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Original Article

Analysis of The Direction and Intensity of Coastal Built Up Land Expansion Using Sentinel-2 Imagery (Case Study of Central Ternate)

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Abstract

Ternate City is one of the cities located on an island in Indonesia with distinctive regional development characteristics due to land space limitations and the influence of coastal areas as the center of city activities. Population growth, increased economic activity, and the accumulation of government and trade functions have driven the expansion of increasingly dense built-up areas in coastal areas. This study aims to analyze the direction and intensity of built-up area growth in the coastal area of Central Ternate District from 2019 to 2024 by utilizing Sentinel-2 imagery processed through the Google Earth Engine (GEE) platform. The techniques used include the Normalized Difference Built-up Index (NDBI) to identify built-up areas, the Normalized Difference Vegetation Index (NDVI) to observe changes in vegetation, and the Land Mask to separate land and water areas. The results of the analysis show that the built-up area increased from 646.10 hectares in 2019 to 720.84 hectares in 2024, with the expansion of new urban areas reaching 146.86 hectares. The growth of built-up areas tends to be concentrated in the eastern and southeastern parts of the coast, which have high accessibility and function as centers of economic and government activities. Space constraints due to Ternate Island's topography have led to urban development following coastal corridors rather than inland areas. These findings indicate that urbanization in Central Ternate is occurring rapidly and requires sustainable spatial management to maintain a balance between development and the coastal environment.

Keywords: Land Expansion, Sentinel-2, GIS, GEE

INTRODUCTION

Urban expansion is a fundamental manifestation of demographic growth, economic development, infrastructure investment, and increasing demand for land to accommodate residential, commercial, institutional, and public-service functions. The process is particularly important in geographically constrained urban areas because the availability of developable land is often limited, causing changes in land use to occur more intensively in locations that provide better accessibility and relatively favorable physical conditions. Remote sensing studies have demonstrated that the transformation of non-built-up surfaces into built-up areas can be effectively monitored through multitemporal satellite imagery, allowing the spatial extent and direction of urban growth to be identified systematically (Zha et al., 2003; Xu, 2008). In rapidly developing urban regions, such information is important because urban expansion is not simply a physical increase in buildings but also represents a transformation of vegetation, open land, hydrological conditions, and the ecological functions of urban landscapes. These challenges become more pronounced in island cities, where the interaction between limited land availability, complex topography, coastal environments, and increasing urban demand produces distinctive patterns of spatial development. Unlike many mainland cities that can expand horizontally toward relatively extensive hinterlands, island cities frequently face stronger physical constraints that influence the direction and intensity of urban expansion. Recent research on island urbanization in Indonesia shows that geographical context and limited environmental carrying capacity can strongly

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influence the spatial trajectory of urban growth and land-cover transformation. In Sofifi, North Maluku, for example, urban expansion has been associated with substantial conversion of vegetation into built-up land, with development initially concentrated in coastal areas and subsequently extending inland in association with road networks and government facilities (Aginda et al., 2025). This island-city context is particularly relevant for Ternate, where the availability of developable land is strongly influenced by the island's volcanic morphology.

Ternate City is an important urban center in North Maluku Province and has historically functioned as a regional center for government, trade, services, education, transportation, and other socioeconomic activities. The concentration of these functions generates continuous demand for residential and non-residential land. Previous research specifically examining Central Ternate District has identified population growth and urbanization as important factors influencing land demand and changes in land cover, with increasing residential development expected to continue as population and urban activity increase (Latue & Rakuasa, 2023). The spatial dynamics of Ternate are therefore closely associated with the relationship between demographic pressure and the limited capacity of the island to accommodate additional development. This situation makes Ternate an important case for examining how urban expansion occurs when the demand for land increases within a geographically restricted island environment. The physical characteristics of Ternate further strengthen this condition. Ternate is a volcanic island dominated by Mount Gamalama, resulting in a landscape characterized by considerable topographic variation from the coastal zone toward the interior. The steep and undulating terrain limits the availability of relatively flat land that is suitable and accessible for intensive urban development. Consequently, urban activities have historically been concentrated in areas with greater accessibility and comparatively favorable terrain, particularly along the coastal belt. Recent spatial analysis confirms that topography and slope have become increasingly relevant to the distribution of built-up land in Ternate, with development pressure extending into areas with increasingly challenging slope conditions (Rifai et al., 2025). This condition indicates that the spatial structure of Ternate cannot be understood solely from demographic or economic factors; rather, urban expansion is produced through the interaction between socioeconomic demand, transportation accessibility, topographic constraints, and the availability of developable land. The concentration of urban development along the coast consequently creates a particular form of land-use transformation. Coastal areas provide relatively accessible and comparatively flat spaces for residential settlements, commercial activities, transportation infrastructure, public facilities, and other urban functions. However, the same areas also perform important ecological and hydrological functions. The conversion of vegetated or open surfaces into impervious built-up land can reduce infiltration capacity, alter surface runoff, fragment vegetation, and increase pressure on coastal ecosystems. This concern is increasingly evident in Ternate Island. A recent assessment of land-use effects on Ternate's water resources found substantial growth of built-up areas between 2009 and 2023 accompanied by a reduction in forest cover, highlighting the potential relationship between urbanization, land-cover transformation, groundwater recharge, and water-resource sustainability. Thus, the expansion of built-up land in Ternate should be considered not only as an indicator of urban development but also as an important environmental process requiring spatial monitoring.

Evidence from Central Ternate further demonstrates that land-cover transformation is already occurring at a substantial scale. Latue and Rakuasa (2023) reported that Central Ternate has experienced extensive urban development associated with population growth, urbanization, and increasing demand for residential land. Their analysis emphasized that continued urban growth could create a disparity between land demand and land availability while reducing environmental carrying capacity. Similarly, analysis of Ternate Island using high-resolution satellite imagery identified an increase in built-up land from 15.19% of the island's area in 2013 to 19.69% in 2023, indicating a continuing process of urban land transformation. These findings provide an important empirical context for examining more recent urban expansion in Central Ternate, particularly during the 2019–2024 period. The transformation of coastal land is also consistent with broader evidence from Indonesian urban areas. Recent research has demonstrated that the combination of Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), and water-related indices can be used to identify spatial relationships between vegetation decline, urban expansion, and coastal land-cover transformation. For example, research in coastal Tangerang integrated Sentinel-2 imagery with NDVI, NDBI, and NDWI to

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distinguish vegetation, built-up areas, and water bodies during a period of rapid coastal land-cover change. Such an integrated approach is particularly appropriate for Ternate because the urban landscape is characterized by close spatial interaction between built-up land, vegetation, and coastal water. Separating these components is necessary to avoid interpreting water surfaces or vegetated land as urban development and to obtain a more reliable representation of the spatial extent of built-up areas.

Remote sensing provides an effective framework for addressing these issues because it enables repeated observation of land-cover conditions across relatively large areas without requiring extensive field measurements. The NDBI has been widely applied to extract built-up surfaces from multispectral satellite imagery by exploiting differences in spectral responses between built-up materials and other land-cover types (Zha et al., 2003). Xu (2008) subsequently developed the Enhanced Built-Up and Bareness Index approach to improve the discrimination of built-up land and bare surfaces, demonstrating that spectral-index approaches remain valuable but must be interpreted carefully because bare land and built surfaces can exhibit similar spectral responses. This limitation has encouraged the combined use of NDBI with vegetation indices and other contextual information rather than relying on NDBI alone. The NDVI provides complementary information by characterizing vegetation density and condition. The simultaneous interpretation of NDBI and NDVI enables changes in built-up surfaces to be examined alongside changes in vegetation cover, thereby providing a stronger basis for identifying potential conversion of vegetated land into urban surfaces. Recent Indonesian research has demonstrated the effectiveness of this combined approach for monitoring urban landscape change. Widiastuti et al. (2024), for example, used NDBI and NDVI to examine urban landscape dynamics in Surabaya and identified areas where increases in built-up surfaces coincided with vegetation decline. Likewise, research in Sleman demonstrated the usefulness of NDBI and NDVI for monitoring changes in built-up areas and vegetation while linking urban expansion with broader environmental changes (2024). These studies suggest that integrating built-up and vegetation indices can provide a more informative interpretation of urban transformation than examining built-up land independently.

The development of cloud-based geospatial platforms has further expanded the potential for multitemporal urban monitoring. Google Earth Engine (GEE) provides access to large collections of satellite imagery and cloud-based computational capabilities, allowing researchers to process, filter, composite, and analyze multitemporal datasets efficiently. Its application has increasingly been demonstrated in urban land-cover studies, including research in North Maluku. Aginda et al. (2025), for instance, integrated multitemporal satellite imagery, Google Earth Engine, supervised classification, and NDBI to investigate urban growth and land-cover transformation in Sofifi. Their findings demonstrated the usefulness of cloud-based remote sensing for understanding urban expansion in an island-city context. The application of GEE in the present study therefore provides both methodological efficiency and a reproducible framework for analyzing urban land transformation across different observation years. Despite the growing number of studies on urban growth in Ternate, an important research gap remains. Previous investigations have examined land-cover dynamics in Central Ternate using Cellular Automata–Markov modelling, analyzed land-cover changes at the island scale, and evaluated the relationship between topography and built-up land development. However, these studies have different analytical objectives and temporal frameworks. In particular, there remains a need for a focused assessment of the 2019–2024 spatial expansion of coastal built-up land in Central Ternate using an integrated NDBI–NDVI approach combined with land masking within the Google Earth Engine environment. Such an approach can provide more direct information about where built-up land has expanded and whether this expansion is spatially associated with changes in vegetation cover.

This gap is important because Central Ternate represents a particularly sensitive urban environment in which the availability of developable land is constrained by volcanic topography while socioeconomic activities remain concentrated in the coastal urban corridor. Consequently, understanding the direction and intensity of built-up expansion is necessary not only for documenting past land-cover change but also for supporting decisions concerning future spatial development. The issue is particularly relevant given evidence that urban development in Ternate has increasingly expanded beyond areas of favorable terrain, suggesting that continued land demand may progressively place pressure on environmentally sensitive and topographically constrained areas (Rifai et al., 2025). Moreover, the documented increase in built-up land and reduction of natural vegetation across Ternate Island reinforces the need for spatially explicit monitoring as a basis for maintaining environmental

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carrying capacity. Therefore, the novelty of this study lies in the integrated application of NDBI, NDVI, and land masking through Google Earth Engine to examine the spatial direction and intensity of coastal built-up land expansion in Central Ternate during 2019–2024. Rather than considering built-up growth solely as an increase in developed land, this approach places urban expansion within the broader context of vegetation transformation and the spatial constraints of an island city. The integration of these spectral indicators allows built-up surfaces to be distinguished more systematically from vegetation and water bodies, while multitemporal comparison provides an opportunity to identify the locations and directions of new urban development. This approach is consistent with the increasing use of integrated spectral-index methods for coastal and urban land-cover monitoring (Widiastuti et al., 2024; Hikmah & Manurung, 2025).

Accordingly, this study aims to analyze the spatial direction and intensity of coastal built-up land expansion in Central Ternate District, Ternate City, during the 2019–2024 period using Sentinel-2 imagery processed through Google Earth Engine. Specifically, the study seeks to identify the spatial distribution of built-up areas, examine changes in vegetation and built-up surfaces through NDBI and NDVI, and determine the locations and patterns of newly developed built-up land. The results are expected to provide spatially explicit evidence that can support sustainable spatial planning, particularly in managing development pressure within the limited and environmentally sensitive land resources of Ternate as an island city.

MATERIALS AND METHODS

This study employed a quantitative spatial approach combining remote sensing and Geographic Information System (GIS) techniques to examine coastal built-up land expansion in Central Ternate District, Ternate City, North Maluku Province, Indonesia. The study area represents one of the main urban centers of Ternate City, where residential, commercial, service, transportation, and other urban functions are concentrated. The analysis focused on changes in built-up land between 2019 and 2024, with particular attention to the spatial distribution and direction of urban expansion. The use of remotely sensed imagery was considered appropriate because satellite observations provide consistent spatial coverage and allow land-cover characteristics to be examined across different observation periods. Sentinel-2 is particularly suitable for this purpose because its Multispectral Instrument (MSI) provides 13 spectral bands, including four bands at 10 m spatial resolution, and systematically covers terrestrial and coastal areas. The Sentinel-2 constellation also provides a five-day revisit capability under nominal conditions, supporting multitemporal land-cover analysis (European Space Agency [ESA], 2026). The primary dataset consisted of Sentinel-2 imagery for 2019 and 2024 accessed and processed through the Google Earth Engine (GEE) platform. GEE was selected because it provides access to a large catalog of analysis-ready satellite data and enables computationally intensive geospatial processing through cloud-based infrastructure (Gorelick et al., 2017). The imagery was subjected to preprocessing before spectral indices were calculated. The preprocessing procedure included selecting images with relatively low cloud contamination, applying cloud and cloud-shadow masking where necessary, clipping the imagery to the administrative boundary of Central Ternate District, and generating representative image composites for each observation year. The use of comparable preprocessing procedures for both years was intended to minimize differences caused by image quality and atmospheric or observational conditions rather than actual land-cover change. Because the study focuses on terrestrial urban expansion in a coastal environment, a land mask was subsequently applied to exclude water surfaces from the built-up land analysis. This step was particularly important for Central Ternate because the study area directly borders the sea, and unmasked water pixels may introduce spectral confusion during the identification of urban surfaces.

Built-up land was extracted using the Normalized Difference Built-up Index (NDBI), originally developed to facilitate the identification of urban and built-up surfaces from multispectral satellite imagery (Zha et al., 2003). The NDBI exploits the contrasting spectral response of built-up surfaces in the Short-Wave Infrared (SWIR) and Near-Infrared (NIR) regions. For Sentinel-2 imagery, Band 11 was used as the SWIR band and Band 8 as the NIR band. The index was calculated using the following expression:

$$\mathbf{NDBI = (SWIR - NIR) / (SWIR + NIR)}$$

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where SWIR represents Sentinel-2 Band 11 and NIR represents Sentinel-2 Band 8. Higher positive NDBI values generally indicate surfaces with spectral characteristics associated with buildings, roads, and other impervious urban features, whereas lower or negative values are more commonly associated with vegetation and other non-built surfaces. The NDBI outputs for 2019 and 2024 were subsequently interpreted spatially to identify the distribution of built-up surfaces and their changes over time. Because NDBI values may also respond to exposed or bare surfaces, the index was not interpreted independently but was integrated with vegetation information and the land mask to reduce potential misclassification.

Vegetation cover was characterized using the Normalized Difference Vegetation Index (NDVI). NDVI is widely used in remote sensing to distinguish vegetated surfaces based on the strong contrast between vegetation reflectance in the NIR and red spectral regions. For Sentinel-2 imagery, Band 8 was used as the NIR band and Band 4 as the red band. The NDVI was calculated as:

$$\mathbf{NDVI = (NIR - Red) / (NIR + Red)}$$

where NIR represents Band 8 and Red represents Band 4. Higher NDVI values indicate relatively dense and healthy vegetation, while lower values generally indicate sparse vegetation, exposed land, impervious surfaces, or water. The NDVI information was used as supporting evidence for interpreting changes in built-up areas. In particular, areas showing an increase in NDBI accompanied by a decline in NDVI were interpreted as potential locations where vegetated or relatively open surfaces had been transformed into built-up land. Following the generation of the NDBI and NDVI layers, the classified built-up maps for 2019 and 2024 were compared using spatial overlay analysis. The overlay procedure was used to identify areas that remained built-up, areas that remained non-built-up, and areas where non-built-up land was converted into built-up surfaces during the observation period. The spatial distribution of newly developed areas was then examined to determine the dominant direction and pattern of urban expansion within Central Ternate. This analysis also allowed the relationship between urban expansion and existing accessibility structures, particularly major transportation corridors and coastal development zones, to be examined spatially.

The extent of built-up land was quantified for each observation year in hectares. The net change in built-up area was calculated by subtracting the built-up area in 2019 from the corresponding area in 2024:

$$\mathbf{\Delta BA = BA_{2024} - BA_{2019}}$$

where ΔBA represents the net change in built-up area, BA_{2024} represents the built-up area in 2024, and BA_{2019} represents the built-up area in 2019. The percentage change was subsequently calculated as:

$$\mathbf{Percentage\ Change = [(BA_{2024} - BA_{2019}) / BA_{2019}] \times 100}$$

The combination of NDBI, NDVI, land masking, and multitemporal overlay provided an integrated framework for identifying not only the quantitative increase in built-up land but also its spatial context. The approach is particularly relevant for island and coastal cities such as Ternate, where the availability of developable land is geographically constrained and urban expansion may increasingly interact with coastal and vegetated environments. The cloud-based processing capability of GEE further facilitates the reproducibility and efficiency of this workflow by allowing satellite image selection, preprocessing, spectral-index calculation, masking, and spatial comparison to be conducted within a single analytical environment (Gorelick et al., 2017).

RESULTS AND DISCUSSION

The analysis of Sentinel-2 imagery using the Normalized Difference Built-up Index (NDBI) demonstrates a clear expansion of built-up land in Central Ternate District between 2019 and 2024. The total built-up area increased from 646.10 ha in 2019 to 720.84 ha in 2024, representing a net increase of 74.74 ha or approximately 11.57% over the five-year observation period. This increase indicates that the physical development of Central Ternate has continued to intensify, particularly in locations with favorable accessibility and relatively suitable physical conditions for urban development. The observed

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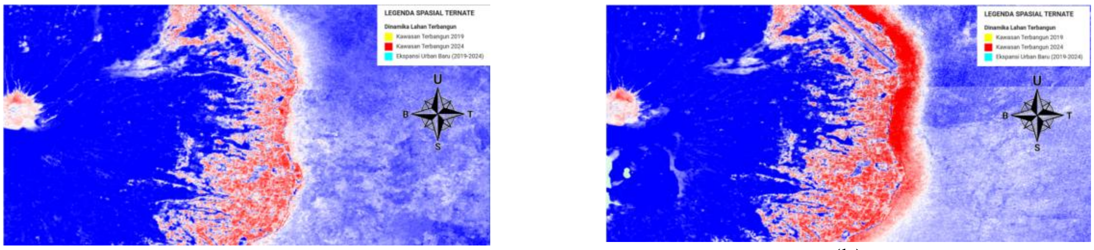
expansion is consistent with the broader dynamics of land-cover transformation in Ternate, where increasing urban activities and population pressure have contributed to the growth of built-up land. Latue and Rakuasa (2023) found that urban growth in Ternate Tengah has been accompanied by significant land-cover changes, particularly the expansion of settlement areas. Similarly, Rakuasa and Pakniany (2023) emphasized that increasing urbanization in Ternate Tengah has generated growing pressure on the availability of land for settlement and other urban functions.

Table 1. Built-up Area Analysis in Central Ternate

Category	Area (ha)	Percentage (%)
Built-up Area (2019)	646.10	89.63
Built-up Area (2024)	720.84	100.00
New Urban Area	146.86	20.37
Built-up Land Growth (2019–2024)	74.74	11.57

The increase in built-up land should not be interpreted simply as an increase in the physical size of settlements. It represents a broader transformation of the urban landscape associated with the expansion of residential areas, commercial activities, government facilities, public services, transportation infrastructure, and other urban functions. Central Ternate occupies an important position within the urban system of Ternate City because administrative, economic, commercial, and service activities are concentrated within this district. Consequently, the demand for strategically located land continues to increase. According to Latue and Rakuasa (2023), the expansion of settlement areas in Ternate Tengah is closely related to urban growth and increasing demand for land. This condition demonstrates that the transformation identified in the present study is part of a broader urbanization process rather than an isolated land-cover phenomenon.

The application of NDBI provides an effective means of identifying this transformation because the index exploits the spectral differences between the Near Infrared (NIR) and Short-Wave Infrared (SWIR) bands to distinguish built-up surfaces from other land-cover types. The original NDBI approach developed by Zha et al. (2003) demonstrated that the index could effectively identify urban and built-up areas from multispectral satellite imagery. In the present study, increasing NDBI values between 2019 and 2024 correspond spatially with the expansion of classified built-up areas. Therefore, the multitemporal NDBI analysis provides an indication of the direction and spatial concentration of physical urban development in Central Ternate.



(a) (b)

Figure 1. NDBI Map: (a) 2019; (b) 2024

The 2019 NDBI distribution shows that built-up areas were primarily concentrated along the eastern coastal zone of Central Ternate. High NDBI values corresponded mainly with established settlements, major roads, commercial areas, and other developed surfaces. Meanwhile, the central and western portions of the study area were characterized by relatively lower NDBI values and were dominated by vegetation and undeveloped land. This spatial differentiation is strongly associated with the physical morphology of Ternate Island. The presence of Mount Gamalama creates substantial topographic constraints for urban development, particularly because extensive portions of the island are characterized by sloping terrain. Consequently, relatively flat and accessible coastal areas have become important locations for settlement and urban activities. The relationship between topography and urban expansion is particularly important for understanding the spatial pattern identified in this study. Urban development is generally influenced by the availability, accessibility, and physical suitability of land. In an island environment, these factors become even more important because the supply of developable land is inherently constrained. Rakuasa and Pakniany (2023) demonstrated that land-cover changes in

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Ternate Tengah are spatially related to urban development pressures and the limited availability of land. The findings of the present study reinforce this argument by showing that built-up land is concentrated in the eastern coastal corridor, while the mountainous interior remains relatively less developed. The 2024 NDBI map further confirms the continuation of this development pattern. Compared with 2019, areas characterized by high NDBI values became more extensive and spatially continuous. The expansion was particularly visible in the eastern and southeastern coastal areas, where existing settlements were progressively surrounded by newly developed surfaces. This indicates that urban development occurred through both outward expansion and spatial intensification. Existing urban areas appear to function as development nuclei from which new settlements and other urban functions progressively expanded. Such a pattern is consistent with the general dynamics of urban growth, in which areas with existing infrastructure and established economic activities tend to attract subsequent development.

Figure 2. Urban Expansion, 2019–2024

The concentration of new development along transportation corridors provides further evidence that accessibility plays an important role in shaping urban expansion. Newly developed built-up areas were frequently located adjacent to existing road networks and major activity centers. Transportation infrastructure increases accessibility, reduces travel constraints, and enhances the attractiveness of locations for residential, commercial, and service activities. This relationship between accessibility and urban development is also reflected in the spatial development of Ternate, where coastal areas with stronger infrastructure connectivity have experienced greater development pressure. Fauzi (2023) showed that the development of waterfront areas in Ternate has contributed to changes in the spatial structure of settlements, particularly in areas connected to coastal urban activities. The overlay analysis provides additional evidence regarding the magnitude and spatial characteristics of urban expansion. The analysis identified 146.86 ha of newly developed urban land during the 2019–2024 period. These areas represent locations that were not classified as built-up in 2019 but were identified as built-up in 2024. Spatially, the newly developed areas were concentrated primarily along the eastern and southeastern coastal corridor. Their proximity to commercial centers, government facilities, residential areas, and transportation networks suggests that the expansion was strongly influenced by existing urban functions. This pattern is consistent with the findings of Latue and Rakuasa (2023), who identified continuing settlement expansion in Ternate Tengah as an important component of land-cover transformation.

An important point that emerges from the quantitative analysis is the difference between the 74.74 ha net increase and the 146.86 ha newly developed area. The 74.74 ha value represents the difference between the total built-up areas in 2019 and 2024, whereas 146.86 ha represents the gross area identified through the spatial overlay as having changed from non-built-up to built-up. Therefore, these two measurements describe different dimensions of urban transformation. The net increase provides information about the overall change in the extent of built-up land, while the overlay value provides information about the total spatial footprint of newly detected development. Distinguishing these indicators is important because urban land transformation can involve simultaneous expansion, redevelopment, reclassification, and changes in the spatial configuration of existing built-up areas. The

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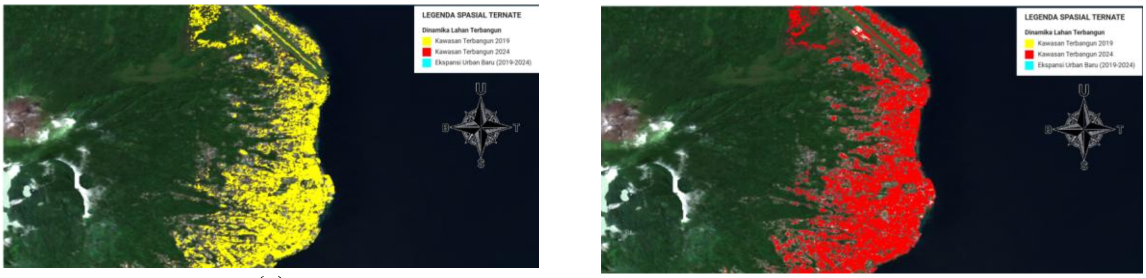
calculated 11.57% growth of built-up land over five years indicates that urban development in Central Ternate was relatively substantial within the spatial limitations of an island environment. The significance of this increase becomes more apparent when considered in relation to the limited availability of flat and accessible land. Research on Ternate Island has shown that settlement areas have continued to expand while land-cover composition has undergone considerable transformation. Kusrini et al. (2023) documented changes in land use and land cover on Ternate Island during the 2017–2022 period, demonstrating that settlement development forms an important component of the island's broader spatial transformation. Thus, the present findings for 2019–2024 provide additional evidence that the urbanization process has continued into the more recent period.

The NDVI analysis provides an important environmental dimension to the interpretation of NDBI-based urban expansion. Several locations showing increased NDBI values also exhibited declining NDVI values between 2019 and 2024. This inverse spatial relationship indicates that some of the expansion of built-up land occurred through the conversion of vegetated surfaces. Areas that exhibited relatively dense vegetation in 2019 became more fragmented or were replaced by built-up surfaces in 2024. The combination of NDBI and NDVI is therefore particularly useful because the two indices provide complementary information: NDBI identifies the spatial expansion of built-up surfaces, while NDVI indicates changes in vegetation cover. The relationship between declining NDVI and increasing NDBI has important environmental implications. Vegetation plays an important role in maintaining ecological functions within urban areas, including regulating surface temperatures, supporting infiltration, reducing runoff, and maintaining environmental quality. When vegetation is replaced by buildings, roads, and other impervious surfaces, these functions may be reduced. Kuc and Chormański (2019) demonstrated the usefulness of Sentinel-2 imagery for monitoring impervious surfaces in urban environments, highlighting the potential of multispectral remote sensing to detect urban surface transformation. In a similar context, the spatial relationship between vegetation and built-up land can be examined through the combined application of NDBI and NDVI to understand the environmental consequences of urban expansion.



(a) (b)

Figure 3. Built Up Areas: (a) 2019; (b) 2024

The environmental implications become particularly important because the observed development is concentrated within the coastal zone. Coastal areas simultaneously provide strategic locations for urban activities and perform important ecological functions. Increasing conversion of coastal vegetation and open land into built-up surfaces may therefore create competition between development needs and environmental conservation. Fauzi (2023) noted that waterfront development in Ternate has influenced changes in the spatial configuration of settlement areas. This suggests that the continuing expansion observed in the present study should be considered within the broader context of coastal spatial transformation rather than being treated exclusively as an inland urbanization process. The spatial pattern identified in this study also demonstrates the distinctive characteristics of an island city. Unlike mainland cities, where urban expansion can potentially extend across broad areas, island cities are constrained by the finite availability of land. In Ternate, this limitation is further strengthened by the presence of Mount Gamalama and its associated slopes. Consequently, urban development tends to concentrate within the coastal corridor where land is comparatively more accessible and suitable for intensive urban functions. Rakuasa and Pakniany (2023) emphasized the strong dynamics of land-cover change in Ternate Tengah associated with urban development, while Latue and Rakuasa (2023) demonstrated that continued urban growth is likely to increase pressure on available land resources.

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The present results support these observations by showing that the most recent expansion continues to follow the coastal urban corridor.

The findings also have methodological implications. Sentinel-2 imagery provides multispectral information that is appropriate for distinguishing vegetation and built-up surfaces, while its temporal availability supports multitemporal analysis. Drusch et al. (2012) explained that the Sentinel-2 mission was designed to provide high-resolution multispectral observations suitable for land monitoring and environmental applications. The use of Google Earth Engine further supports this approach because large volumes of satellite imagery can be processed using cloud-based computational infrastructure. Gorelick et al. (2017) emphasized that Google Earth Engine enables planetary-scale geospatial analysis by providing access to extensive remote-sensing datasets and computational resources. Consequently, the methodological framework applied in this research can be replicated for continued monitoring of urban expansion in Ternate. The results have important implications for spatial planning. The concentration of new built-up areas along the eastern and southeastern coastal corridor indicates that future urban development is likely to remain concentrated in these areas if the existing spatial structure continues. While coastal concentration may be understandable from the perspective of accessibility and economic efficiency, uncontrolled development could increase pressure on vegetation, open space, drainage systems, and coastal environmental functions. Therefore, spatial planning needs to balance the demand for additional urban land with the maintenance of environmental carrying capacity. Latue and Rakuasa (2023) argued that the continuing growth of settlements in Ternate Tengah requires attention to the spatial consequences of urban expansion, while Rakuasa and Pakniany (2023) emphasized the importance of understanding land-cover dynamics as a basis for sustainable spatial management. From a practical perspective, the integration of NDBI and NDVI provides a useful monitoring framework for identifying locations where urban development and vegetation loss occur simultaneously. Areas characterized by increasing NDBI and decreasing NDVI can be considered priority locations for further assessment because they represent zones where urban expansion is directly associated with the transformation of vegetated land. Repeated monitoring using the same methodological framework could therefore support the identification of emerging development pressures before they become difficult to control.

The findings further suggest that the management of Central Ternate should move beyond a simple expansion-oriented approach toward a more spatially selective model of urban development. Development should prioritize areas that already possess adequate infrastructure and urban services while limiting unnecessary conversion of vegetated or environmentally sensitive land. This approach is particularly relevant in an island city because the opportunity to compensate for inappropriate land conversion through outward expansion is considerably more limited than in mainland urban systems. Overall, the analysis demonstrates that urban development in Central Ternate during 2019–2024 was progressive, spatially concentrated, and strongly influenced by accessibility and topographic constraints. The increase in built-up land from 646.10 ha to 720.84 ha, the 74.74 ha net increase, and the identification of 146.86 ha of newly developed urban land collectively demonstrate the continuing transformation of the urban landscape. At the same time, the observed decline in NDVI in several areas experiencing increased NDBI values indicates that urban expansion has occurred partly through the conversion of vegetated land. These findings are consistent with previous studies of Ternate that have documented continuing urbanization, settlement expansion, and land-cover transformation (Latue & Rakuasa, 2023; Rakuasa & Pakniany, 2023; Kusrini et al., 2023; Nugroho, 2024). Thus, the principal issue revealed by this study is not simply the increase in the quantity of built-up land but the direction and spatial concentration of that growth. The dominance of the eastern and southeastern coastal corridors demonstrates that urban development in Central Ternate is shaped by the interaction between accessibility, economic activity, and the physical limitations imposed by the island's mountainous terrain. The integration of NDBI and NDVI through multitemporal Sentinel-2 analysis therefore provides an important basis for understanding these dynamics and can support future spatial planning aimed at maintaining a balance between urban development, vegetation conservation, and the sustainability of Ternate's coastal environment.

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CONCLUSION

The study demonstrates that urban expansion in Central Ternate District during 2019–2024 occurred progressively and was strongly influenced by the limited availability of developable land on Ternate Island. Sentinel-2 imagery processed using NDBI shows that the built-up area increased from 646.10 ha in 2019 to 720.84 ha in 2024, representing a net increase of 74.74 ha or 11.57%. This increase reflects continuing demand for land to accommodate residential development, commercial activities, public facilities, services, and urban infrastructure. The spatial analysis indicates that urban expansion was not evenly distributed. New built-up areas were concentrated mainly along the eastern and southeastern coastal zones, particularly around major transportation corridors, commercial centers, government facilities, and other urban activity areas. This pattern confirms that accessibility and proximity to economic activities are important factors influencing the direction of urban growth. At the same time, the steep terrain associated with Mount Gamalama restricts inland development, making the relatively flat coastal zone the primary area for urban expansion. Overlay analysis identified 146.86 ha of newly developed urban land between 2019 and 2024. These changes indicate the conversion of previously non-built-up areas into urban surfaces and demonstrate the continuing pressure on available coastal land. The NDVI analysis further shows that several areas experiencing built-up expansion were accompanied by declining vegetation values, indicating the conversion of vegetated land into residential areas and infrastructure. These findings confirm that Central Ternate exhibits the characteristic spatial pattern of an island city, where topographic constraints, limited land availability, accessibility, and economic concentration collectively determine urban development. The combination of NDBI, NDVI, Land Mask, and multitemporal Sentinel-2 imagery provides an effective approach for monitoring urban land transformation. The findings emphasize the need for more sustainable spatial management in Central Ternate. Future urban development should consider the protection of remaining vegetation, maintenance of green open spaces, control of coastal land conversion, and the environmental carrying capacity of the island. Such measures are important to ensure that continued urban and economic development does not compromise the ecological sustainability and long-term resilience of Central Ternate.

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