

Monitoring and Evaluation the Urban Growth Pattern in Weh Island, Indonesia

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ABSTRACT

Urban development in small-island environments presents complex challenges due to limited land resources and ecological sensitivity. This study investigates the pattern and magnitude of urban growth on Weh Island, Sabang City, Indonesia, over a ten-year period (2010–2020). Using multi-temporal Landsat imagery combined with Geographic Information System (GIS) analysis, land use and land cover (LULC) changes were classified into six categories and evaluated through supervised classification and accuracy assessment. The results indicate a significant expansion of built-up areas, increasing from 489.06 ha to 736.92 ha (50.68%), while woodland decreased by 10.18% during the same period. Agricultural land experienced moderate growth, reflecting intensified land utilization. Despite the decline, woodland remains the dominant land cover type on the island. The transition analysis reveals that urban expansion primarily occurred through the conversion of woodland and agricultural land into built-up areas. These findings highlight increasing development pressure within a spatially constrained island system and emphasize the importance of continuous spatial monitoring to support sustainable urban planning. The study provides a spatial evidence base for policymakers to balance economic growth, tourism development, and environmental conservation in small-island contexts.

Keywords: GIS, LULC, remote sensing, urbanization

1. Introduction

Urbanization is increasingly influenced by demographic growth and government-driven regional development policies. These dynamics not only affect metropolitan regions but also extend to small islands that possess strategic economic and geopolitical value. Sabang City, located at the westernmost point of Indonesia in Aceh Province, consists of a cluster of islands—Weh, Klah, Rubiah, Seulako, and Rondo—covering approximately 122.13 km² (Figure 1). Among these, only Weh Island is permanently inhabited and functions as the administrative and economic center of the region. Legally, Sabang has been designated as a Free Trade Area and Free Port under Act No. 37 of 2000 [1]. In addition, Government Regulation No. 26 of 2008 identifies Sabang as a National Strategic Area due to its economic, defense, and border security importance [2]. Within Indonesia's national urban system, Sabang is positioned as a regional growth pole intended to stimulate development in border territories. These policy frameworks create strong developmental pressure and investment incentives that may accelerate spatial transformation, particularly on Weh Island.

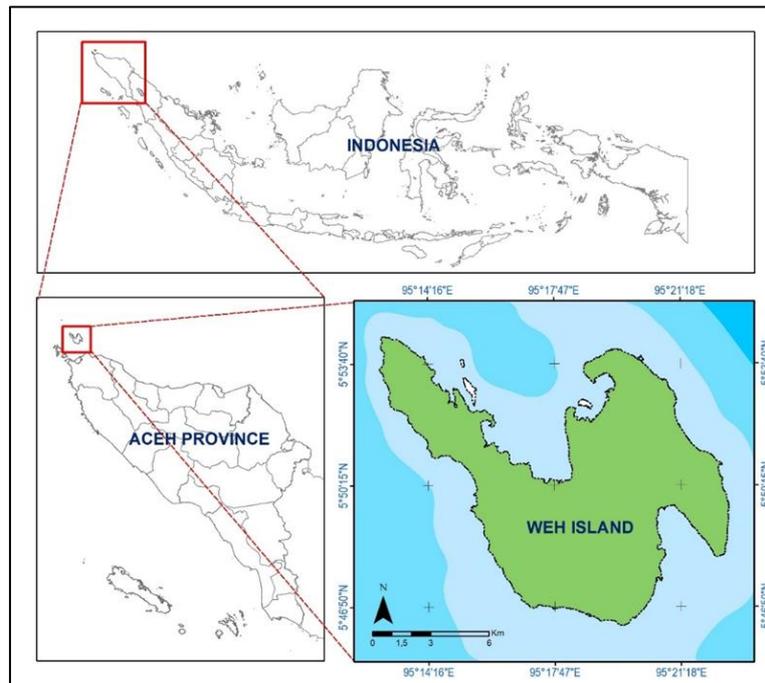


Figure 1. Study area

Although such strategic status presents economic opportunities, the geographical characteristics of small islands impose ecological constraints. Land availability is limited, and environmental carrying capacity must be carefully managed to prevent unsustainable expansion. Sustainable urban growth therefore becomes a critical concern, as it seeks to balance development needs with environmental protection and long-term social welfare [3]. Sustainable urbanization is widely understood as a response to contemporary challenges such as globalization, decentralization, and rapid population increase [4]. In island cities, these pressures can lead to complex land-use competition between settlement expansion, agricultural land, conservation areas, and tourism facilities.

Sabang is widely recognized for its marine tourism potential and as the symbolic “kilometer zero” of Indonesia. The growth of tourism activities, coupled with population increase and migration, has intensified the demand for housing, infrastructure, and food production [5]. As a result, land conversion processes become increasingly evident. Expansion of built-up areas frequently alters natural and semi-natural landscapes, influencing ecological balance and spatial structure. According to urban development theory, incremental increases in built-up land often serve as early indicators of broader urban growth processes [6]. Land use and land cover (LULC) dynamics are shaped by infrastructure development, economic centers, accessibility, and physical geographic conditions. Monitoring these dynamics provides valuable insights for spatial planning and environmental management [7]. Advances in geospatial analysis and modeling approaches have enabled more accurate detection and prediction of urban expansion patterns [8]. In small-island contexts, such monitoring is particularly important due to spatial limitations and higher vulnerability to climate change and natural hazards.

Despite its strategic designation and growing development activities, comprehensive temporal assessments of LULC changes in Weh Island remain limited. The sustainability of the island’s urban system depends on maintaining balanced land allocation between built-up areas, agriculture, woodland, and conservation zones. Uncontrolled spatial expansion may threaten fertile land, environmental stability, and ecosystem services [7]. Therefore, systematic monitoring of land use change over time is essential to support evidence-based spatial planning policies. Considering these challenges, this study aims to analyze land use and land cover changes in Weh Island over a ten-year period (2010–2020). By evaluating spatial transformation patterns, this research seeks to provide empirical evidence that can support sustainable urban growth strategies in small-island environments.

2. Method

This research was carried out on Weh Island, located in Aceh Province, Indonesia, between 05°46'28"–05°54'28" North Latitude and 95°13'02"–95°22'36" East Longitude. The island covers approximately 12,084.45 hectares and represents one of Indonesia's outermost territories facing the Indian Ocean. The topography is predominantly mountainous, accounting for nearly half of the island's surface, while the remaining areas consist of undulating terrain, sloping plains, limited flat land, and steep zones. Slope gradients exceeding 15% are mainly distributed in the western and central-eastern parts of the island, influencing spatial development patterns. In addition, Weh Island contains a designated conservation forest area of approximately 1,201 hectares, functioning both as a protected ecosystem and a tourism asset. Demographically, the population residing on Weh Island increased from 30,653 inhabitants in 2010 to 43,391 in 2020, indicating substantial growth pressure within a geographically constrained environment [9].

The identification of land use and land cover (LULC) dynamics was conducted using geospatial analysis and remote sensing techniques. Remote sensing has been widely recognized as an effective approach for observing spatial variations and monitoring land cover at multiple temporal scales [10][11]. The integration of Geographic Information Systems (GIS) enhances data processing efficiency and enables structured spatial analysis for urban studies [12][14]. Landsat imagery was selected due to its medium spatial resolution and long-term temporal availability, which are appropriate for multi-year comparative analysis [11]. This study utilized Landsat 7 imagery for the year 2010 and Landsat 8 imagery for 2020. Ancillary data included administrative boundary maps and regional spatial datasets. Image processing and spatial analysis were conducted using ArcGIS 10.6, QGIS 2.18.20, and Microsoft Excel for tabulation and statistical comparison.

Prior to classification, the satellite images underwent radiometric and atmospheric corrections to minimize sensor and atmospheric distortions. Supervised classification was then applied to categorize land cover types based on training samples derived from field knowledge and visual interpretation. Six thematic classes were defined to represent the dominant land characteristics of the island: woodland, built-up area, water body, agricultural land, grassland, and bare land. This classification framework aligns with previous LULC studies conducted in small island and coastal environments [5][12]. The selection of supervised classification is consistent with established methodologies in urban growth detection and spatial modeling [7][13][15].

To evaluate classification reliability, an accuracy assessment was performed using stratified random sampling. Ground verification points were obtained through field observations and supported by high-resolution imagery from Google Earth. A confusion matrix was constructed to compute Overall Accuracy and the Kappa coefficient, which measure classification agreement beyond chance levels [7]. Only classification outputs meeting acceptable accuracy standards were used for further analysis. Following validation, spatial overlay analysis was performed to generate a land cover change matrix for the 2010–2020 period. This approach enabled quantification of transitions among classes and identification of dominant conversion patterns. The use of overlay and transition analysis is widely adopted in studies examining urban expansion and land transformation processes [8][15]. By integrating temporal satellite imagery, supervised classification, and transition matrix analysis, this methodological framework provides a systematic approach for detecting and evaluating spatial changes in small island environments. The results serve as a basis for assessing urban growth trends and supporting evidence-based spatial planning strategies.

3. Results and Discussion

The reliability of the land use and land cover (LULC) classification was first evaluated through an accuracy assessment. The confusion matrices presented in Table 1 indicate that the overall classification accuracy reached 87% for 2010 and 88% for 2020. These values exceed the commonly accepted minimum threshold of 85% for thematic land cover mapping, demonstrating that the classification results are sufficiently reliable for spatial analysis. In 2010, the highest user accuracy values were recorded for water bodies and bare land, both reaching 1.00, while woodland and agricultural land also showed strong agreement levels. Similarly, in 2020, woodland and water bodies achieved high user accuracy values, confirming stable classification performance across the two time periods. Although grassland and bare land classes exhibited relatively lower producer

accuracy in certain cases, the overall performance of the supervised classification is considered robust. Therefore, the Landsat-based mapping outputs provide a dependable foundation for analyzing spatial transformation trends.

Table 1. Error matrices of the LULC classifications

Category	Classified values						Total	User accuracy
	Woodland	Built-Up Area	Water Body	Agriculture Land	Grassland	Bareland		
2010								
Woodland	44	0	0	5	0	1	50	0.88000
Built-Up Area	0	3	0	0	0	1	4	0.75000
Water Body	0	0	1	0	0	0	1	1.00000
Agriculture Land	1	0	0	30	2	1	34	0.88235
Grassland	0	0	0	2	7	0	9	0.77778
Bareland	0	0	0	0	0	2	2	1.00000
Total	45	3	1	37	9	5	100	
Producer accuracy	0.97778	1.00000	1.00000	0.81081	0.77778	0.40000		0.87000
2020								
Woodland	44	0	0	1	0	0	45	0.97778
Built-Up Area	0	5	0	1	0	0	6	0.83333
Water Body	0	0	1	0	0	0	1	1.00000
Agriculture Land	2	0	0	31	3	0	36	0.86111
Grassland	3	0	0	1	5	0	9	0.55556
Bareland	0	1	0	0	0	2	3	0.66667
Total	49	6	1	34	8	2	100	
Producer accuracy	0.8980	0.8333	1.0000	0.9118	0.6250	1.0000		0.8800

Note: Overall Accuracy in 2010 = 87%; and Overall Accuracy in 2020 = 88%

The spatial distribution of LULC categories derived from the classification process is illustrated in Figure 3(a) for 2010 and Figure 3(b) for 2020. These maps visually demonstrate changes in land allocation across Weh Island over the ten-year period. Woodland areas remain predominantly located in the central and mountainous regions, while built-up areas are concentrated around coastal settlements and transportation corridors. The quantitative comparison of land cover areas is summarized in Table 2, which presents the extent and percentage of each LULC class for both years. Woodland decreased from 6,071.22 ha (50%) in 2010 to 5,452.92 ha (45%) in 2020, indicating a net reduction of forested land. In contrast, built-up areas expanded from 489.06 ha (4%) to 736.92 ha (6%) during the same period. Agricultural land showed moderate growth, increasing from 4,130.01 ha (34%) to 4,378.05 ha (36%). Water bodies and bare land also experienced incremental increases, whereas grassland exhibited a slight decline. The comparative proportions of land cover classes are further visualized in Figure 4, which confirms that woodland remained the dominant land cover type despite its gradual reduction.

Table 2. LULC change in Weh Island in 2010 and 2020

LULC	2010 (ha)		2020 (ha)	
Woodland	6,071.22	50%	5,452.92	45%
Built-Up Area	489.06	4%	736.92	6%
Water Body	93.51	1%	112.14	1%
Agriculture Land	4,130.01	34%	4,378.05	36%
Grassland	1,107.00	9%	1,076.76	9%
Bareland	244.17	2%	378.18	3%
Total	12,134.97	100%	12,134.97	100%

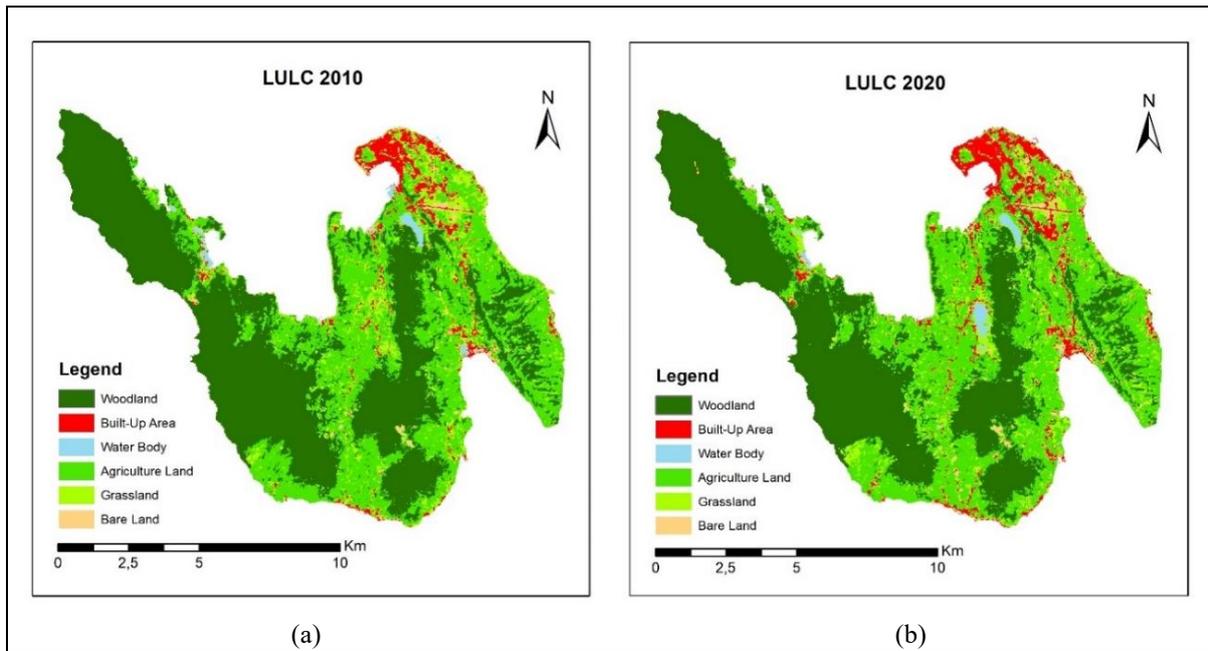


Figure 3. Weh Island Maps LULC in (a) 2010 & (b) 2020

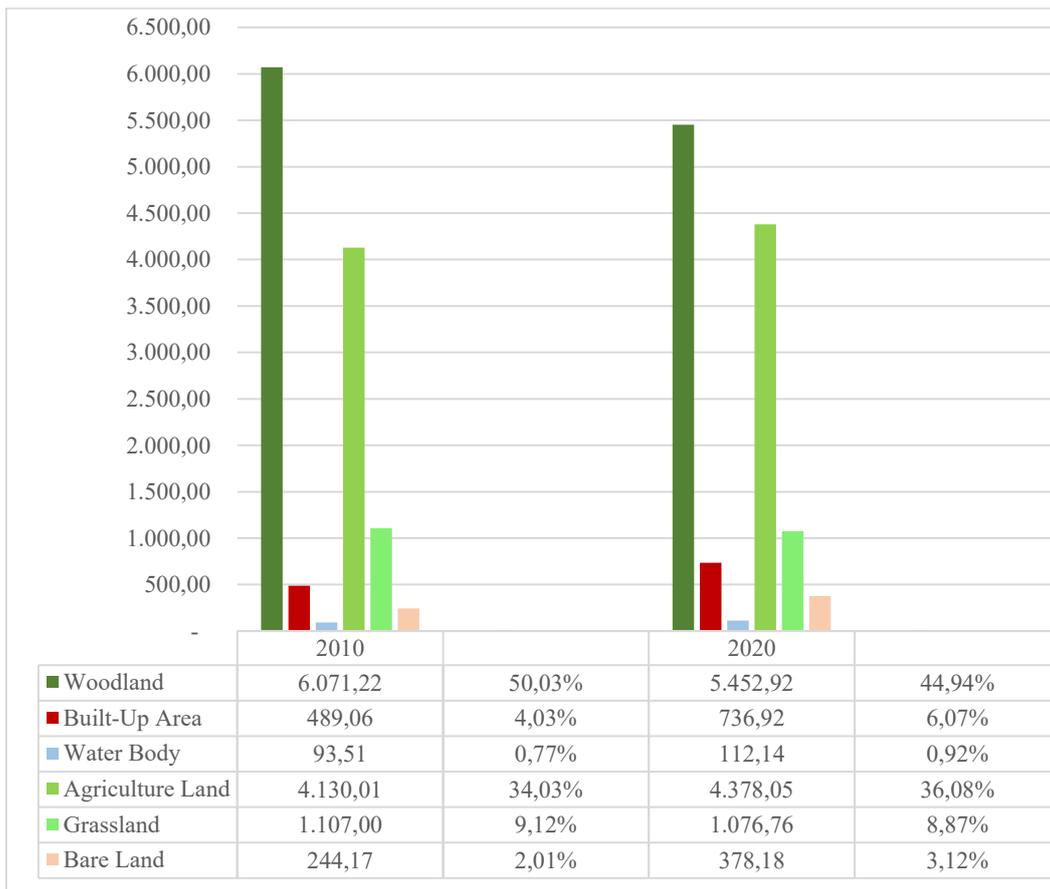


Figure 4. LULC for Weh Island in 2010 and 2020

To better understand the dynamics of land transformation, a transition matrix analysis was conducted, as presented in Table 3. This matrix quantifies conversions between different land categories from 2010 to 2020. A substantial portion of woodland was converted into agricultural land and built-up areas, indicating land development pressure in previously vegetated zones. Grassland also experienced transitions toward agricultural and built-up functions. Meanwhile, expansion of built-up areas originated not only from woodland but also from former agricultural and grassland areas. These transition patterns suggest that urban growth is

occurring through a combination of forest conversion, agricultural intensification, and infill development. The matrix also reveals that certain land categories, such as water bodies, remained relatively stable with minor fluctuations.

Table 3. Transition matrix form of LULC in Weh Island in 2010 and 2020

LULC	2020						Total
	woodland	built-up area	water body	agriculture land	grassland	bareland	
woodland	5,444.82	8.55	2.79	453.15	139.77	22.14	6,071.22
built-up area	-	449.91	-	-	-	39.15	489.06
water body	-	19.08	56.88	0.36	10.62	6.57	93.51
agriculture land	7.92	62.19	29.25	3,425.04	498.06	107.55	4,130.01
grassland	0.18	120.51	18.00	467.28	380.16	120.87	1,107.00
bareland		76.68	5.22	32.22	48.15	81.90	244.17
Total	5,452.92	736.92	112.14	4,378.05	1,076.76	378.18	12,134.97

Changes in land cover were further analyzed to determine the rate of urban growth, as detailed in Table 4. The built-up area increased by 247.86 hectares over the ten-year period, representing a growth rate of 50.68%. This significant expansion reflects intensified demand for residential areas, tourism facilities, and supporting infrastructure. Agricultural land also expanded by 248.04 hectares (6.01%), possibly driven by increased food production needs associated with population growth and tourism activities. Conversely, woodland decreased by 618.30 hectares, corresponding to a reduction of 10.18%, while grassland declined slightly. Bare land recorded a relatively high percentage increase (54.88%), which may indicate ongoing land clearing and transitional development processes.

Table 4. Urban Growth Weh Island 2010-2020

LULC	2010 (Ha)	2020 (Ha)	Change Area 2010-2020		Change Rate 2010-2020	
Woodland	6,071.22	5,452.92	(618.30)	-10.18%	(61.83)	-1.02%
Built-up area	489.06	736.92	247.86	50.68%	24.79	5.07%
Water body	93.51	112.14	18.63	19.92%	1.86	1.99%
Agriculture land	4,130.01	4,378.05	248.04	6.01%	24.80	0.60%
Grassland	1,107.00	1,076.76	(30.24)	-2.73%	(3.02)	-0.27%
Bareland	244.17	378.18	134.01	54.88%	13.40	5.49%

Overall, the spatial and quantitative findings demonstrate a clear trend of urban expansion on Weh Island between 2010 and 2020. Field observations and regional development reports indicate that population growth, tourism development, and trade activities have contributed significantly to land conversion processes. The concentration of built-up growth in accessible and economically active areas suggests that infrastructure availability and coastal attractiveness play important roles in shaping urban patterns. While woodland remains the dominant land cover, its gradual decline signals increasing pressure on ecological resources within this small island environment. The observed LULC transitions highlight the need for integrated spatial planning strategies that balance development objectives with environmental sustainability.

4. Conclusion

This study examined the spatial dynamics of urban growth on Weh Island over a ten-year period (2010–2020) through the analysis of land use and land cover (LULC) changes derived from multi-temporal satellite imagery. By applying GIS-based classification and change detection techniques, the research provides empirical evidence of the direction and magnitude of land transformation within a geographically constrained small-island environment. The findings reveal a substantial expansion of built-up areas, which increased by more

than 50% during the study period. Agricultural land also experienced moderate growth, while woodland—the dominant land cover—declined by approximately 10%. Although forested areas remain the largest land category, the observed reduction indicates increasing development pressure on natural ecosystems. The transition matrix analysis further demonstrates that urban expansion has primarily occurred through the conversion of woodland and agricultural land into built-up areas. These spatial changes reflect the influence of demographic growth, tourism development, and economic activities associated with Sabang’s strategic designation. The pattern of expansion suggests a gradual shift toward intensified land utilization, particularly in accessible and economically active zones. In a small-island context where land resources and ecological resilience are inherently limited, such transformations require careful monitoring and proactive spatial regulation. The results of this research contribute to the understanding of urban growth processes in small-island settings and provide a spatial evidence base for sustainable land management. Future studies are recommended to integrate socio-economic variables, policy evaluation, and community perceptions to better understand the driving forces behind LULC changes. Additionally, incorporating higher-resolution imagery and predictive modeling approaches may enhance the ability to forecast long-term spatial scenarios. Strengthening spatial planning control and environmental protection mechanisms will be essential to ensure that future development on Weh Island aligns with sustainable urban growth principles.

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6. Conflict of Interest

The authors declare that there are no financial, professional, or personal conflicts of interest that could have influenced the design, analysis, interpretation, or reporting of this research. All authors have approved the final version of the manuscript and agree with its submission for publication.

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