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PREDICTION OF LAND COVER CHANGES ON THE AVAILABILITY OF IRRIGATION WATER IN THE BOLON RIVER BASIN

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ABSTRACT

Increasing food demand and urban development have driven rapid land cover change and affected water supply. Globally, irrigated agriculture is the largest consumer of water. This study aimed to assess the prediction of land cover change on water supply in the Bolon watershed. Land cover change was analyzed using CA-MC method with QGIS plug in Molusce model and prediction of future land cover change. SWAT integration model with GIS was used to evaluate water supply. The results of image analysis during the 2017-2024 period revealed an increase in urban areas (4.8%), shrublands (1.0%) and water bodies (0.6%) and a decrease in forests (0.5%), irrigated agriculture (1.5%) and vegetations (4.5%) of the total area of the Bolon watershed. While in the period 2024-2033 showed an increase in urban areas (5.2%), vegetations (1.5%), irrigated agriculture (4.5%) and a decrease in forests (5.9%), shrublands (4.8%) and water bodies (0.5%) of the total area of the Bolon watershed. Modeling with SWAT+ resulted in monthly Q80 supply discharge with average discharge in 2017 (50.70 m3/s), 2024 (49.99 m3/s), 2029 (47.85 m3/s) and 2033 (47.27 m3/s). This study retrived that the impact of LULC changes on irrigation water supply at the sub-watershed scale during the 2017-2024 and 2024-2033 periods using SWAT+ is different from the result at the watershed scale. Land cover change of irrigated agriculture into urban areas, specifically in the downstream of the Bolon watershed during 2017-2033 period, caused a decrease in irrigation water demand so that the downstream watershed changes from low supply to medium supply and changes in vegetations land cover, and shrublands into urban areas in sub-watersheds during 2017-2033 period have caused a decrease in water supply in the river so that sub-watershed changes from high supply to medium supply.

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INTRODUCTIONS

Over the past few decades, the demand for water, which is primarily driven by population growth and economic development, has increased at a rate of 1% per year. Agriculture is still the sector with the largest water consumption globally. In areas experiencing water scarcity, optimizing water use by plants spatially is a crucial aspect in efforts to improve irrigation efficiency and support water resource management at the regional level. This can be true in areas experiencing a crisis in water distribution, for example in agriculture in the Bolon Watershed where the use of irrigation water accounts for almost 90% of the total surface water consumption. The Bolon watershed is a watershed under the authority of the North Sumatra Provincial Government which has experienced quite rapid development, one of which is due to the existence of the Sei Mangkei Industrial Estate and the Kuala Tanjung Industrial Estate development plan. In addition, the Bolon watershed is a rice barn area in North Sumatra which has thousands of hectares of agricultural land. The existence of Pematang Siantar City as a settlement center and urban area development also plays an important role so that the area has the potential to experience land changes which will certainly affect the availability of water, especially irrigation water. (Zhang et al., 2023) (He et al., 2020)

Previous research has shown that an increase in irrigation water supply, for example due to the construction of reservoirs or water displacement, leads to an increase in irrigated agriculture, Changes in land use and cover have a large role to play on the spatial and temporal dynamics of water resources. However, a clear understanding of how the spatial distribution of future dryland use will affect the balance between water supply and demand is still limited. (Gharaibeh et al., 2020)

Land-use changes have had a significant impact on the hydrological characteristics at the watershed level over the past few decades. Variations in land cover types, particularly vegetation distribution, contribute to changes in basin hydrological responses, including increases or decreases in surface runoff. The complex interactions between vegetation and the physical properties of the soil can modify key components in the hydrological cycle, such as infiltration, evapotranspiration, and groundwater storage, which in turn affect the pattern of annual discharge distribution. Land conversion, especially towards open land or built-up areas (urbanization), is generally associated with increased peak discharge and total runoff volume due to decreased infiltration capacity and increased impermeable surface area. (Hamad et al., 2018)

Over the past two decades, the Cellular Automata–Markov Chain (CA–MC) modeling approach has evolved to become one of the most widely used methods globally in the analysis of spatial and geographic changes. The Cellular Automata Markov Chain (CA-MC) model combines Cellular Automata and Markov Chain to predict trends and characteristics of land cover over time. Markov Chain is an empirical/statistical model, while Cellular Automata is a dynamic model that is incorporated into the GIS platform. (Gebrie Habte et al., 2024) (Eekhout et al., 2024) (Gashaw et al., 2017)

Along with this, the need for water in the future must be met and allocated according to the order of priority, especially in order to provide daily basic needs and also for people's agriculture. The government must be adaptive to the impact of changes in water availability by providing the right public infrastructure for the provision of water needs in a watershed.

Understanding the response of the hydrological component to land use and land cover (LULC) is essential for water resource management planning for catchment areas in a changing environment. Comparative analysis of land cover and land use maps (LULCs) from different time periods allows the identification of patterns of spatial change that impact hydrological responses, particularly river flows. This evaluation provides a deeper understanding of the hydrological consequences of changes in the LULC, both past and projected in the future, on the dynamics of river discharge temporally. (Beshir et al., 2023) (Jawarneh et al., 2024)

To investigate the impact of LULC changes by taking into account year-to-date historical land cover changes on water balance components on an annual, seasonal, and monthly basis, some studies used a SWAT (Soil and Water Assessment Tool) model that was calibrated and validated and integrated with GIS (Geographic Information System)

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data to analyze the response of water balance components to changes in LULC. SWAT models typically work well in runoff simulations based on Nash-Sutcliffe Efficiency (NSE) and Coefficient of Determination (R2), the integration of remote sensing, GIS and SWAT models provides powerful tools for runoff simulation of watersheds. (Anand et al., 2018; Ayalew et al., 2024) (Asra et al., 2020; Khalid et al., 2024)

The purpose of this study is to determine the relationship between the prediction of land cover change in an eight-year period in the Bolon Watershed to the availability of water at the sub-watershed level due to changes in surface infiltration and runoff as well as to irrigation water needs due to changes in the area of agricultural land that requires water.

This research focuses on the problem of water availability affected by changes in land cover in the future, especially in the Bolon Watershed. The problems raised include how the development of agricultural land changes in the Bolon watershed, how to predict changes in agricultural land cover in the future, and how these changes affect the availability of irrigation water in the area. Based on the formulation of this problem, this study aims to analyze the development of agricultural land changes, project future land cover changes, and formulate predictions of the effect of land cover changes on the availability of irrigation water in the Bolon watershed.

The benefits of this research are expected to make a real contribution both academically and practically. Practically, the results of this study can be used as a reference for policy makers in formulating sustainable land use management strategies and in planning for the development of water resources infrastructure. In addition, understanding the relationship between land cover change and water availability can provide useful recommendations in water resource management, including in determining priorities for infrastructure development. Academically, this research is expected to be the basis for further research exploring the social and economic aspects of land cover change on water resources.

The scope of this study is limited to the Bolon watershed area in North Sumatra with a focus on analyzing changes in agricultural land cover in a certain period based on historical data. The analysis focused on the main land cover category, namely agricultural land, taking into account changes in forest land, settlements, plantations, shrubs, and water bodies. The prediction model used is the Cellular Automata Markov Chain, without involving other statistical methods such as multivariate regression. In the hydrological aspect, the analysis of water availability is carried out using the SWAT (Soil and Water Assessment Tool) model without considering the influence of future climate change or water discharge on the level of water withdrawal in irrigation areas. The data used includes land cover data from satellite imagery and secondary data from related agencies in the period 2017 to 2024. The analysis of predictions of land cover changes and their effects on the availability of irrigation water is limited to the period 2029 to 2033 so that the results of the study remain consistent and relevant to the availability of data.

Overall, this research is expected to make an important contribution in improving understanding of the interaction between land cover change and water availability at the watershed level, as well as a reference for future environmental sustainability-oriented development planning.

METHOD

This study uses a descriptive quantitative approach with spatial and hydrological modeling methods to analyze the relationship between changes in agricultural land cover and the availability of irrigation water in the Bolon Watershed, North Sumatra. The analysis was carried out through the integration of the Cellular Automata Markov Chain (CA–Markov) model to predict changes in land cover and the Soil and Water Assessment Tool (SWAT) model to analyze the hydrological response to these changes. The entire process of modeling and spatial analysis is carried out using the QGIS application with the help of the MOLUSCE and QSWAT+ plugins. (Judijanto et al., 2024)

The main data used in this study include multi-temporal satellite image data from 2017, 2021, and 2024 which were used to identify and map land cover. This data is complemented by data on rainfall, air temperature, relative humidity, wind speed, solar irradiation, as well as soil type and topography (DEM) data. Data sources were obtained from related institutions such as BMKG, BIG, and the Ministry of Environment and Forestry. All satellite images used

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underwent a process of radiometric correction and area clipping based on the hydrological boundaries of the Bolon watershed so that the focus of analysis remained in accordance with the research area.

The modeling of land cover change in this study uses the Cellular Automata Markov Chain (CA–Markov) model through the MOLUSCE plugin in QGIS to analyze and predict future changes in agricultural land based on historical patterns. This process includes four stages, namely determining the factors driving change (slope slope, distance from roads, settlements, and activity centers), correlation analysis between factors and the creation of transition matrices, modeling the transition potential using the Artificial Neural Network (ANN-CA), and simulating the projected land cover change for the period 2029–2033. Validation was carried out using a Kappa value with a standard ≥ 0.70, where an accuracy above 70% indicates a good model.

Furthermore, the analysis of the hydrological response was carried out with the SWAT (Soil and Water Assessment Tool) model through QSWAT+ in QGIS to simulate the effect of land cover changes on water availability in the Bolon watershed. The stages include watershed delineation using DEM data, the formation of a Hydrologic Response Unit (HRU) based on a combination of land cover, soil type, and slope, as well as climate data input to simulate surface flows using the SCS-CN method. The simulation results produce a reliable discharge that is compared to the irrigation water requirement, while the model validation uses R^2 and NSE values to assess the conformity with the observational data. The final analysis correlates the results of the CA–Markov projections with the results of SWAT simulations to identify the extent to which changes in agricultural land affect the availability of irrigation water and provide a scientific basis for sustainable land and water resources management strategies in the Bolon watershed.

RESULT AND DISCUSSIONS

Development of Bolon Watershed Land Cover

The land cover data used in this study are ESRI data for 2017, 2021 and 2024. This data is then classified into six classes according to existing needs and conditions. Land cover classification data and maps are shown in Table 4.1 and Figure 4.1, Figure 4.2 and Figure 4.3.

Table Error! No text of specified style in document.**.1 Land cover data for 2017, 2021 and 2024**

Land cover	2017		2021		2024	
	Km2 area	%	Km2 area	%	Km2 area	%
Forest	183,55	9,53	85,87	4,46	174,41	9,05
Agriculture	236,26	12,26	339,34	17,61	207,60	10,77
Plantation	1364,28	70,80	1346,64	69,88	1277,82	66,32
Bush	84,27	4,37	26,16	1,36	104,36	5,42
Water bodies	0,07	0,00	2,87	0,15	10,99	0,57
Settlements	58,51	3,04	126,06	6,54	151,68	7,87
Total	1.927	100	1.927	100	1.927	100

Source: ESRI, 2025

There are significant land use dynamics in the seven-year period from 2017-2024, especially in the forest, agriculture, and settlement categories. This development reflects the pressure on land due to human activities, such as

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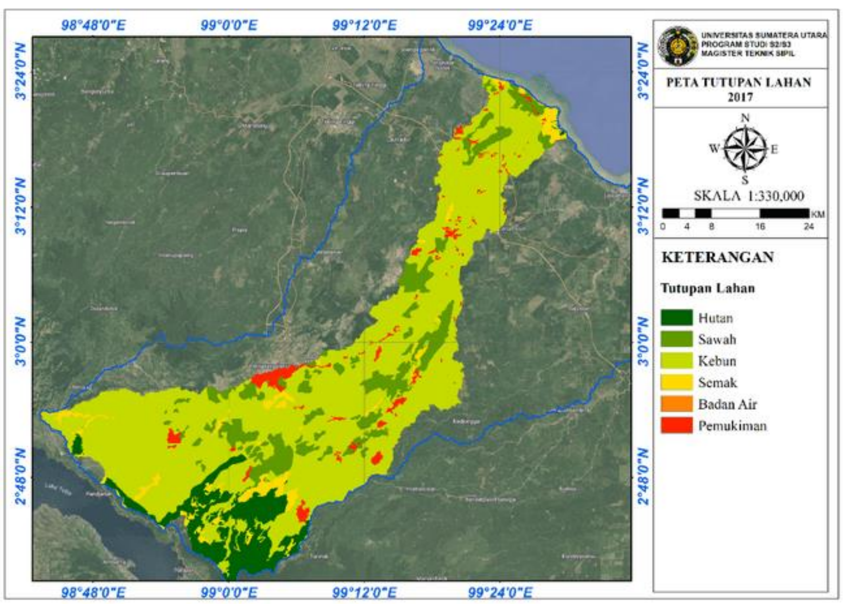
urbanization and expansion of agricultural land and settlements, as well as land rehabilitation efforts in 2024 which are reflected in the re-increase in forest and shrub area.

Based on table 4.1. Agricultural land increased from 236.26 km² (12.26%) in 2017 to 339.34 km² (17.61%) in 2021, but declined again to 207.60 km² (10.77%) in 2024. Forest land has decreased in area from 183.55 km² (9.53%) in 2017 to 85.87 km² (4.46%) in 2021, then increased to 174.41 km² (9.05%) in 2024. Plantations remain the dominant category in land use with an area of about 70% of the total area, although there are slight fluctuations, the area is relatively stable, previously 1,364.28 km² (70.80%) in 2017, 1,346.64 km² (69.88%) in 2021, and 1,277.82 km² (66.32%) in 2024.

Bushland has decreased drastically from 84.27 km² (4.37%) to only 26.16 km² (1.36%) in 2021, but rose again to 104.36 km² (5.42%) in 2024. Water bodies were almost non-existent in 2017 (0.07 km²), but increased to 2.87 km² (0.15%) in 2021 and 10.99 km² (0.57%) in 2024. Meanwhile, settlements experienced consistent growth, from 58.51 km² (3.04%) in 2017 to 126.06 km² (6.54%) in 2021, and increased again to 151.68 km² (7.87%) in 2024.

Some studies (e.g., Andayani *et al.*, 2019) revealed that agricultural land in watersheds fluctuates due to changes in land use policies, climate change, and agricultural intensification. The significant increase in agricultural land in 2021 in the Bolon watershed followed by a decrease in 2024 reflects this dynamic. This suggests that land use patterns are not always linear, but responsive to socio-economic and policy conditions.



Picture **Error! No text of specified style in document.**.1 2017 land cover map

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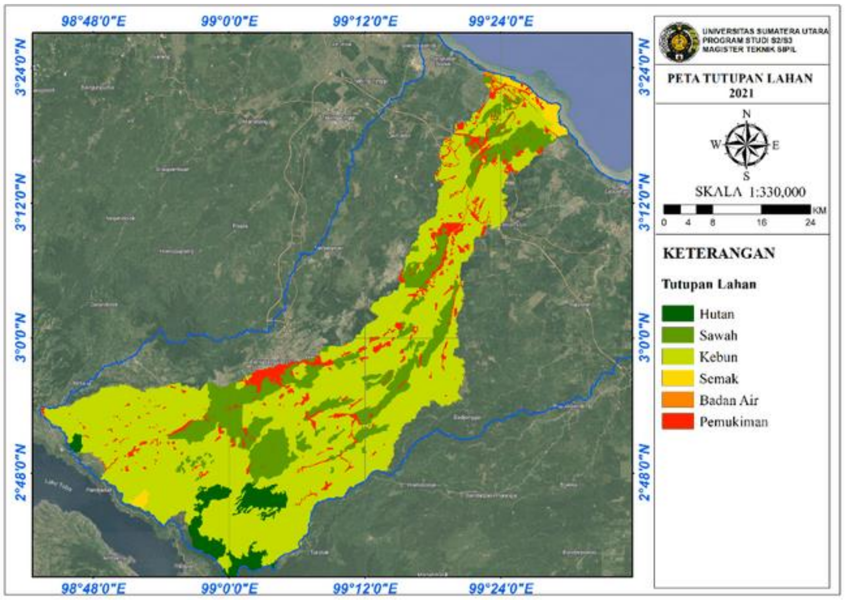
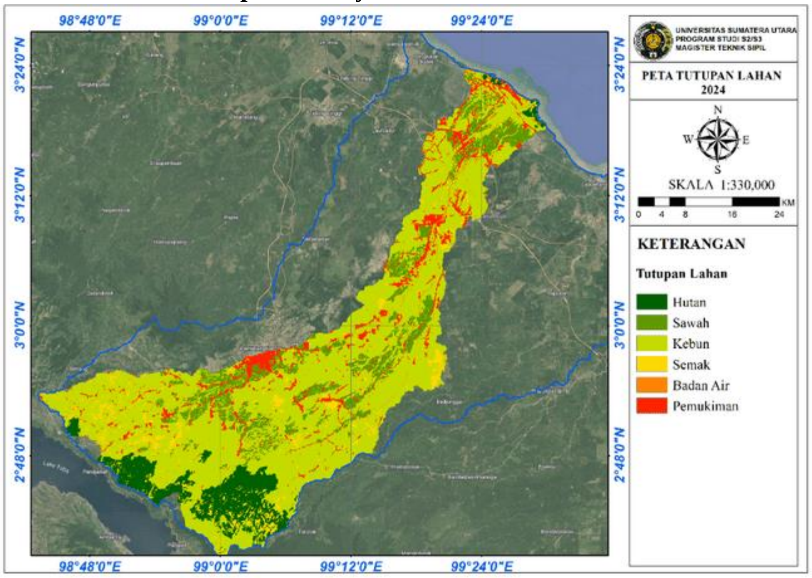


Picture **Error! No text of specified style in document.**.2 2021 land cover data



Picture **Error! No text of specified style in document.**.3 Land cover data in 2024

The changes in land cover during the period 2017-2024 in Table 4.2 and Figure 4.4 show an increase in residential land (+4.8%), shrubs (+1.0%) and water bodies (+0.6%) as well as a decrease in forests (-0.5%), agriculture (-1.5%) and plantations (-4.5%) of the total area of the Bolon watershed.

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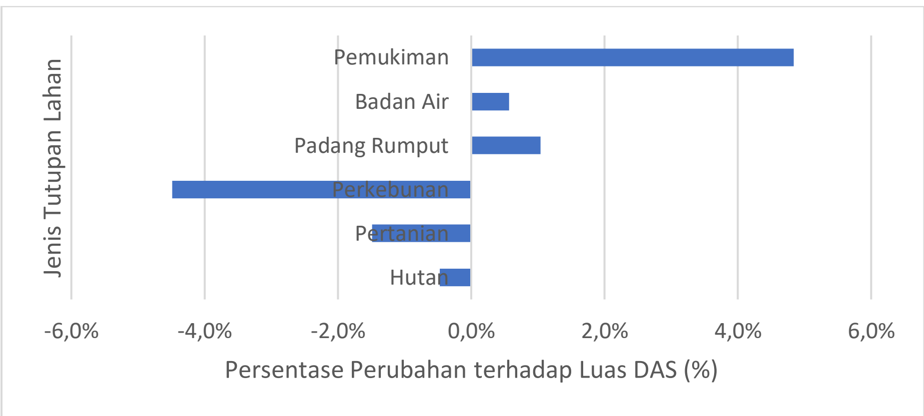
Table Error! No text of specified style in document.**.2 Land cover changes 2017-2024**

Land Cover	Δ (2017-2021)		Δ (2021-2024)		Δ (2017-2024)	
	Km2 area	%	Km2 area	%	Km2 area	%
Forest	-97,68	-5,07	88,54	4,59	-9,14	-0,47
Agriculture	103,08	5,35	-131,74	-6,84	-28,66	-1,49
Plantation	-17,64	-0,92	-68,74	-3,57	-86,38	-4,48
Bush	-58,12	-3,02	78,20	4,06	20,09	1,04
Water bodies	2,81	0,15	8,12	0,42	10,92	0,57
Settlement	67,55	3,51	25,62	1,33	93,17	4,84
Total	0,00	0,00	0,00	0,00	0,00	0,00



Picture Error! No text of specified style in document.**.4 Percentage of land change for the period 2017-2024**

Changes in land use from one type of land cover to another in the 2021-2024 period also occurred. Forest land has increased from 85.87 km² in 2021 to 174.56 km² in 2024. Most of the forest is the result of conversion from plantations (127.31 km²). Agriculture has reduced its area, from 339.33 km² in 2021 to 207.60 km² in 2024. The conversion of agricultural land to plantations (128.04 km²) is the largest contributor and the slightest to settlements (21.51 km2) and bushes (2.59 km2). Plantations decreased to 1,277.83 km² (from 1,346.54 km²), the largest shifting functions to forests (127.31 km²) and shrubs (99.72 km²). However, this could indicate consolidation even if the total area is slightly reduced. The bush increased drastically from 26.42 km² to 104.36 km², mostly from plantation land (99.72 km²) and agriculture (2.59 km2). Water bodies increased significantly from 2.87 km² to 11.02 km². Settlements experienced a significant surge from 126.04 km² to 151.69 km², with most of them coming from the conversion of agricultural land (21.51 km²) and plantations (32.44 km²). The matrix of land cover change for the 2021-2024 period is presented in Table 4.4.

Table Error! No text of specified style in document.**.3 Land cover change matrix for the 2021-2024 period**

Land Cover	Forest	Agriculture	Plantation	Bush	Water bodies	Settlement	Total Year 2021
Forest	33,30	**0,00**	51,70	0,87	0,00	0,00	85,87
Agriculture	**0,00**	**186,17**	**128,04**	**2,59**	**1,03**	**21,51**	**339,33**

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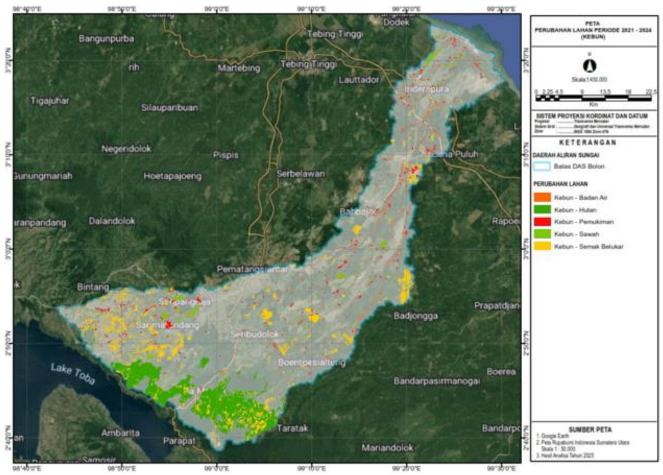
Plantation	127,31	**16,38**	1.064,70	99,72	5,98	32,44	1.346,54
Bush	13,87	**0,08**	8,45	0,28	1,82	1,92	26,42
Water bodies	0,08	**0,01**	0,87	0,01	1,80	0,10	2,87
Settlement	0,00	**4,96**	24,07	0,90	0,40	95,71	126,04
2024 total	174,56	**207,60**	1.277,83	104,36	11,02	151,69	1.926,94

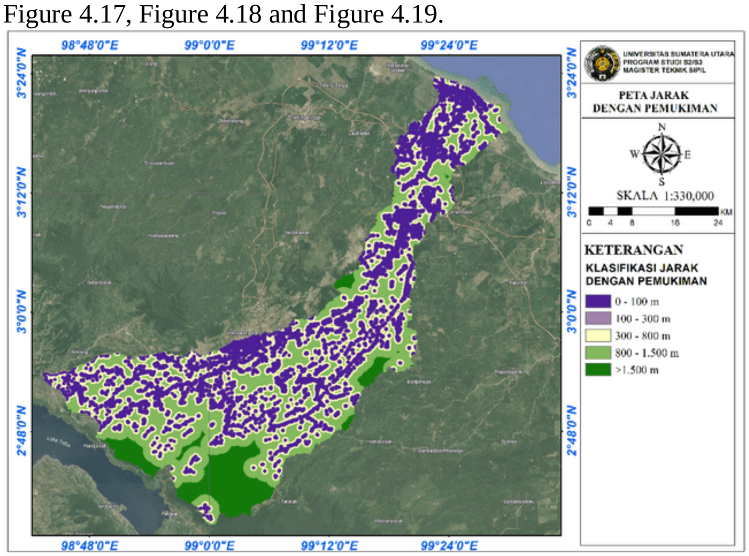
The change in land cover to other land cover for the 2021-2024 period is presented in Figure 4.11 – Figure 4.15.



Picture Error! No text of specified style in document.**.5 Map of plantation land changes for the period 2021-2024**

Factors driving land change

The driving factor is a map of the spatial variables that affect land use. The factors that affect land cover changes in this study are distance from settlements, distance from public facilities, distance from roads and land slope. The driving factor map explains that 1 is the highest area and 5 is the lowest area that affects land cover growth can be seen in Figure 4.16, Figure 4.17, Figure 4.18 and Figure 4.19.



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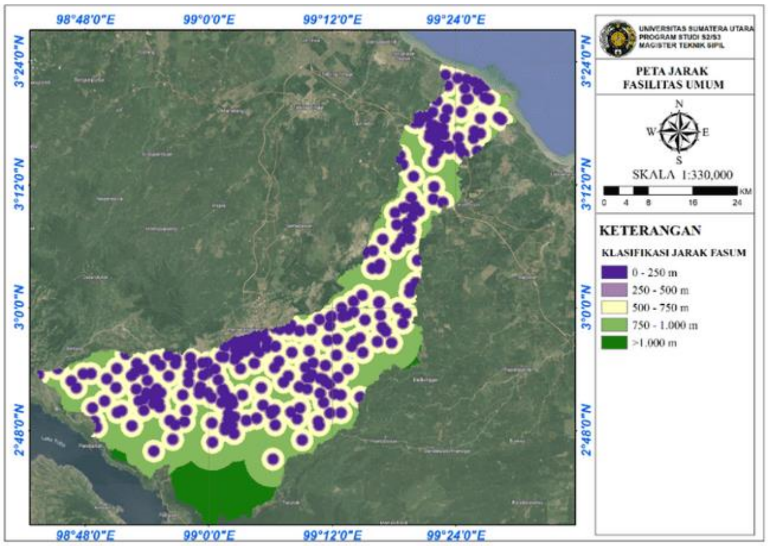
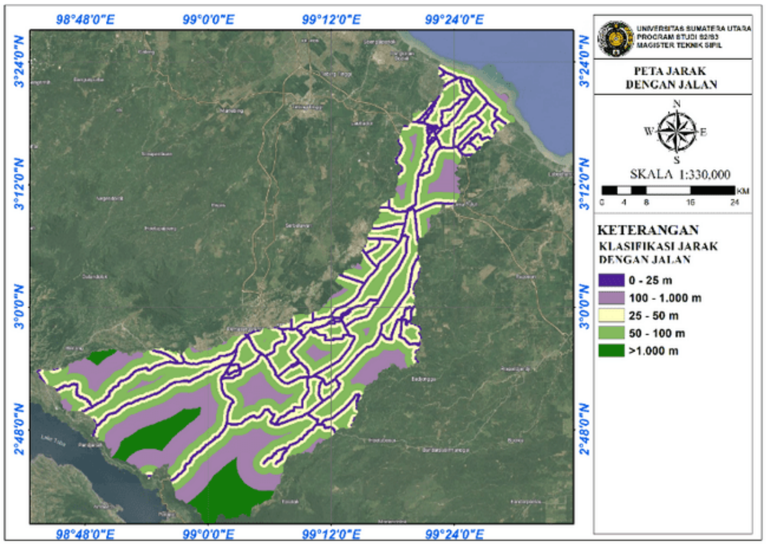
Picture Error! No text of specified style in document.**.6 Driving factors in the classification of distance from settlements**



Picture Error! No text of specified style in document.**.7 Driving factors in the classification of distance from public facilities**



Picture Error! No text of specified style in document.**.8 Driving factors in the classification of distance from the road**

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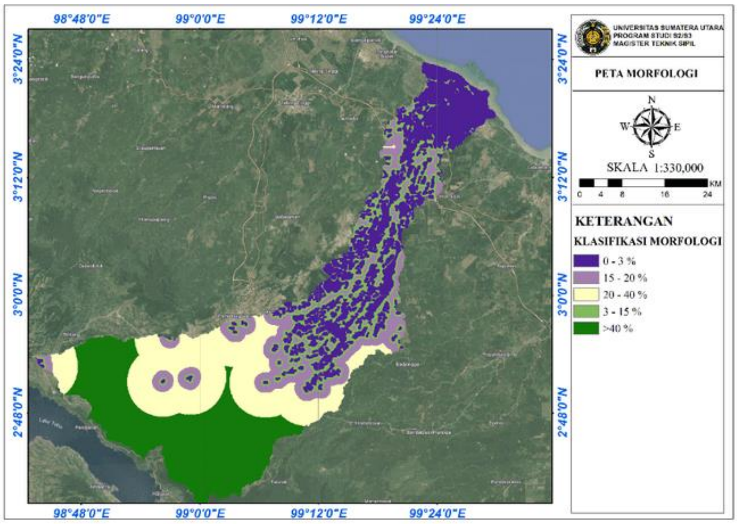

Picture Error! No text of specified style in document.**.9 Motivating factors in morphological classification (land slope)**

Source: analysis results, 2025

Each of these factors has a value and classification that shows the degree of its influence on the development of land cover. The closer the distance to public facilities, the higher the driving value, because ease of access increases the attractiveness of the location.

Locations close to the main road are more accessible, making it more attractive to develop as a settlement. Locations close to existing settlements are usually easier to develop due to social networks and infrastructure. Land with a low slope is easier and cheaper for land to be built compared to land with a high slope. These driving factors are used to classify and assess the potential of a location in residential development. Locations that have low scores (1 or 2) on these factors show high potential for settlement development due to accessibility and supportive land conditions. Conversely, a high value (4 or 5) indicates an obstacle that can impede the balance.

Development of land change for the period 2024-2033

Land cover changes from 2017 to 2024 (Table 4.2) as well as transition matrices from each area's data (Table 4.5) were used to predict future land cover changes for 2029 and 2033 using simulations of initial conditions in 2024.

Table Error! No text of specified style in document.**.4 Land cover transition matrix in 2017-2021**

Land Cover	Forest	Agriculture	Plantation	Bush	Water bodies	Settlement
Forest	0,42	0,00	0,56	0,02	0,00	0,00
Agriculture	0,00	0,74	0,17	0,02	0,00	0,08
Plantation	0,00	0,11	0,82	0,00	0,00	0,06
Bush	0,08	0,06	0,69	0,14	0,00	0,02

Water bodies	0,00	0,00	0,12	0,85	0,00	0,04
Settlement	0,00	0,12	0,36	0,01	0,00	0,50

Source: Mollusce analysis results, 2025

Table 4.5 above shows the probability matrix of land cover change transitions between six land use classes, namely: forests, agriculture, plantations, shrubs, water bodies, and settlements. Each value in the table represents the probability that a land cover class in a row will change to a class in the column in a given time period. Some important points that can be explained from the 4.5 table:

1. Forests have a chance of surviving as a forest of 0.42, but also have a considerable chance of turning into plantations (0.56).
2. Agriculture tends to remain a farm with a probability of 0.74, but it can also turn into plantation (0.17) or settlement (0.08).
3. Plantations have a very high chance of remaining plantations (0.82), while the chances of turning into agriculture (0.11) and settlements (0.06) also exist.
4. Shrubs have a 0.14 chance of remaining as shrubs, but are more likely to turn into plantations (0.69).
5. Water bodies have a high chance of becoming a bush 0.85, although there is a possibility of turning into a garden (0.12) or a settlement (0.04).
6. Settlements have a 0.50 chance of remaining as settlements, but also have the potential to turn into plantations (0.36) and agriculture (0.12).

In general, Table 4.5 illustrates the dynamics of land cover change, some classes such as plantations and settlements show a higher tendency to change than other classes such as water bodies and agriculture.

The transition potential model stage at this stage uses *the Artificial Neural Network* (ANN) method using *random sampling techniques* for the type of transition and the number of samples used 10,000 (ten thousand) samples.

In this process, a *validation Kappa value* was obtained, which means that the prediction process is good and can be continued for the next stage. The reliability of the model is reinforced by a *validation Kappa* value of 0.70 which belongs to the category of "*substantial agreement*" according to the *Landis & Koch* classification. Previous research confirmed that *a Kappa* coefficient close to 1 indicates a perfect deal, while close to 0 is only slightly better than a random prediction.

Simulation of changes with *Cellullar Automata* using 2 iteration simulations, then the results of the simulation in 2029 and 2033 were obtained. Basically, MOLUSCE emphasized that the data used is the latest data for 2024 in comparison with past data, namely 2017 and 2021.

Before continuing the 2nd iteration process, validation was carried out to measure the level of accuracy of the 2024 land cover simulation results by comparing it to the 2024 reference map. Validation uses the *Multiple-Resolution Validation* method available in the MOLUSCE plugin, with a maximum of five iterations of validation. The map of the simulation results can be seen in Figure 4.20.

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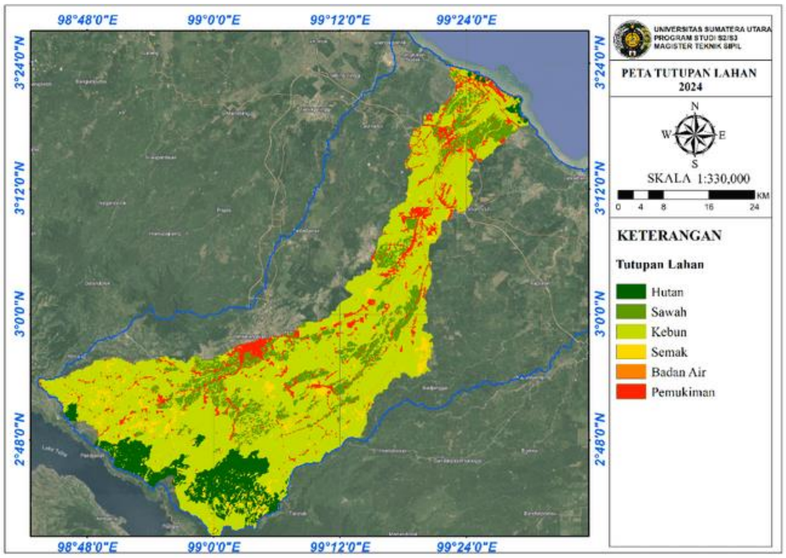
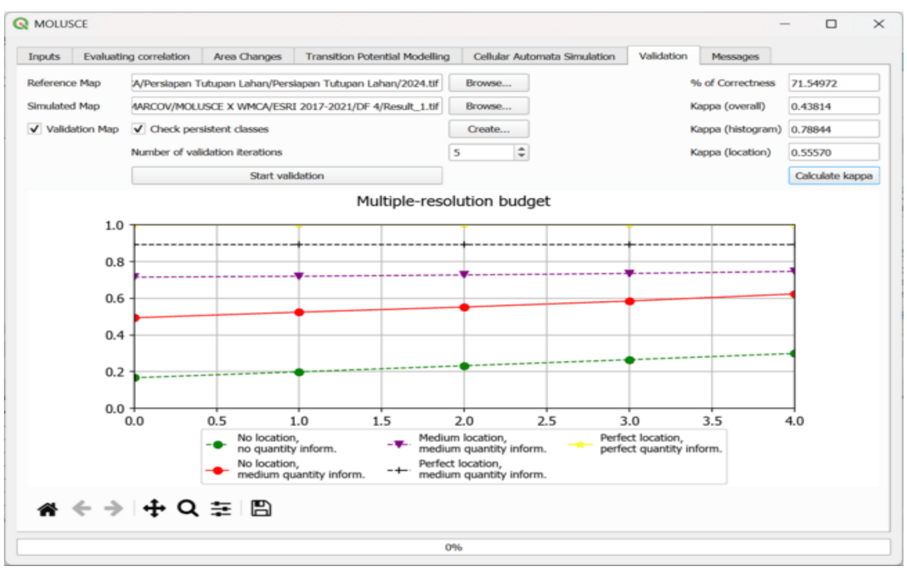


Picture Error! No text of specified style in document.**.10 Simulated land cover map in 2024**

The validation results showed a *percentage of correctness* of 71.55%, which indicates that more than two-thirds of the prediction results corresponded to the actual conditions of the reference. In addition, an *Overall Kappa value* of 0.438 was obtained, which reflects the model's general accuracy being in the sufficient category. The *Kappa Histogram* value was recorded as 0.789 which is shown in Figure 4.21. This indicates that the model has high accuracy in predicting the proportion or distribution of the number of each land cover class. Meanwhile, the *Kappa Location* value of 0.556 indicates that the accuracy of the location of the predicted pixels is at a moderate to good level.



Picture **Error! No text of specified style in document.**.11 Screenshot of the validation test *Kappa* with MOLUSCE

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The *Multiple-resolution budget* graph supports this result, where the red and purple lines show the match of the quantity and location of land cover classes at various resolution scales. Overall, the results of this validation show that the constructed simulation model is reliable enough to be used in projecting future land cover changes. The results of the 2nd simulation for 2029 can be seen in Figure 4.22. The 2029 land cover simulation shows a trend of sustainable deforestation, plantation land dominance, and a significant increase in residential areas in the Bolon watershed. Factors such as population growth, urbanization, and economic needs are the main drivers of this change. Table 4.6 shows the predicted results of the *land change of the MOLUSCE* Plugin.

Table **Error! No text of specified style in document.**.5 Predicted results of land cover in 2029 and 2033

Land Cover	2024 (km2)	029 (km2)	2033 (km2)	Δ 2024–2029 (km2)	% Δ (2024–2029)	% Δ against watershed	Δ 2029–2033 (km2)	% Δ (2029–2033)	% Δ against watershed
Forest	174,41	63,73	60,17	-110,68	-63,46	-5,75	-3,56	-5,59	-0,18
Agriculture	207,60	307,54	294,43	+99,94	+48,14	+5,19	-13,11	-4,26	-0,68
Plantation	1.277,82	1.324,67	1.307,23	+46,85	+3,67	+2,43	-17,44	-1,32	-0,91
Bush	104,36	12,68	12,03	-91,68	-87,85	-4,76	-0,65	-5,13	-0,03
Water bodies	10,99	0,91	0,79	-10,08	-91,72	-0,52	-0,12	-13,19	-0,01
Settlement	151,68	217,57	252,47	+65,89	+43,45	+3,42	+34,90	+16,04	+1,81
Total	1.926,94	1.926,94	1.926,94	0,00	0%	0%	0,00	0%	0%

Source: Mollusce analysis results, 2025

Predicting land cover changes for the 2024-2029 period, there will be significant changes in land cover with the rate of forest change greatly reduced by 110.68 km2 or −5.75% of the watershed area, most likely converted to agricultural land and settlements. The bush also experienced a sharp decrease of −4.76% of the watershed's area, to only about 12.68 km2. Agriculture increased by 5.19% of the watershed's area, indicating a massive conversion of forests and shrubs. Settlements increased by 65.89 km2 or +3.42% of the watershed's area, supporting indications of urbanization. The plantations have experienced a slight increase, and the water bodies have almost disappeared. A map of predicted land cover change in 2029 using MOLUSCE is seen in Figure 4.22.

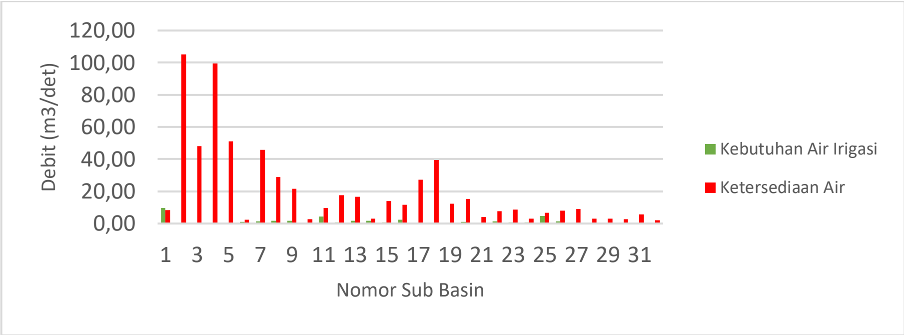
The period of 2024-2029 has experienced many changes between types of land cover. Table 4.7 shows the pattern of land use change from 2024 to 2029 in the Bolon watershed area (in km² units). The row represents the land cover classification in 2024, while the column shows the land cover classification as a result of the change in 2029. The diagonal value reflects the unchanged land, while the value outside the diagonal indicates the transfer of functions.

Prediction of Land Cover Change on Water Availability

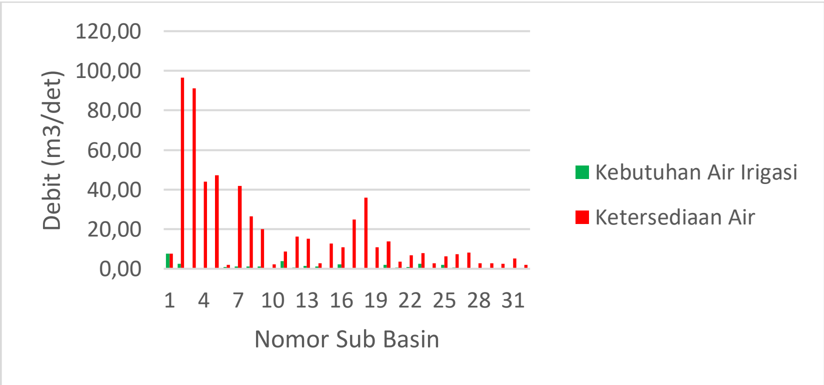
This method of assessing the hydrological impact of LULC change illustrates the hydrological impact of LULC change. The average annual availability discharge is estimated based on continuous simulations over 16 years (2009–2024). Simulated annual discharge, availability, and runoff maps of the two LULC situations were then compared to explore the spatial patterns of change and to assess the hydrological impact of LULC changes between 2017 and 2033. Good simulation model performance with land use change shows the contribution of land use change to river flow change. The results of the simulation with land use changes showed that the water balance of the Bolon watershed changed over a period of 16 years, but it was not significant. It is known that the decrease in forest area leads to a reduction in trees which significantly reduces the evapotranspiration of plants, but also reduces soil vegetation and foliage waste as humus. The absence of vegetation affects the type of soil of the upper part . (Nurhami, 2025; Yue et al., 2024)

For more in-depth research, if you look at the graphs in Figure 4.61, Figure 4.62, Figure 4.63 and Figure 4.64, it is necessary to review the relationship between water availability and irrigation water needs at the sub-watershed scale considering that the dynamics of land change tend to occur at the sub-watershed scale.

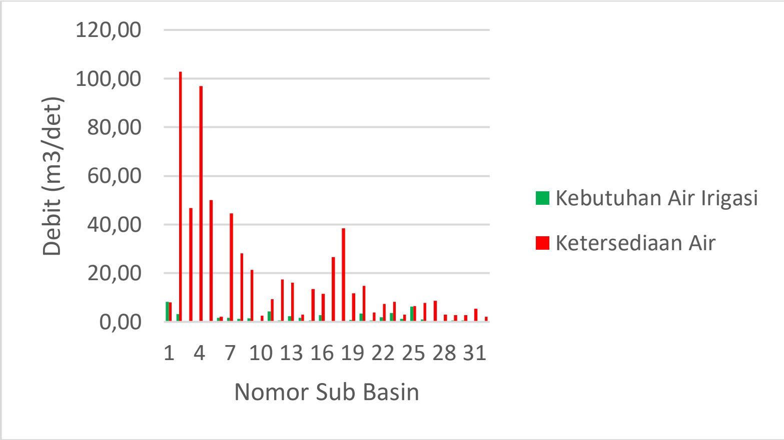
This is in line with previous research which stated that in general the impact of LULC changes is more pronounced at the sub-watershed scale, as the contrast effect is not averaged by the variation in land cover found across watersheds. The impact of LULC changes on the sub-watershed scale on the hydrological components i.e. surface runoff and water output was found to be higher than the overall watershed level. Figure 4.65, Figure 4.66, Figure 4.67 and Figure 4.68 show the water balance balance at the sub-watershed scale of the year of the land cover change scenario. (Khalid et al., 2024; Liu et al., 2022)



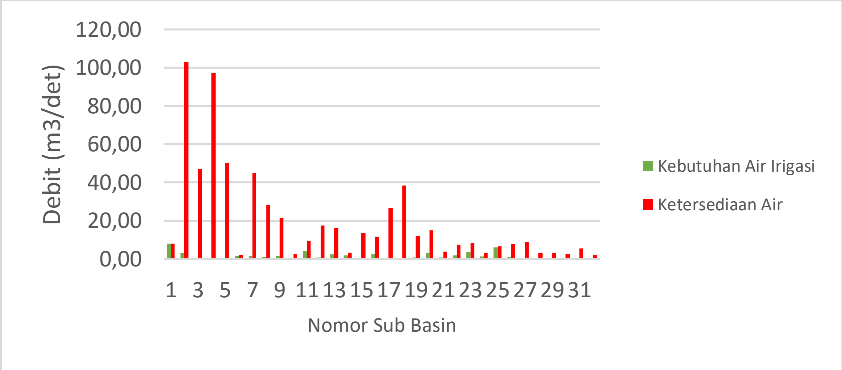
Picture Error! No text of specified style in document.**.12 Graph of water balance at the sub-watershed scale in 2017**



Picture Error! No text of specified style in document.**.13 Chart of water balance at the sub-watershed scale in 2024**



Picture Error! No text of specified style in document.**.14 Chart of water balance at the sub-watershed scale in 2029**



Picture Error! No text of specified style in document.**.15 Graph of water balance at the sub-watershed scale in 2033**

This is in line with previous research which stated that changes in LULC and hydrological components at the sub-watershed level cause the highest increase in surface runoff to occur in areas dominated by agricultural/residential land, surface runoff increases in almost all sub-watersheds due to the conversion of forest land and shrubs/grasses to agricultural/residential LULC types. However, at the sub-watershed scale, the impact of LULC variation on hydrological parameters is not uniform. Average annual lateral flow, groundwater flow, groundwater content, and evaporation decreased on the watershed scale due to changes in the LULC. (Bal et al., 2021; Di Baldassarre et al., 2018) (Abuhay et al., 2023; Bal et al., 2021)

On the sub-watershed scale, there are several sub-watersheds that are critical to water availability. The author divides the critical condition into 3 parameters, namely: Critical if the ratio of debit availability: debit needs < 1, Quite Critical if the ratio of debit availability: debit needs ranges from 1 – 5, and Safe if the ratio of debit availability: debit needs > 5.

Figure 4.70, Figure 4.71, Figure 4.72 and Figure 4.73 show a map of discharge criticality at the sub-watershed scale for each year of the land cover scenario.

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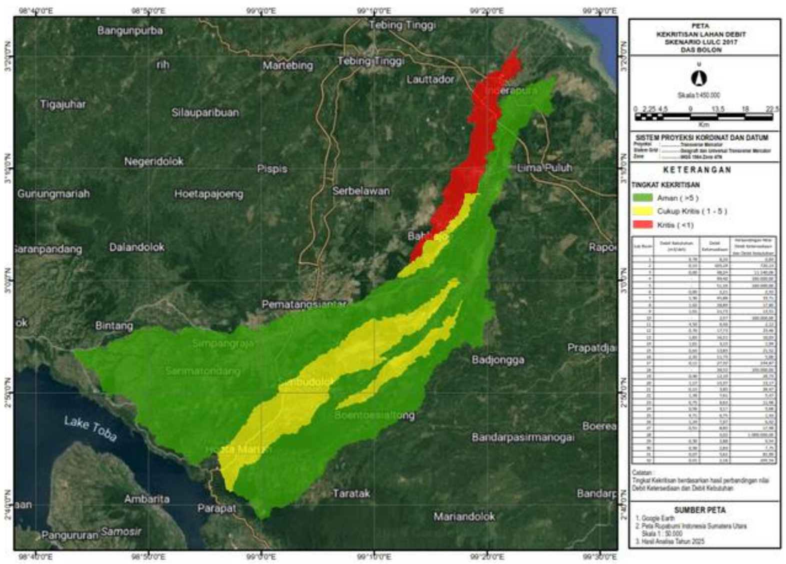
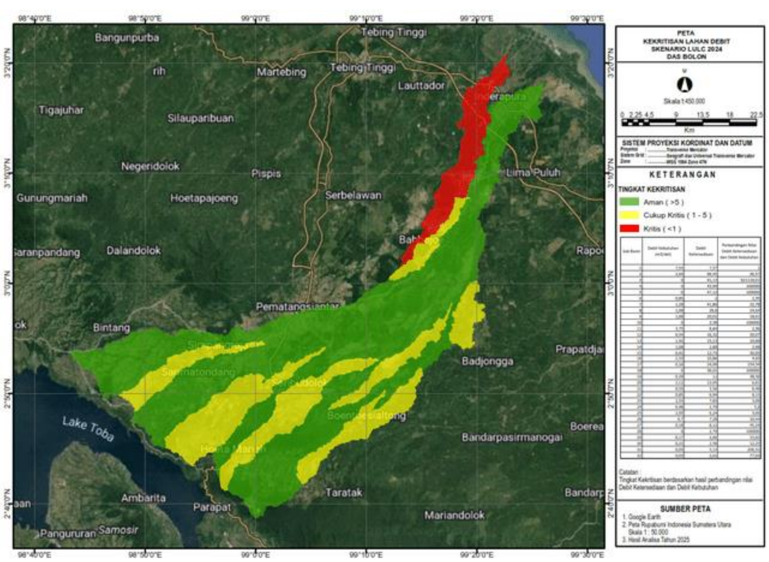


Picture Error! No text of specified style in document.**.16 Map of discharge criticality at the sub-watershed scale in 2017**



Picture Error! No text of specified style in document.**.17 Map of discharge criticality at the sub-watershed scale in 2024**

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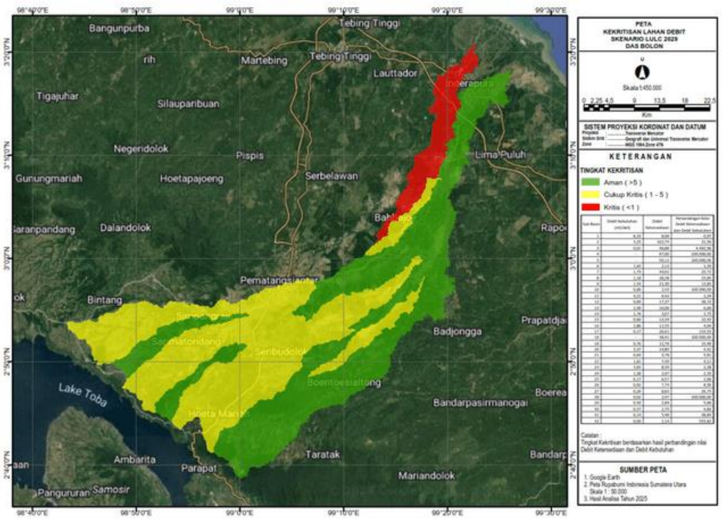
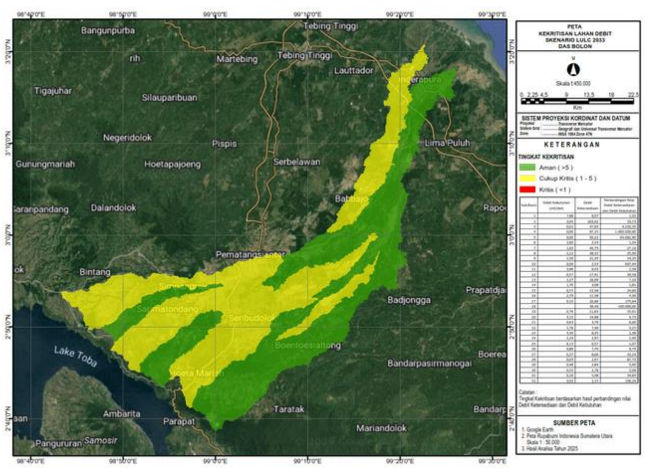


Picture Error! No text of specified style in document.**.18 Map of discharge criticality at the sub-watershed scale in 2029**



Picture Error! No text of specified style in document.**.19 Map of discharge criticality at the sub-watershed scale in 2033**

This study confirms that the change in agricultural land cover to settlements, especially in the downstream part of the Bolon watershed for the 2017-2033 period, has caused a decrease in irrigation water demand where irrigation is the largest water consumer, so that the downstream sub-watershed that was originally critical has become quite critical.

This study also explains that the change in plantation land cover, and shrubs into settlements in several sub-watersheds for the period 2017-2033 has caused a decrease in the availability of water in rivers so that the sub-watersheds that were originally safe are quite critical.

Conclusion

The development of changes in agricultural land cover in the Bolon Watershed (DAS) during the 2017–2024 period shows that there are significant dynamics. In 2017, the area of agricultural land was recorded at 236.36 km², increasing to 339.34 km² in 2021, but declining again in 2024 to 206.7 km². Thus, during this period, agricultural land experienced a net decrease of 28.66 km². The results of satellite image analysis showed that there was an increase in residential land by 4.8%, bushes by 1.0%, and water bodies by 0.6%, while forest, agricultural, and plantation cover decreased by 0.5%, 1.5%, and 4.5% of the total area of the Bolon watershed, respectively. This change reflects a significant shift in land use, especially from agricultural and plantation areas to settlements and bush areas.

Based on the results of the Cellular Automata–Markov Chain modeling using the MOLUSCE plugin in QGIS, it is predicted that in the 2024–2033 period the area of agricultural land will increase by 4.5% of the total area of the Bolon watershed. In addition, residential and plantation land is also estimated to increase by 5.2% and 1.5%, respectively, while the cover of forests, shrubs, and water bodies decreases by 5.9%, 4.8%, and 0.5%, respectively. The results of the hydrological simulation show that this change in land cover has an effect on the decrease in Q80's mainstay discharge, which illustrates the ability of the watershed to maintain water discharge during the dry season. The average discharge of the Q80 was recorded at 50.70 m³/s in 2017, decreasing to 49.99 m³/s in 2024, 47.85 m³/s in 2029, and 47.27 m³/s in 2033. At the sub-watershed scale, some areas show critical water conditions with a ratio of low discharge availability and irrigation water demand (<1), while others are in the critical category (ratio 1–5). The change of agricultural land to settlements in the downstream area of the Bolon watershed has caused a decrease in water demand, making the area that was originally critical to quite critical. On the other hand, the conversion of plantation and shrub land into settlements in several sub-watersheds has led to a decrease in the availability of water in the river, so that the area that was originally safe becomes quite critical. However, on the overall watershed scale, the discharge of water availability is still greater than the irrigation water requirement in the entire period 2017–2033, so in general there is no significant change in water availability at the watershed level.

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