Contribution

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During the preparation of this work, the author used Grammarly to assist in improving the grammar, clarity, and academic tone of the manuscript. After using this tool, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

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