

Analysis of urban village sprawl in Boyolali Regency from 2014 to 2024 using landsat 8 and sentinel-2 imagery based on google earth engine

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Abstract. Rural sprawl refers to the spatial phenomenon of built-up area expansion into previously rural regions dominated by agricultural lands and green open spaces. In Boyolali Regency, urbanization and infrastructure development over the past decade have become major drivers of land use change, leading to the spread of settlements into rural areas. Understanding this phenomenon is essential to analyse its patterns and impacts on spatial planning and environmental sustainability. Therefore, this study aims to identify and analyse rural sprawl in Boyolali Regency over the period from 2014 to 2024. This research utilizes the Google Earth Engine (GEE) platform to analyse land cover changes using Landsat 8 imagery (for 2014 and 2017) and Sentinel-2 imagery (for 2020 and 2024). Image processing was conducted using Normalized Difference Built-up Index (NDBI). A threshold-based classification was applied to distinguish between built-up and non-built-up areas. Spatial changes were analysed using overlay techniques across the study years, and the growth rate of built-up areas in rural zones was calculated. The results are the development is no longer tied to the main infrastructure corridor, but is instead spreading widely, reflecting the characteristics of fringe sprawl around the city center.

1 Introduction

Urban village sprawl is a phenomenon of residential and infrastructure growth that spreads to rural areas outside city centres. This expansion often occurs in an unplanned and uncontrolled manner, driven by population growth, economic development, and increasing demand for housing [1]. As a result, it leads to the conversion of agricultural land into residential and commercial use, reducing food security and disrupting traditional rural livelihoods.

In Indonesia, this trend is becoming more common in areas around cities, especially where cities are growing fast. Boyolali Regency in Central Java is a good example. It is located between three big cities: Yogyakarta, Semarang, and Surakarta. Because of its

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location, Boyolali has grown quickly in the last ten years, attracting investment and people from nearby cities. This phenomenon highlights the urgency of conducting spatial monitoring and evaluation of sprawl patterns in rural areas within the context of sustainable spatial planning [2].

Studying how land use changes is a good way to see how land changes over time and space. Landsat 8 and Sentinel-2 give useful information for mapping built-up areas over a long time. This data is processed using Google Earth Engine (GEE), a cloud-based system that analyses large amounts of geospatial data efficiently, especially for detecting large-scale changes [3]. The combination of satellite imagery and cloud-based processing enables continuous and accurate spatial monitoring for areas with high dynamics of change such as Boyolali.

Normalized Difference Built-Up Index (NDBI) is a spectral index developed to extract built-up areas by combining SWIR and NIR channels, where positive NDBI values indicate the presence of settlements or man-made structures. The use of NDBI is widely applied in studies of urban and rural expansion due to its reliability in distinguishing built-up areas from vegetation cover or water bodies. Research by Zha [4] shows that NDBI is effective in detecting residential areas, even in heterogeneous environments. Further studies have also shown high accuracy when NDBI is applied in remote sensing-based spatial classification systems [5].

The study of the dynamics of built-up area spread can be conducted by utilizing the Normalized Difference Built-up Index (NDBI) from multi-temporal remote sensing data, such as Landsat or Sentinel-2 imagery. NDBI is used to extract built-up areas consistently, thereby providing a picture of spatial changes over time [4]. The results of NDBI mapping can then be further analysed using Relative Entropy (RE) to evaluate the level of development spread or urban sprawl [6].

2 Method

2.1 Study Area

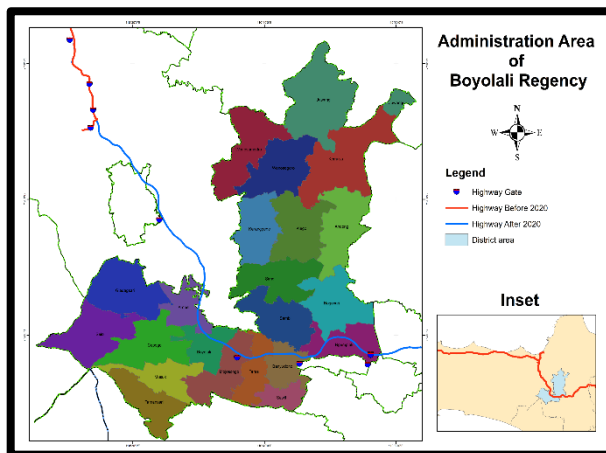


Fig. 1. Administration area of Boyolali Regency.

This study was conducted in the Boyolali region as shown in Fig 1, Central Java, which covers 19 subdistricts and 267 villages/kelurahan. Geographically, the Boyolali region is located at 110° 22'–110° 50' east longitude and 7° 36'–17° 71' southern latitude, and has a diverse topography, ranging from 75 to 1,500 meters above sea level [7]. This region occupies a strategic position as a buffer zone for the city of Surakarta (Greater Solo), thus offering opportunities for urban development.

Boyolali Regency is divided into two areas: northern Boyolali and southern Boyolali. The northern area includes Sambu, Ngemplak, Nogosari, Simo, Karanggede, Klego, Andong, Kemusu, Wonosegoro, and Juwangi. The southern area includes Banyudono, Sawit, Teras, Mojosongo, Boyolali, Musuk, Cepogo, Ampel, and Selo. This division is due to differences in economic conditions and urban environments. The national roads Yogyakarta - Surakarta and Surakarta - Semarang in southern Boyolali also help to separate the two areas.[8]

2.2 Data Used

This study uses multi-temporal satellite imagery data to analyse land cover changes in the coastal areas of Kendal Regency. The satellite imagery used consists of:

- a) Landsat 8 OLI (Operational Land Imager) in 2014, 2018
- b) Sentinel-2 MSI (Multispectral Instrument) in 2021 and 2024

The use of Landsat 8 and Sentinel 2 satellite imagery is due to their sufficiently high spatial resolution for open data and their ability to be used to process data to produce NDBI.

2.3 Methodology

2.3.1 NDBI

Normalized Difference Built-up Index (NDBI) is a spectral index widely used in remote sensing to detect and quantify built-up areas by utilizing the difference in SWIR and NIR band reflectance. This index is formulated as $(SWIR - NIR) / (SWIR + NIR)$ and proven effective in mapping urban expansion with high classification accuracy[4]. NDBI is often combined with NDVI to distinguish between vegetation and built-up areas, thereby improving mapping accuracy [9]. A study in Makassar shows that the application of NDBI has been able to identify an increase in built-up areas of up to around 18% in recent years[10]. Similarly, research in Surabaya found a 21% increase in built-up land since the beginning of the 21st century through NDBI analysis [11]. The formula from NDBI is as follows[12]

$$NDBI = \frac{(SWIR - NIR)}{(SWIR + NIR)} \tag{1}$$

2.3.2 *Relative Index*

Shannon Entropy (H) measures how spread out or uncertain something is. For urban sprawl, it looks at how developed land is spread across different areas. A high H value means land is spread out evenly. A low H value means development is focused in a few areas. The highest H value depends on how many areas are looked at, which makes it hard to compare results from different studies or times with different numbers of areas. This is a concern in sprawl risk analysis due to limitations in inter-temporal or inter-regional validity [13]. As a solution to these limitations, researchers developed a normalization method known as Relative Entropy (RE), with the following formula:

$$RE = \frac{H}{\ln(N)} \quad (2)$$

The RE value ranges from 0 to 1, making it easy to compare between regions and time periods, even if the number of zones differs. An RE close to 0 reflects a compact and centralized development pattern, while an RE close to 1 reflects widespread development a strong indication of urban sprawl. This approach has been implemented in various spatio-temporal studies, including an analysis of urban sprawl dynamics in four medium-sized cities in India during the period 1991–2021, which showed an increasing trend in RE values approaching 1 as evidence of increasing levels of sprawl [14].

3 Result

3.1 Increasing Built-up Area

In Fig 2 show from 2014 to 2024, the built-up areas in Boyolali Regency have grown quickly. This has caused big changes in how the land is used. The growth is not the same everywhere. Some subdistricts have grown much more than others. All subdistricts have seen a big increase in built-up areas, with the most notable growth occurring in Ngemplak (from 199.45 Ha to 1385.21 Ha) and Sambu (from 14.86 Ha to 908.99 Ha). Central subdistricts such as Boyolali, Mojosongo, and Cepogo also experienced a surge in built-up area, reflecting intense development expansion in the core areas and their surroundings. This growth pattern indicates the phenomenon of rural sprawl, namely the rapid and uncontrolled physical development of suburban areas, which can lead to the conversion of agricultural land, pressure on infrastructure, and spatial fragmentation.

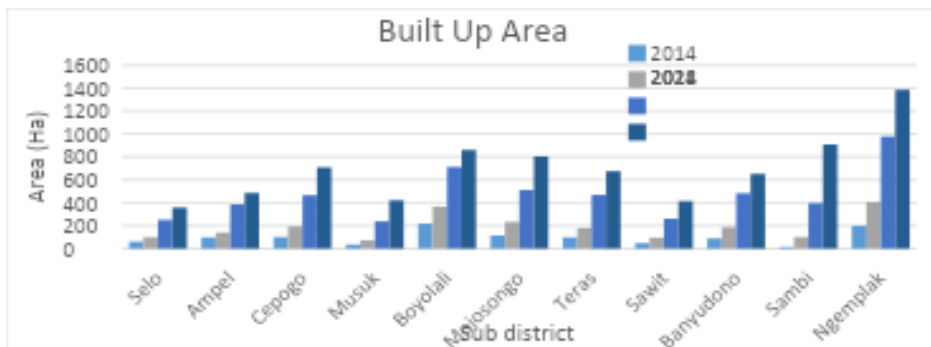


Fig. 2. Built up area graph.

In Fig 3 show data on the development of built-up areas in the northern and western parts of Boyolali Regency shows a significant increase over the past decade, particularly in subdistricts such as Nogosari, Simo, Karanggede, and Kemusu. Nogosari experienced a surge in built-up area from 87.29 hectares in 2014 to 996.80 hectares in 2024, making it one of the areas with the highest growth. Similarly, Andong, Klego, and Karanggede have shown rapid growth patterns since 2018, indicating accelerated development in non-urban areas. Even subdistricts that previously had very small built-up areas, such as Tamansari and Wonosamodro, have also experienced significant increases, reaching 337.87 hectares and 411.12 hectares, respectively, in 2024. This increase indicates the spread of rural sprawl to remote rural areas, which has the potential to put pressure on the environment, cause agricultural land conversion, and create new challenges in comprehensive spatial planning.

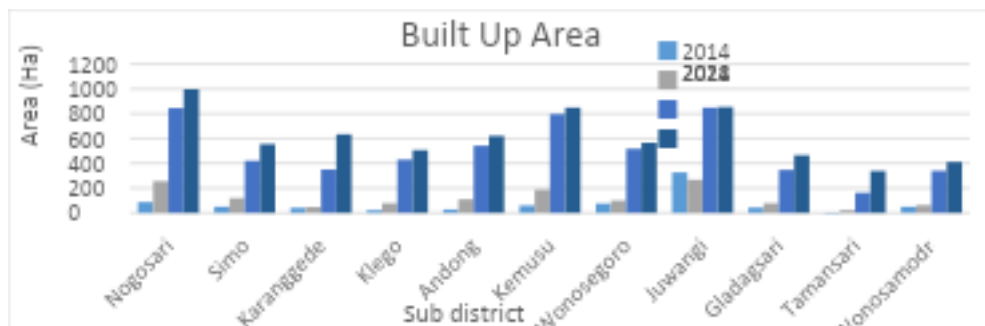


Fig. 3. Built Up Area Graph

Based on spatial imagery of built-up area changes from 2014 to 2024 as shown Fig 4, the most rapid growth in development occurred in the southern and southeastern areas of Boyolali Regency, which is geographically close to Surakarta Regency. Areas such as Mojosoango, Boyolali, Banyudono, and Ngemplak show an intensive concentration of built-up areas (colored red) that continue to expand over time. This is in line with quantitative data showing a significant increase in the size of built-up areas in these subdistricts, such as Ngemplak, which increased from 199.45 hectares in 2014 to 1,385.21 hectares in 2024. This growth indicates strong urbanization pressure from the core area of Surakarta to the buffer zone in Boyolali, creating a rapidly developing new suburban

zone due to road connectivity, economic activity, and housing needs. This pattern reinforces the indication of peri-urban expansion, which requires integrated cross-regional spatial planning to anticipate environmental degradation and land use imbalances.

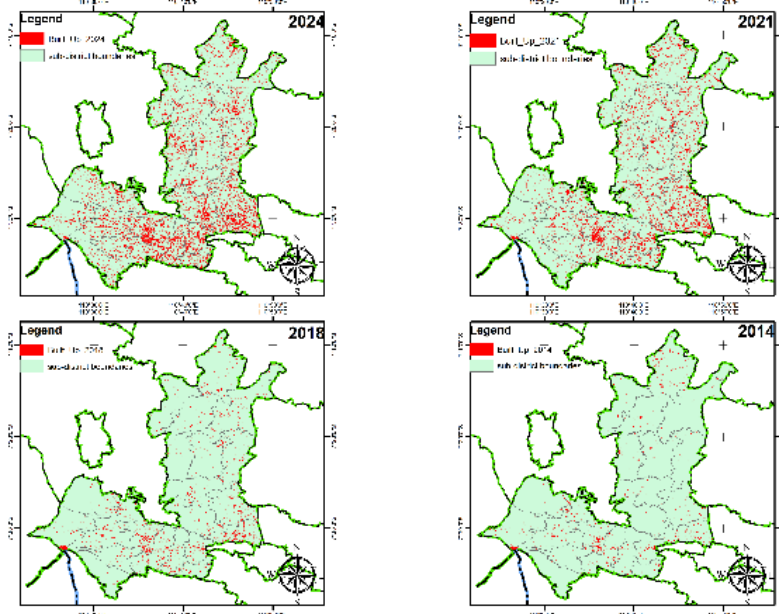


Fig. 4. Map built up area in Boyolali Regency.

3.2 Pattern Built-up Area

This approach allows us to measure the level of dispersion or concentration of a phenomenon, in this case built-up areas, within a region. By using buffer zone parameters that refer to the distance to the main road network and the distance to the district centre as shown Fig 5, we can identify spatial trends in development. This analysis helps reveal whether the growth of built-up areas tends to follow a centralized pattern (concentrated near roads and district centres) or spreads randomly.

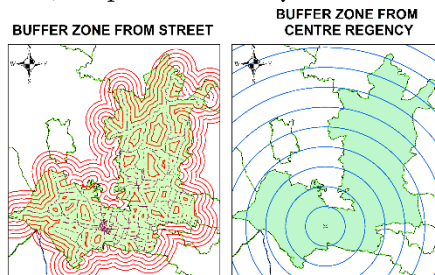


Fig. 5. Buffer zone analysis.

Based on the results of calculations and visualization of spatial matrices using the Relative Entropy Index (REI) as shown in Table 1, the spatial pattern of development in Boyolali

Regency during the 2014–2024 period shows a consistent trend in quadrant D, which is spreading towards the city centre but away from the main road. The REI value for the city centre (H'p) is in the high range, above 0.89 for the entire year, indicating that development has spread evenly to the suburbs. Meanwhile, the REI value relative to roads (H'j) has decreased from 0.51 in 2014 to around 0.35 in 2024. This indicates that development is no longer centred around access to main roads but has begun to spread to areas further away from the road network. His distribution pattern shows characteristics of fringe sprawl, which is not concentrated along major infrastructure corridors but spreads outward from the city centre.

Table 1. REI.

Year	REI towards the district highway	REI to the district centre
2014	0.5129	0.9270
2018	0.3488	0.9029
2021	0.4014	0.9235
2024	0.3532	0.8962

4 Conclusion

Development in Boyolali Regency shows a trend of spreading to the suburbs (quadrant D), moving away from the main road between 2014 and 2024. This is evident from the consistently high REI value toward the city center (H'p) (above 0.89), while the REI value relative to the road (H'j) dropped significantly from 0.51 to 0.35. This change indicates that development is no longer tied to the main infrastructure corridor, but is instead spreading widely, reflecting the characteristics of fringe sprawl around the city center.

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