Asian Journal of Environmental Research
E-ISSN: 3047-4930
DOI: https://doi.org/10.69930/ajer.v2i1.310
Research Article

ScienceTech. Group

Vol. 2 (1), 2025
Page: 101-114

Simulation of Urban Growth in Ternate Island using Cellular Automata Markov Chains Models

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Abstract. *Ternate Island is part of the administrative area of Ternate City, North Maluku Province which was once the capital of the province and the center of government continues to experience physical development. This study aims to analyze the development of urban growth in Ternate Island in the period 2004-2032. The cellular automata markov chain method uses 2004, 2014 and 2024 land cover data and driving factors consisting of elevation, slope, distance from road and distance from POI to predict urban growth. The results of the analysis show that the urban area continues to increase in area, namely in 2004 the urban area had an area of 1,424.14 ha, 2014 an area of 1,728.45 ha and in 2024 an area of 2,010.78. The prediction results of urban growth on Ternate Island in 2032 show that the urban area has an area of 2,884.37 ha. Based on the research results from the application of the markov chain cellular automata method, it is hoped that these findings can be taken into consideration in designing a sustainable spatial arrangement of Ternate City. So that ecological balance, environmental balance and food security can be maintained and meet the requirements of a city that has the carrying capacity and environmental capacity.*

Keywords: *Cellular automata markov chains, Ternate, GIS, urban growth*

1. Introduction

The growth of the City at this time shows rapid progress in line with the increasing population and the increasing volume of development activities in various sectors (1), (2). This causes the increase and development of supporting facilities and infrastructure that always demands changes that lead to the quality and quantity of land use. The need for land use in urban areas is increasing in line with population growth and accompanying socio-economic activities (3),(4). The increase in land use is an implication of the increasingly diverse functions in urban areas (government, trade and services, education) due to its advantages in terms of the availability of public facilities and ease of accessibility so as to attract various activities to agglomerate (5),(6). Population growth and increased urban activity in Indonesia have led to the development of many commercial areas. One sector that needs to be considered to anticipate the development of these commercial areas is the handling of land use issues (7),(8).

Urban growth occurs in several cities in the world which results in land use change in a city. Urban growth occurs in developed countries such as Saga City Japan, with the results of the analysis of land use change increasing from 12% in 2006-16% in 2042 of the area of Saga City Japan (9). Urban growth in developing countries also occurs such as in Turkey Adana City with the results of the urban area analysis of 59 km2 for 2023 (2023-

Received: 23 February 2025 / Accepted: 12 April 2025 / Available online: 25 April 2025

2007) and 156 km2 (2007-1967) for the 2007 application model. Growth resulted in 146 km2 of total urban area for 2007 and 75 km2 for 2023 respectively. The urban change observed between 1967 and 2007 time periods was 136 km2 (10).

Indonesia has the third largest urban land area in East Asia after China and Japan. Between 2000 and 2010, the amount of urban land in Indonesia increased from about 8,900 square kilometers to 10,000 square kilometers, an increase of 1.1% per year. The urban population density in Indonesia also increased rapidly from about 7,400 people per square kilometer to 9,400 people per square kilometer while the amount of new urban land for each person living in the city is less than 40 square meters, which is the smallest size of all countries in the East Asian region (11).

Ternate Island is part of the administrative area of Ternate City, Maluku Utara Province (Figure 1). Ternate Island is a small volcanic island with an area of 111 km2. Ternate Island was formed from the deposition of volcanic material from the eruption of Mount Gamalama, which has been going on for thousands of years until now (12). Ternate Island is divided into 5 sub-districts, namely South Ternate, North Ternate, West Ternate, Central Ternate, and Ternate Island. The number of villages in Ternate Island is 59 villages (13). In North Maluku Province, Ternate Island has a very strategic role because it is the center of economy, services, and trade (14). In addition, Ternate Island is also the main entrance to the air and sea transportation routes. This cannot be separated from the existence of Sultan Baabullah International Airport and Ahmad Yani National Port which serve transportation to various regions in Indonesia. Ternate City is one of the important cities in Eastern Indonesia. The increase in human activity can also be seen in terms of population growth which tends to increase from year to year. Based on data from North Maluku Province in Figures, population growth on Ternate Island has increased since 2014 until 2024. In 2014, the total population on Ternate Island reached 204,920 people (13).

With the pressure of increasing population, the need for land for various facilities increases, so in overcoming this problem, there is a concept of urban development in the form of developing new cities around the city (15). In addition, according to Qingsong et al., when population growth increases, the need for land also increases (16). In the long term, humans will experience a land crisis (17). As the population increases, the demand for land will increase. As the population increases, it is estimated that more land will be transformed to meet the needs of the growing population for settlement and food production (18). Rapid population growth and changes in people's lifestyles result in an increasing need for housing (19).

However, unplanned and uncontrolled settlement can result in serious social and environmental problems. In addition, changes in land cover that occur have an impact on environmental damage, increasing land surface temperatures, and natural disasters that occur (20). In the increasing conversion of land to residential land along with population growth, it is necessary to implement a development strategy to overcome the problems that will be faced continuously by reviewing the carrying capacity of residential land and the need for residential land (21).

The phenomenon of city growth in Ternate Island needs to be studied through a model that is able to analyze the spatial dynamics of city growth. Urban land use change models are important for analyzing the driving forces of land use change, and simulating urban growth scenarios. This is very important in developing countries that experience rapid urban growth (22). Land use change due to population growth and development caused by urbanization process in Ternate Island can be analyzed through cellular automata model (7). This is in line with research conducted by Fitawok et al., that the cellular automata model integrated with dynamic systems is not only able to examine social economic conditions on population growth but also able to evaluate spatial patterns (23). Aburase et al. revealed that in the case of cities in developing countries, urbanization will move together with economic growth but the rate of population growth will be a burden for spatial planning in the city (24). Therefore, planning and policy makers need a reliable land change model, which can be used to simulate the growth or development of a city (25).

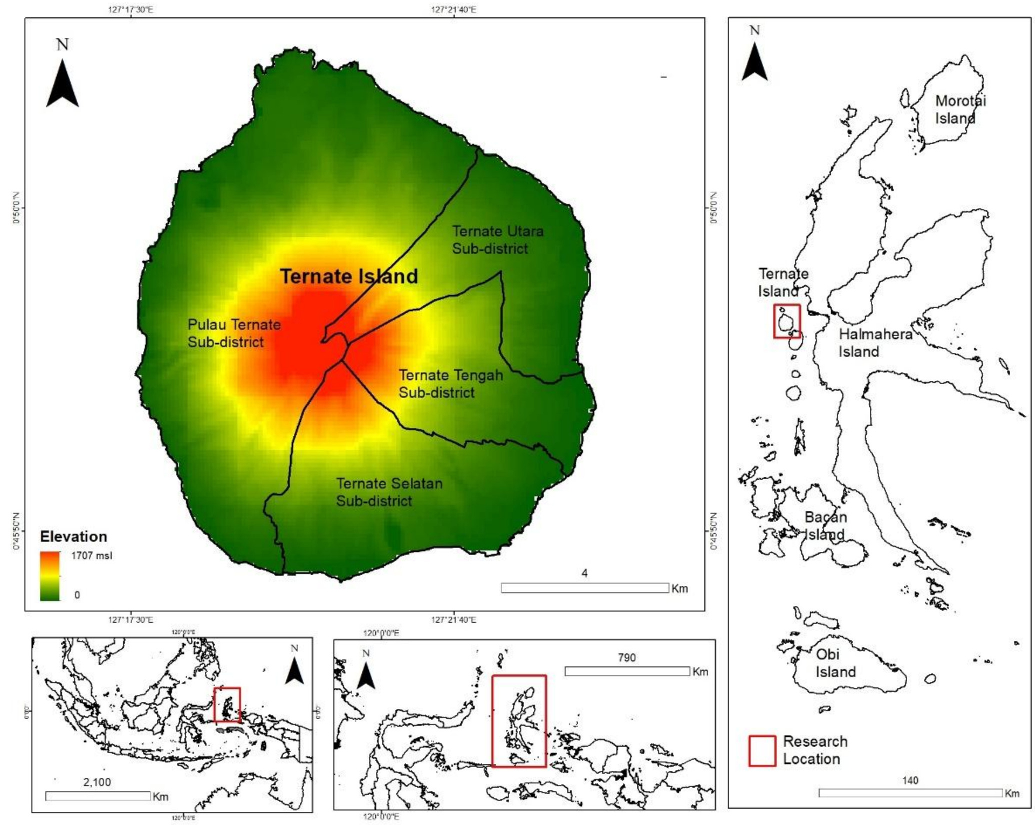

Figure 1. Research location: Ternate Island, Indonesia

In implementing a sustainable development strategy to monitor and predict the rate of urban growth, it is necessary to use Geographic Information System technology, which functions to store, analyze and present spatial information with the help of data and attributes (26). The Cellular Automata-Markov Chain method is one of the modeling methods that can be used to determine future city growth (27), (28), (29). The Cellular Automata-Markov Chain method is the most accurate and useful modeling to simulate and predict future spatial and temporal land changes (23), (30). The selection of the Cellular Automata-Markov Chain model is because the model has the ability to predict spatial temporal and statistical land cover changes that are very accurate and dynamic (31), (32).

The variables or driving factors used in this study are elevation, slope, distance from the road, POI distance. These variables or driving factors are selected based on factors that influence the development of residential areas. The plans that have been set are often not in line with development or land use. Therefore, this research will also compare settlements based on the RTRW of Ternate City in 2012 - 2032. Based on the description above, this research is a reference in overcoming the phenomenon of urban growth, especially on Ternate Island. City growth has an impact on land use on Ternate Island, so planning is needed as a reference for policy formulation and integrated real action efforts. Based on the background and problems of urban growth on Ternate Island, the purpose of this study is to determine the development of Ternate Island growth in the period 2004-2032.

2. Methods

2.1. Data Collection

This research was conducted on Ternate Island, North Maluku Province, Indonesia (Figure 1). The data used in this study consisted of primary and secondary data. Primary data obtained from surveys in the form of field validation by conducting observations and documentation. Observation and documentation were carried out at sample points that had previously been determined before conducting field surveys. The stratified random sampling method is the method used to conduct validation samples. Stratified random sampling determines random points in each classification class and is attempted to be evenly distributed throughout the study area. The sample points selected were the results of observations on the 2024 image of Ternate Island. Validation was conducted to verify the location of settlements from the processed data with the actual situation. The sampling points are based on the rule of thumb theory where the minimum sample points are 50.

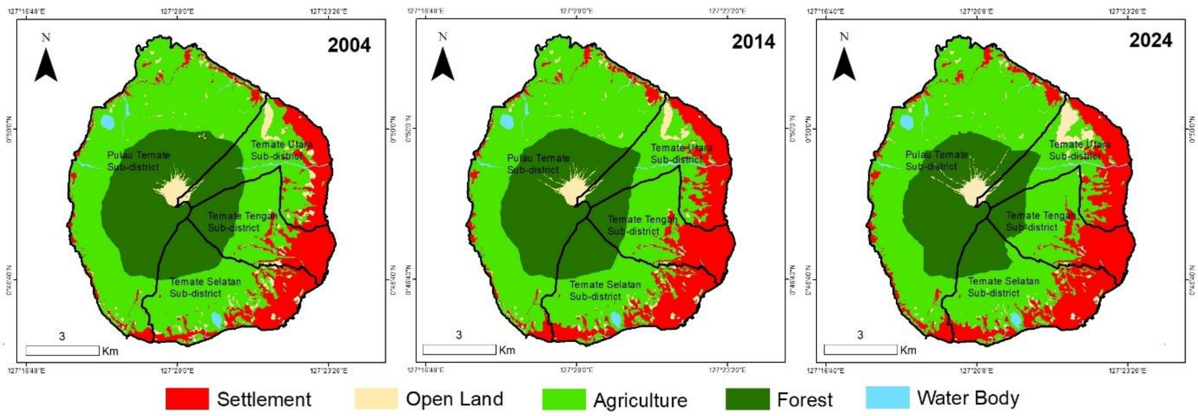

Figure 2 Land cover of Ternate Island in 2004, 2014, and 2024

Secondary data includes land cover data (2004, 2014 & 2024), sub-district administration, elevation, slope, road network, POI (distance from economic, health and education facilities), and Ternate City Spatial Plan 2012-2032. Land cover data was obtained from interpretation and classification of Landsat 5 TM (02/08/2004), Landsat 8 OLI satellite image datasets on 20/05/2014 and 15/06/2024 on the Google Earth Engine platform. These three satellite images have the same spatial resolution of 30m. The selection of these three Landsat images is based on the availability of existing data and has a recording interval of 10 years. Elevation and slope data were processed using the National Digital Elevation Model (DEMNAS) data obtained from the Indonesian Geospatial Information Agency. Road network data was obtained from the Indonesian Earth Shape map - Indonesian Geospatial Information Agency. POIs (distance from economic, health and education facilities) were obtained from OpenStreetMap data. According to Zhou et all., the flat elevation and steep slopes are very suitable areas for future development of residential areas, and are safe from landslides that often occur on Ternate Island (15). Based on previous studies, settlements will tend to develop following the road network and proximity to economic facilities and education centers, this is certainly very easy for accessibility (9), (15).

2.2. Data Processing and Analysis

Data processing is done with several software, namely Google Earth Pro, ArcGIS Pro, IDRISI Selva, and Microsoft Excel. Landsat 5 TM image data in 2004, and Landsat 8 OLI 2014 & 2024, then radiometric and atmospheric correction. The land cover images obtained were radiometrically and atmospherically corrected in Google Earth Engine. The purpose of radiometric and atmospheric correction is to improve the accuracy of the image by correcting image errors caused by inconsistencies in the shape of the Earth's surface due to various factors, such as the direction of sunlight towards the Earth's surface, and cloud cover. The corrected image is then transformed into land cover data by performing supervised classification of the Landsat image using the machine learning feature of Google EarthEngine. The machine learning algorithm used is Classification and Regression Tree (CART).

Basically, this method is a method that consists of two methods, namely the regression tree method and the classification tree (16). If the dependent variable has a categorical type then CART will produce a classification tree. Meanwhile, if the dependent variable has a continuous or numeric type, CART will produce a regression tree. In supervised classification of Landsat imagery, the output is categorical so the method used is classification tree (16). The advantage of this system is that land cover mapping can be done quickly, because mapping is done by inputting training data to the machine to detect various characteristics of the image and assign it to the specified class. In addition, the images used can be automatically corrected (20). The downside of the algorithm is that the accuracy of the map is based on the imagery used and the training data created, as the land cover classification is pixel-based (16). The land cover classification was divided into settlements, open land, agriculture, forests and water bodies (Figure 2), after being classified more specifically into urban and non-urban areas (Figure 6).

Driving factors are used to determine locations that can change from each pixel of land cover to other types. The four driving factors, namely slope, elevation, distance from road, distance from POI are processed in ArcGIS Pro software using Multi Ring Buffer and slope tools. The driving factors were classified based on previous research. The driving factors data was then converted into a raster form using the polygon to raster tool, then the raster data of each driving factor was resampled to equalize the resolution with the spatial image data used, which is 30 meters per pixel. After that, the driving factor data that has been resampled is then carried out fuzzy membership with a value of 0-1 with the fuzzy membership tool and then overlaid using the fuzzy overlay (0-1) tool which can then produce a combined suitability of all driving factors (Figure 3).

To generate a prediction of land use in 2032, a two-stage Markov Chain process was conducted. The first stage involved using 2004 and 2014 land use data to obtain the 2024 transition probability matrix. The next stage used 2011 and 2024 land use data to obtain the 2032 transition probability matrix. All data were processed with the help of IDRISI Selva software, and the digitized land use maps from ArcGIS Pro software were saved in (.rst) format so that they could be read by IDRISI Selva software. The approach used in this research combines two methods, namely Markov Chain and Cellular Automata, through IDRISI Selva software. The method applied is Cellular Automata-Markov Chain modeling which is already available in the software. This process involves the use of driving factors data that has been overlaid with fuzzy overlay, as well as the area transition matrix from the Markov Chain process. This process was conducted in two separate stages to test accuracy. The first stage involved the creation of a 2024 land use simulation model, while the second stage involved the creation of a 2032 land use simulation model. Although the Cellular Automata-Markov Chain (CA-MC) model has proven to be accurate and dynamic in predicting urban growth, it is important to note some limitations that may affect the analysis results (22). The model may not be able to accommodate sudden socio-economic changes, such as economic crises or significant policy changes, which can drastically alter urban growth patterns (22).

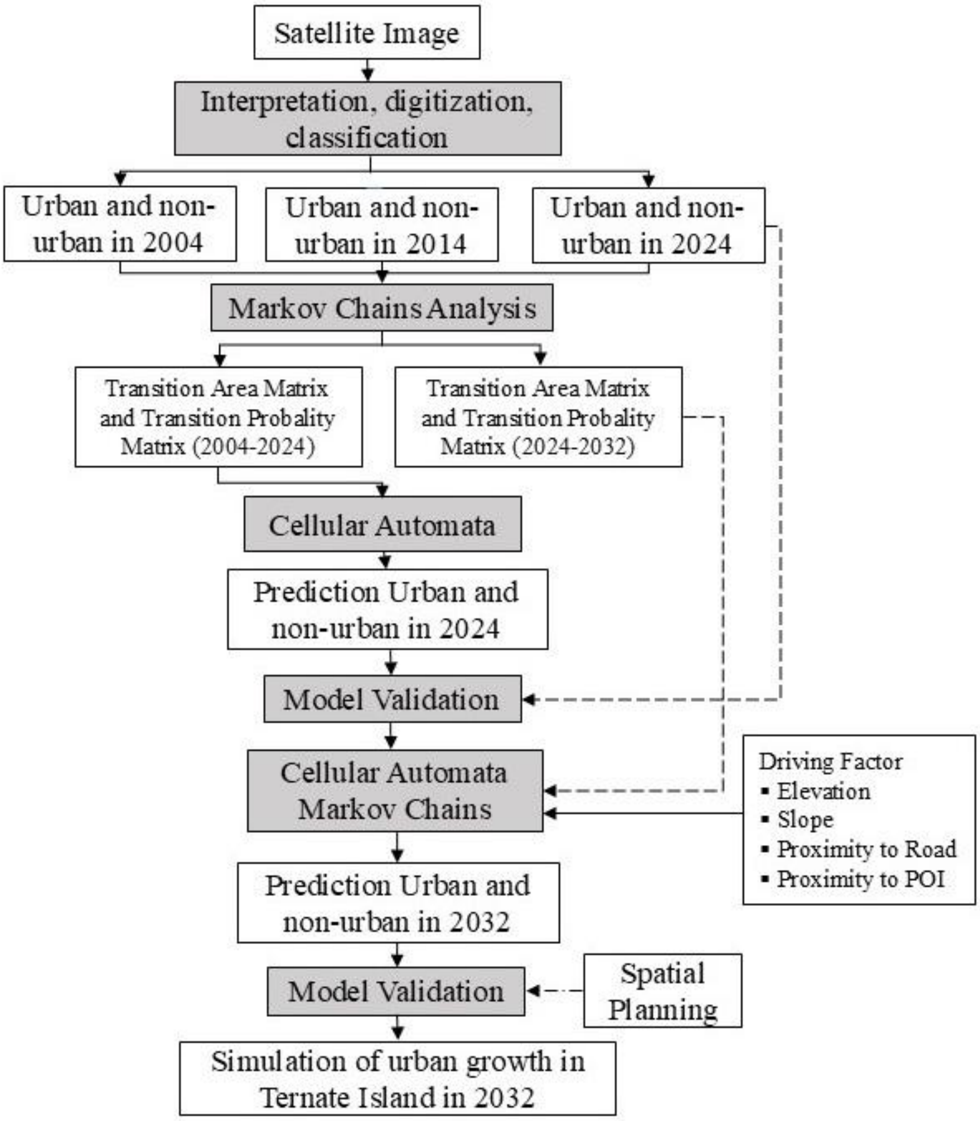

Figure 4. Workflow

In the Kappa validation test stage, the validate tool in IDRISI Selva software was used to compare the 2023 land use from the field validation results with the 2023 land use prediction from the simulation model. The Kappa value itself can be classified into several categories, namely Kappa value <0 which indicates no agreement, 0-0.2 indicates poor results, 0.0-0.41 as medium value results, 0.41-0.60 as substantial, 0.60-0.80 as significant, and 0.81-1.0 as almost perfect agreement (30). If the resulting Kappa value is at least 70% (0.7), then the process of predicting land use in 2031 can continue. In processing the suitability of urban areas on Ternate Island based on driving factors data. The results obtained are then overlaid with the Ternate City RTRW urban area area in 2012-2032. Settlement development also considers urban areas based on the prediction of urban areas in 2032 on Ternate Island. The complete workflow can be seen in Figure 4.

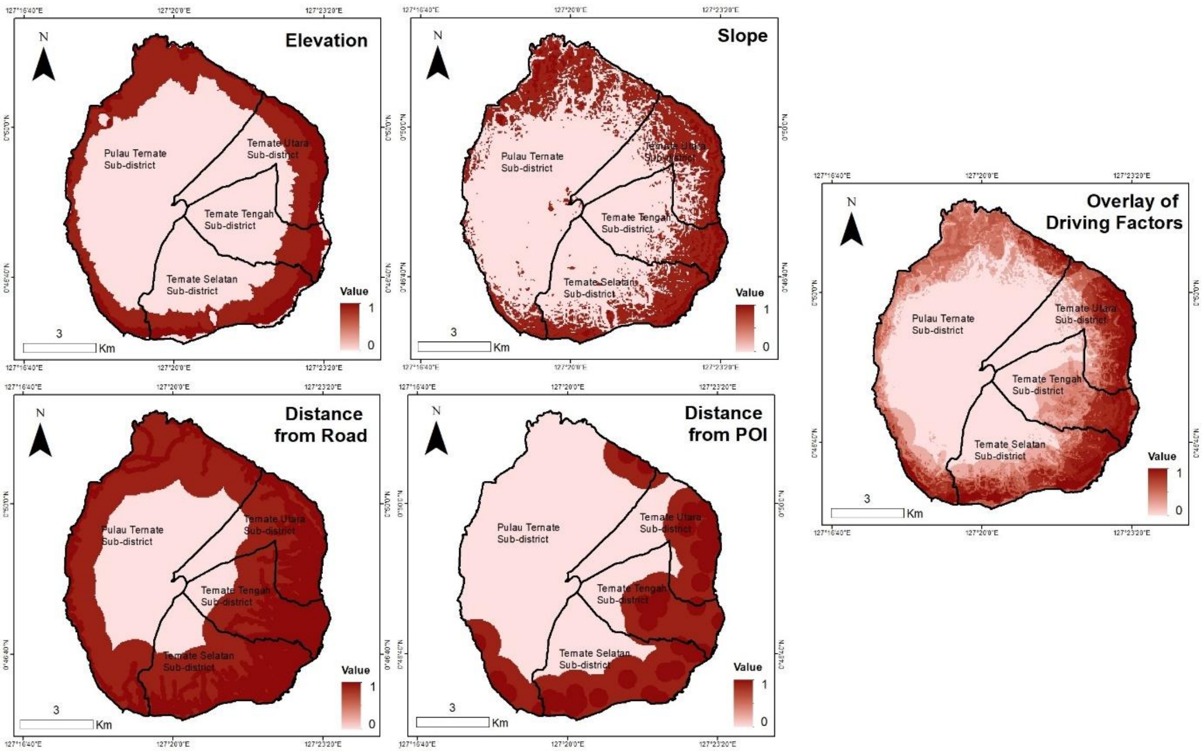

Figure 3. Driving factors of urban growth in Ternate Island

3. Results and Discussion

3.1. Development of Urban Areas in Ternate Island

Over the last 20 years, residential land or urbanized areas of Ternate Island have increased significantly. Figure 5 shows that every 10-year period, sub-districts in Ternate Island experienced an increase in the land cover area of residential buildings. The increase in area was driven by the high population growth in Ternate Island because it is the center of education, economy, and government.

Urban areas in 2004 had an area of 1,424.14 ha and non-urban areas had an area of 8,786.32 ha. Urban areas (2014) in Ternate Island continued to increase in size by 1,728.45 ha and non-urban areas decreased in size by 302.32 ha (8,484.01 ha). In 2024, the urban area of Ternate Island will continue to increase by 2,010.78 ha and the non-urban area will decrease by 283 ha, leaving an area of 8,291.68 ha. Ternate Tengah and South sub-districts continue to be the sub-districts that have a large percentage of area increase compared to other sub-districts. Urban development of Ternate Island in 2004, 2014 and 2024 can be seen in Figure 5.

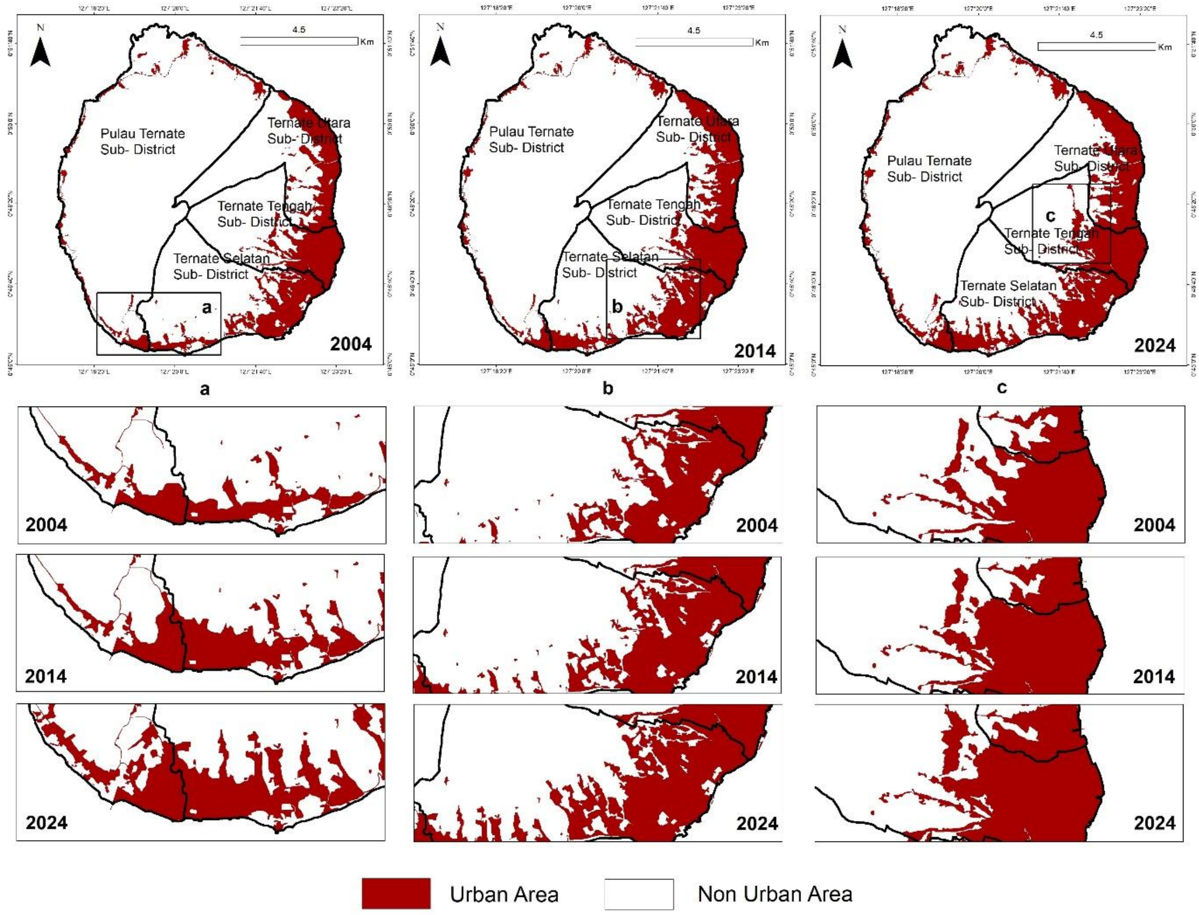

Figure 5. Urban development of Ternate Island in 2004, 2014 and 2024

3.2. Urban Area Simulation 2024

The simulation of urban areas in 2024 is used to be a prediction model in the next iteration with a model that has a kappa coefficient value above 0.70 which is in accordance with the categorization in the literature review, the kappa value has a good accuracy category. The model was obtained using the probability matrix from 2004 - 2014 resulting from the Markov process shown in Table 1.

Table 1. Transition Probability Matrix (TPM) from 2004-2024

	Urban Area	Non Urban Area
Urban Area	0.9850	0.0150
Non Urban Area	0.0485	0.9515

The 2024 urban prediction results in Figure 6 show that the urban area has an area of 2,376.64 ha, different from the 2024 analysis results, which is 2,010.78 ha. The non-urban area of the simulation results has an area of 7,835.82 ha in contrast to the 2024 analysis results which has an area of 8,20.68 ha. The results of the validation of the 2024 land cover model with actual land cover using the kappa index were found to be 0.89, in other words, the results of the 2024 land cover prediction model are included as significant with a value of 0.60 - 0.80. The validation results of the 2024 land cover model with actual land cover using ROC with area under the ROC curve (AUC). The ROC results show an area under the ROC curve (AUC) value of 0.75 where the value is classified into acceptable with a range of 0.7 -

0.8. So based on the validation results of kappa and ROC, the Cellular Automata- Markov Chain model can be continued to predict land cover on Ternate Island in 2032.

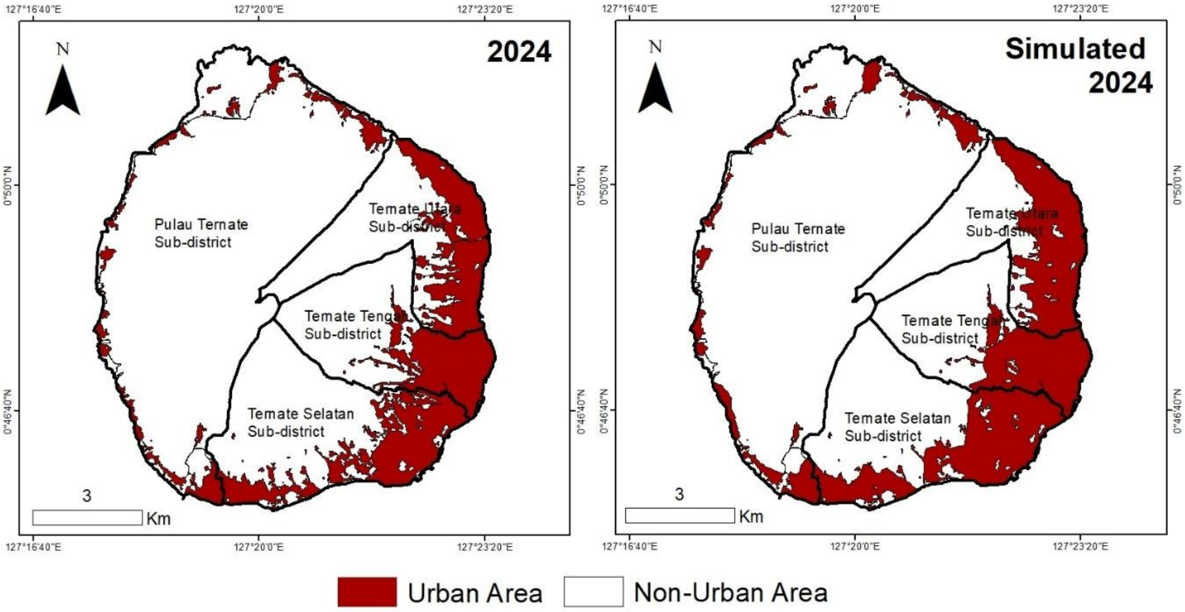

Figure 6. Urban areas in 2024 and simulation results 2024

3.3. Predicted Urban Area Development 2004-2032

The results of the analysis obtained from the Markov Chain of land cover in 2014 and 2024 obtained a probability matrix between land cover in 2014 and 2024. The row in the table is the original land cover classification, while the column in the table is the purpose of land cover change from the original land cover classification. The probability matrix of land cover change has a value in the interval 0-1. The closer the value of the probability matrix is to 1, the higher the probability of land cover change. Vice versa, the closer the probability matrix value is to 0, the lower the probability of change (Table 2).

Table 2. Transition Probability Matrix (TPM) from 2024-2032

	Urban Area	Non Urban Area
Urban Area	0.8500	0.1500
Non Urban Area	0.1789	0.8211

The prediction results of urban development on Ternate Island using Cellular Automata-Markov Chain in Figure 7 show that the urban area has an area of 2,884.37 ha and the non-urban area continues to decrease in area of 7,428.37 ha. While the spatial plan set by the Ternate City government predicts that the urban area has an area of 2,589.51 ha. The suitability of the prediction of settlement land in 2032 with the Regional Spatial Plan (RTRW) of Ternate City in 2012-2032 was conducted with the aim of evaluating the RTRW to optimize land use. The evaluation conducted on settlement land in the RTRW aims to ensure that settlement development is in line with community needs, produces sustainable settlements, is safe from natural disasters, and can accommodate the population optimally in accordance with projections in 2032.

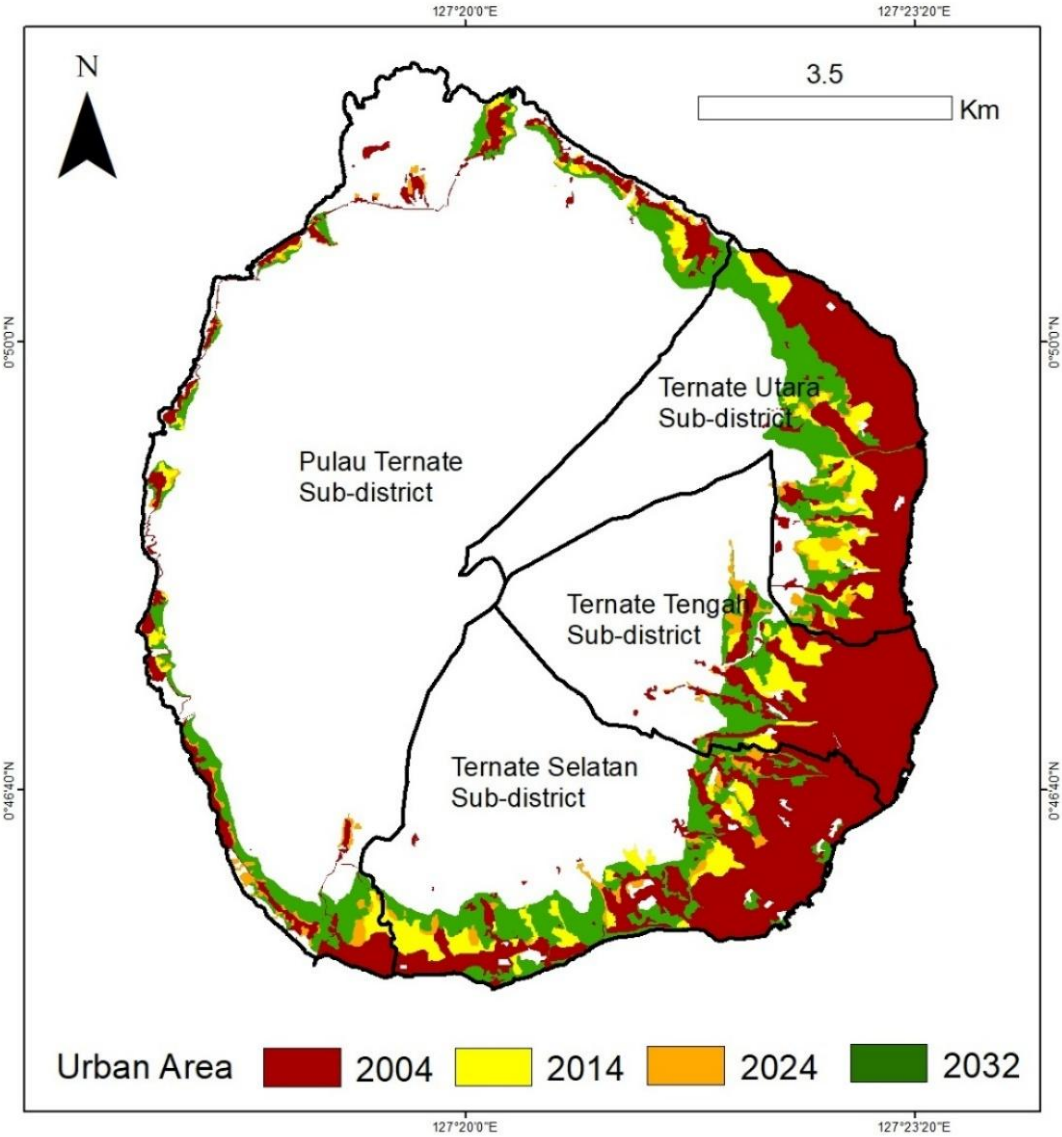

Figure 8. Urban Growth 2004-2032 Ternate Island

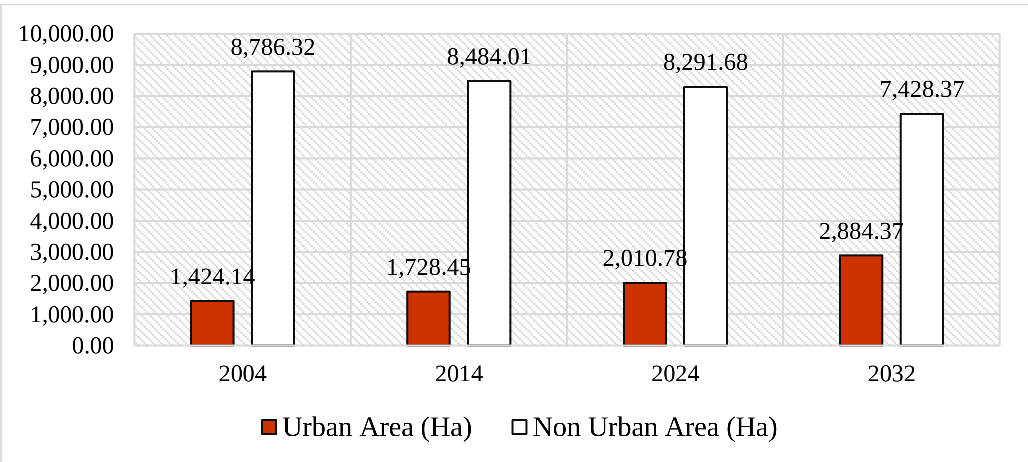

Figure 9. Urban Growth Area 2004-2032 Ternate Island

The predicted results of urban development on Ternate Island from 2004 to 2032 (Figure 8 and 9), analyzed through the Markov Chan Cellular Automata Model, revealed significant changes in land use patterns. Non-urban areas continue to decline, especially in the sub-districts of Central Ternate and South Ternate, which are urbanizing faster than other areas on the island. The growth of built-up land is mainly concentrated along major highway routes, suggesting that infrastructure development plays a crucial role in shaping urban expansion. This trend confirms the influence of transport networks in driving urban sprawl and emphasizes the need for strategic planning to manage future growth. The findings indicate that without appropriate intervention, Ternate Island's ecological and environmental balance could be further jeopardized, potentially undermining food security and the overall sustainability of the region.

The results of this study confirm the importance of integrating sustainable spatial planning principles in the development of Ternate City. By considering rapid urbanization trends and their environmental impacts, policy makers can design strategies that balance urban growth with ecological preservation (18). Maintaining the carrying capacity and environmental capacity of the city is essential to ensure long-term sustainability (30). This includes protecting non-urban areas, such as agricultural land and natural ecosystems, which are essential for food security and environmental stability. In addition, urban development should prioritize efficient land use, green infrastructure, and the integration of ecological considerations in the planning process. Thus, Ternate City can achieve a harmonious balance between urbanization and environmental sustainability, ensuring a resilient future for its residents.

The findings of this research are expected to be an important reference in designing sustainable spatial planning in Ternate City. Rapid urban development in Ternate Tengah and Ternate Selatan sub-districts, particularly along the main highway routes, confirms the need for policies that mitigate the negative impacts of urbanization on ecological and environmental balance. Sustainable spatial planning should focus on preserving non-urban areas, increasing green open spaces, and compact urban development to reduce urban sprawl. In addition, the integration of food security considerations in urban planning is essential to ensure that urban growth does not come at the expense of meeting the needs of its population. By applying a holistic approach that balances urban expansion and environmental conservation, Ternate City can maintain its ecological integrity, support food security, and achieve sustainable development goals, thereby creating a resilient and livable urban environment for future generations.

Conclusions

Based on the results of this study, it is concluded that the growth of Ambon Island is followed by changes in land use from 2004 - 2024. Urban areas in Ternate Island continue to experience an increase in area, namely in 2004 the urban area had an area of 1,424.14 ha, 2014 an area of 1,728.45 ha and in 2024 an area of 2,010.78. The prediction results of urban growth on Ternate Island in 2032 show that the urban area has an area of 2,884.37 ha. City growth in Ternate Island is caused by the factor of social economic activities and education that dominate the utilization of land for the construction of facilities and supporting infrastructure. It is expected that these findings can be taken into consideration in designing a sustainable spatial planning of Ternate City. So that ecological balance, environmental balance and food security can be maintained and meet the requirements of a city that has carrying capacity and environmental capacity.

Funding

This research received no external funding

Conflicts of Interest

The authors declare no conflict of interest

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