Analysis Of Land Cover Change And Its Impact On Runoff Discharge In Komodo District, West Manggarai Regency

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Abstract. Land use and land cover (LULC) changes significantly affect surface runoff, especially in data-poor areas. This study analyzes LULC changes and their impacts on runoff coefficients and surface runoff discharge in four selected villages in Komodo District, West Manggarai Regency, using an integrated hydrological and geospatial approach. ESRI land cover and ERA5 rainfall data were used to assess spatial land cover dynamics. Runoff coefficients were estimated using the Hassing method by integrating topography, soil characteristics, and land cover through a GIS-based overlay analysis. In contrast, runoff discharge was calculated using the Rational Method. The results indicate that runoff coefficients increased by approximately 0.02–0.09 in the four villages due to land conversion from vegetated to built-up areas, thereby increasing peak runoff discharge by 4.7%-11.43%. These findings highlight the hydrological impacts of rapid land development and provide a scientific basis for local water resource management and sustainable spatial planning.

Keywords: Land cover change; Surface runoff; Runoff discharge; Rational Method; Komodo District

1 Introduction

Land use and land cover (LULC) change is a global phenomenon that has intensified in recent decades, in line with population growth, urbanization, and economic development [1]. LULC change has been identified as a major factor influencing hydrological systems, as it directly controls infiltration, evapotranspiration, and surface runoff formation [2]. Various studies have shown that converting vegetated land to built-up areas tends to reduce soil infiltration capacity and increase surface runoff, thereby altering river flow characteristics and the local air balance, and impacting runoff discharge in Komodo District, West Manggarai Regency [3].

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2 Methodology

The analysis focuses on selected villages within the district that have experienced significant land-cover changes; therefore, the watershed is relatively small and methodologically suitable for applying the Rational Method [4]. The Rational Method was chosen because it is simple and practical, and it allows direct integration of runoff coefficient (C) with land-cover data from ESRI Land Cover imagery [5]. Although this method has limitations in large or heterogeneous watersheds, the analysis remains relevant at the local scale and supports spatial planning and air resource management.

This methodology integrates statistical rainfall analysis, spatial analysis using Geographic Information Systems (GIS), and hydrological modeling to quantify runoff characteristics under different land cover conditions. By combining hydrological and geospatial analyses, this approach enables an assessment of how land-cover dynamics influence runoff response while accounting for the watershed's physical characteristics. The overall research framework was designed to systematically examine the relationship between land cover change and surface runoff discharge at the local scale. A detailed description of the rainfall analysis, determination of the runoff coefficient, and estimation of runoff discharge is presented in the following subsections.

2.1 Data Collection and Preparation

This study uses hydrological and spatial datasets to examine the impact of land-cover change on runoff discharge in the Komodo District, West Manggarai Regency, with particular focus on identifying runoff discharge characteristics in several urban villages that have experienced significant land-cover change. The hydrological data consist of annual maximum rainfall derived from the ERA5 satellite, based on previous research [6]. which demonstrated that ERA5 data are suitable and reliable for hydrological analysis in the Labuan Bajo region. Spatial data include slope, soil type, and land-cover maps, obtained from geospatial databases and remote-sensing sources. Land cover data derived from ESRI Land Cover imagery for 2017 and 2024 [7] were used to assess temporal changes in land cover. All spatial datasets were standardized to the same coordinate system and spatial resolution to ensure analytical consistency. The land-cover maps were then classified into the following categories: built-up areas, trees, bare ground, Rangeland, water, flooded vegetation, and crops.

2.2 Rainfall Frequency Analysis

Annual maximum rainfall data for 21 years (2004–2024) were analyzed using frequency analysis to estimate design rainfall for various return periods. The rainfall data were derived from the ERA5 reanalysis dataset, which has been validated and recommended by previous studies as a reliable data source for the Labuan Bajo region and its surroundings [6]. The use of ERA5 data provides a relevant alternative given the limited availability of long-term observed rainfall records in the study area.

Several probability distributions commonly used in hydrological studies were tested, namely the Gumbel, Normal, Log-Normal, and Log-Pearson Type III distributions [8]. Each distribution was fitted to the observed rainfall data using statistical parameters, including the mean, standard deviation, and skewness coefficient. Next, the design rainfall value corresponding to the

selected return period was calculated for each distribution and used as the basis for subsequent hydrological analysis.

2.3 Goodness-of-Fit Testing and Distribution Selection

To evaluate the goodness of fit between the theoretical distributions and the observed data, Chi-Square and Kolmogorov–Smirnov (K–S) tests were applied at a significance level (α) of 5%.

a. Chi-Square test

The Chi-Square test was applied to evaluate the agreement between observed and theoretical rainfall frequency distributions. The test statistic was calculated using Equation 1:

$$X^2 = \sum_{i=1}^{k} \left(\frac{Oi-Ei}{Ei}\right)^2 \quad (1)$$

Where;

Oi = observed frequency in the *i*-th class

Ei = expected frequency derived from the theoretical distribution

K = number of classes

$\chi 2$ = Chi-Square test statistic

b. Kolmogorov–Smirnov test

The Kolmogorov–Smirnov test was used to assess the maximum deviation between the empirical and theoretical cumulative distribution functions. The test statistic was determined using the following expression, as shown in Equation (2):

$$D = \max|Fo(x) - Ft(x)| \quad (2)$$

Where;

$Fo(x)$ = empirical cumulative distribution function

$Ft(x)$ = theoretical cumulative distribution function

A distribution is considered to fit the observed data if the calculated D value is smaller than the critical D value at a significance level of α=5

2.4 Rainfall Intensity Determination

The selected design rainfall was converted to rainfall intensity using the Mononobe equation, which relates rainfall depth to rainfall duration. A 6-hour rainfall duration was adopted in this study, representing the time of concentration in the watershed in Komodo Regency. The Mononobe equation is given in Equation 3.

$$\mathrm{I} = \frac{R24}{24}\left(\frac{24}{t}\right)^{2/3} \quad (3)$$

Where:

I = rainfall intensity (mm/h)

R24 = 24-hour design rainfall (mm)

T = rainfall duration (hours)

2.5 Runoff Coefficient Determination

The runoff coefficient (C) is determined by integrating three key parameters: topography (C_t), soil characteristics (C_s), and vegetation or land cover (C_v). Each parameter is determined by criteria derived from standard hydrological references. Spatial overlay analysis was performed using GIS to combine maps of slope, soil type, and land cover [9]. The runoff coefficient was determined using the Hasing method, which allows calculation of the C value from the additive components of the three parameters. Each parameter is classified by a runoff coefficient, as shown in Table 1. This approach employs a damping additive component, which limits the capture of complex hydrological behavior. Calibration, validation, and sensitivity analysis were not performed due to the limited availability of field hydrological data in the Komodo District. Nevertheless, this method provides an estimate of relative runoff potential, which is useful for spatially removing the influence of land-cover changes on runoff discharge. The obtained C values are approximate and should be interpreted with methodological limitations in mind; however, they remain relevant for supporting local air resource management and spatial planning.

Table 1. Runoff coefficient values based on the hassing method

No	Topography (Ct)	C	Runoff Coefficient: C= Ct+Cs+Cv
1	Flat (<1%)	0.03	
2	Wavy (1–10%)	0.08	
3	Hills (10–20%)	0.16	
4	Mountains (>20%)	0.26	
No	Soil (Cs)	C	
1	Sand and gravel	0.04	
2	Sandy loam	0.08	
3	Clay and silt	0.16	
4	Stone layer	0.26	
No	Vegetation (Cv)	C	
1	Forest	0.04	
2	Agriculture	0.11	
3	Grass	0.21	
4	Bare land (no vegetation)	0.28	

2.6 Runoff Discharge Estimation

The runoff discharge in this study uses the Rational Method. This method calculates peak runoff discharge based on rainfall intensity, runoff coefficient, and watershed area. In this study, the Rational Method is used not to determine the discharge plan, but rather as a comparative analysis tool to show the effects of land-cover changes on surface runoff through variations in the runoff coefficient (C). The discharge values obtained are indicative and are used for relative trend analysis, so the limitations of the Rational Method in large-scale watersheds have been

methodologically considered. The Rational Method equation can be seen in equation 4.

$$Q = 0.278\ x\ C\ x\ I\ x\ A \quad (4)$$

Where:

Q = peak runoff discharge (m^3/s)

C = runoff coefficient

I = rainfall intensity (mm/h)

A = catchment area (km^2)

3 Results and Discussion

3.1 Land Cover Changes between 2017 and 2024

Land-cover analysis in Komodo District between 2017 and 2024 reveals clear spatial changes, while the total area remained constant at 377.27 km^2. The spatial distribution of land cover in 2017 and 2024 is presented in Figures 1 and 2, respectively.

Tree-covered areas decreased from 277.97 km^2 in 2017 to 260.79 km^2 in 2024, resulting in a net loss of 17.18 km^2. In contrast, built-up areas increased significantly from 15.67 km^2 to 32.21 km^2, with a net gain of 16.53 km^2, indicating rapid urban expansion.

Agricultural land (crops) also increased from 13.88 km^2 to 17.32 km^2 (+3.44 km^2), while rangeland remained relatively stable. Minor reductions were observed in bare ground, water bodies, and flooded vegetation.

Overall, land-cover changes indicate a shift from vegetated land to built-up and agricultural areas. These changes, as clearly illustrated in Figures 1 and 2, are expected to increase the potential for surface runoff due to reduced infiltration and increased surface imperviousness.

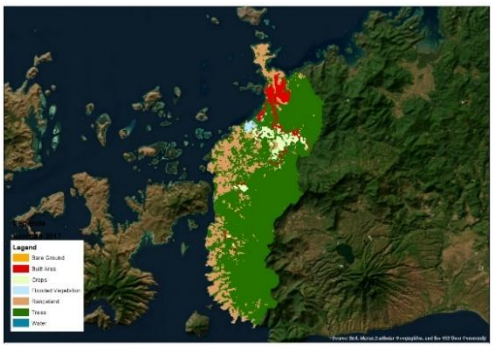

Fig. 1. Spatial distribution of land cover classes in komodo district in 2017 based on ESRI land cover data.

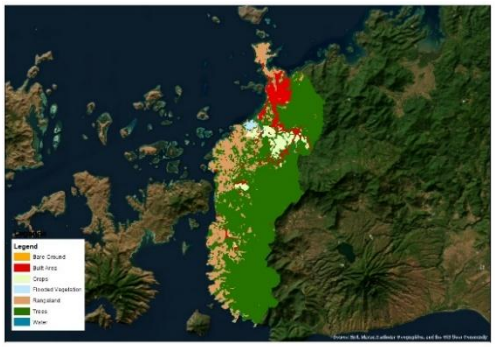

Fig. 2. Spatial distribution of land cover classes in komodo district in 2024 based on ESRI land cover data

3.2 Soil Type and Slope Characteristics

The soil type and slope maps depict the physical characteristics that influence runoff processes in Komodo District (Figures 3 and 4). The study area consists solely of loam and clay soils, with clay soils dominating lowland and developed areas, while loam soils are more common in transitional and upland zones (Figure 3). Due to their lower infiltration capacity, clay soils exhibit greater runoff potential.

Slope analysis indicates that the district ranges from flat to mountainous terrain (Figure 4). Flat to gently undulating slopes (<10%) are primarily found in coastal and lowland areas where urban development is concentrated, whereas hilly (10–20%) and mountainous (>20%) slopes predominate in inland and upland regions. Steeper slopes enhance surface runoff by reducing infiltration time, and when combined with clay-dominated soils and expanding built-up areas, they may intensify hydrological responses across the district.

Fig. 3. Soil type distribution map of komodo district.

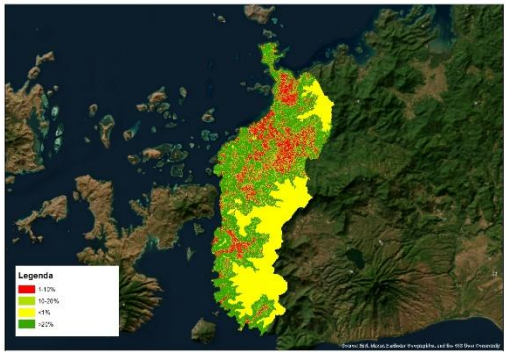

Fig. 4. Slope classification map of komodo district.

3.3 Rainfall Analysis Results

Rainfall analysis was conducted using annual maximum rainfall data to estimate design rainfall for several return periods. Four probability distributions were evaluated, namely Gumbel, Normal, Log-Normal, and Log Pearson Type III, to identify the most suitable distribution for the study area.

The goodness-of-fit tests, including the Kolmogorov–Smirnov and Chi-Square tests, indicated that the Log Pearson Type III distribution provided the best fit to the observed rainfall data. This distribution satisfied the acceptance criteria of both tests and showed the smallest deviation between observed and theoretical values.

Based on the selected distribution, design rainfall values were calculated for return periods of 2, 5, 10, and 20 years. The resulting design rainfall depths are presented in Table 2. These values were subsequently used to derive rainfall intensity and runoff discharge in the hydrological analysis.

Table 2. Estimated design rainfall using the log pearson type III distribution

Periods (Year)	X (mm)	Intensity (mm/h)
2	50.605	5.313
5	66.602	6.992
10	76.900	8.074
20	89.650	9.412

3.4 Surface Flow Discharge Analysis in Selected Sub-districts

To support the runoff discharge analysis, a combined land cover map of the selected kelurahan for 2017 and 2024 is first presented in Figure 5. This map highlights the spatial extent of land cover changes within the four urban villages analyzed: Labuan Bajo, Gorontalo, Wae Kelambu, and Batu Cermin, which were identified as areas experiencing the most significant land cover transformation in Komodo District during the study period.

Runoff discharge was estimated using the Rational Method, incorporating key hydrological parameters, namely the runoff coefficient (C), rainfall intensity (I), and catchment area (A). These parameters were derived from rainfall frequency analysis and spatial datasets and applied consistently for both years to allow comparison of runoff conditions.

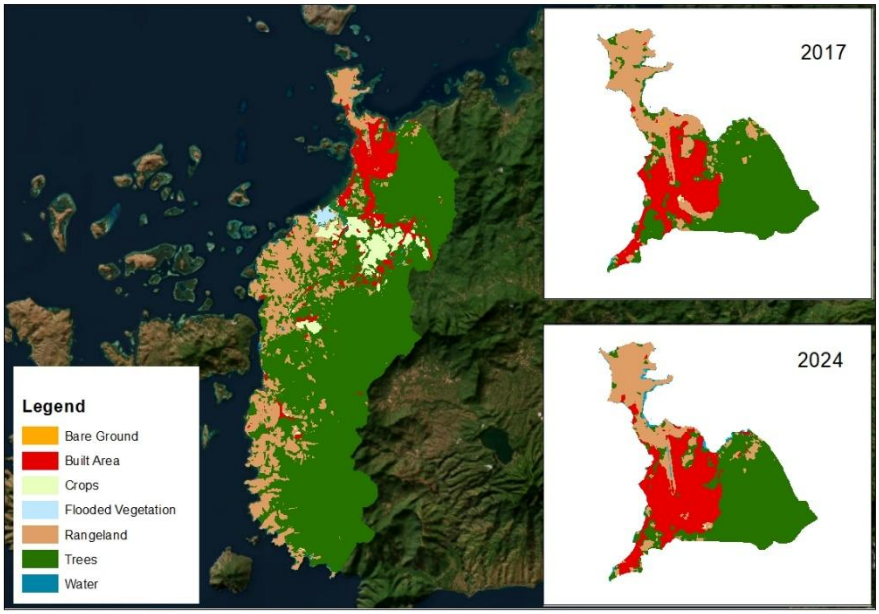

Fig. 5. Combined land cover change map (2017–2024) in selected sub- districts in komodo district

a. Labuan Bajo Subdistrict

Labuan Bajo Village covers an area of 10.06 km² and experienced the most significant land cover changes during the 2017–2024 period. Built-up area increased from 1.35 km² in 2017 to 2.24 km² in 2024, while tree cover decreased substantially from 1.79 km² to 0.83 km² due

to rapid urban development and tourism. This change in land cover directly increases the runoff coefficient, as indicated by the increase in C from 0.74 in 2017 to 0.79 in 2024, with corresponding changes in the Ct, Cv, and Cs components, as presented in Table 3.

Table 3. Changes in runoff coefficient (C) in labuan bajo subdistrict (2017–2024)

No	Topography	Area 2017 (ha)	C	Ct	C = Ct+Cs+Cv	Area 2024 (ha)	C	Ct	C = Ct+Cs+Cv
			2017				2024		
1	Flat (<1%)	0.07	0.03			0.20	0.03		
2	Wavy (1–10%)	1.28	0.08			1.40	0.08		
3	Hills (10–20%)	2.50	0.16	0.21		2.41	0.16	0.21	
4	Mountains (>20%)	6.70	0.26			6.60	0.26		
	Total		10.6			5.3	10.6		
		Soil (Cs)							
1	Sand and gravel	0	0.04			0	0.04		
2	Sandy loam	0	0.08			0	0.08		
3	Clay and silt	10.6	0.16	0.16		10.55	0.16	0,16	
4	Stone layer	0	0.26		0.74	0	0.26		0.79
	Total		10.6			5.3	10.6		
	Vegetation (Cv)								
1	Built Area	1.35	0.7			2.24	0.7		
2	Crops	0.00	011			0	0.11		
3	Bare Ground	0.03	0.5			0	0.5		
4	Flooded Vegetation	0.00	0.11	0.37		0	0.11	0,42	
5	Rangeland	7.24	0.4			7.13	0.4		
6	Trees	1.79	0.04			0.83	0.04		
7	Water	0.17	0.05			0.41	0.05		
	Total		10.6			5.3	10.6		

The increase in the runoff coefficient significantly increases runoff discharge from 2017 to 2024, as shown in Figure 6, indicating that Labuan Bajo Village has the highest potential for inundation and surface flooding compared to other villages, particularly during extreme rainfall events.

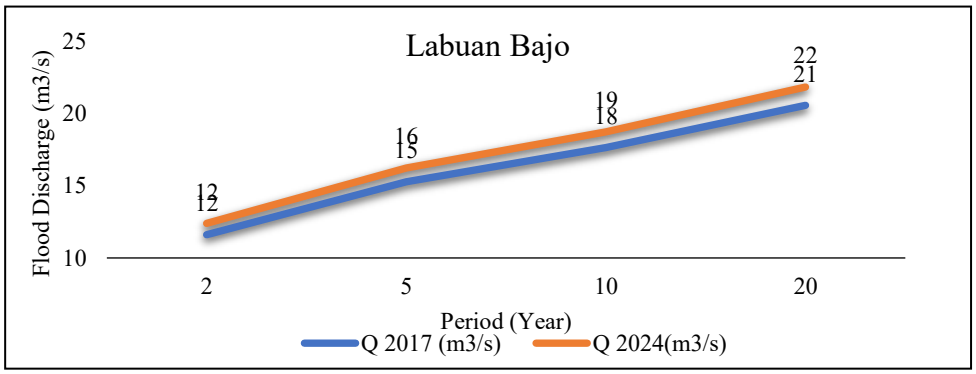

Fig. 6. Changes in runoff discharge in response to land cover conversion in labuan bajo subdistrict

b. Gorontalo Subdistrict

Gorontalo Village covers an area of 5.3 km² and experienced noticeable land cover changes during the 2017–2024 period. The Built-up Area increased from 2.58 km² in 2017 to 3.18 km² in 2024, while Tree Cover decreased from 2.23 km² to 1.85 km², indicating a gradual conversion of vegetated land into developed areas. These land-cover changes directly affected the runoff coefficient, as indicated by an increase in the C value from 0.72 in 2017 to 0.80 in 2024, with corresponding changes in the Ct, Cv, and Cs components, as presented in Table 4.

Table 4. Changes in runoff coefficient (C) in Gorontalo subdistrict (2017–2024)

No	Topography	Area 2017 (ha)	C	Ct	C = Ct+Cs+Cv	Area 2024 (ha)	C	Ct	C = Ct+Cs+Cv
			2017				2024		
1	Flat (<1%)	0.18	0.03			0.20	0.03		
2	Wavy (1–10%)	1.65	0.08			1.66	0.08		
3	Hills (10–20%)	1.34	0.16	0.17		1.29	0.16	0.17	
4	Mountains (>20%)	2.16	0.26			2.16	0.26		
	Total	5.3	0.5		0.72	5.3	0.5		0.80
	Soil (Cs)								
1	Sand and gravel	0	0.04			0	0.04		
2	Sandy loam	0	0.08	0.16		0	0.08	0.16	
3	Clay and silt	5.3	0.16			5.33	0.16		
4	Stone layer	0	0.26			0	0.26		

	Total	5.3	0.5		5.3	0.5	
	Vegetation (Cv)						
1	Built Area	2.58	0.7		3.18	0.7	
2	Crops	0.03	0.11		0.04	0.11	
3	Bare Ground	0.00	0.5		0	0.5	
4	Flooded Vegetation	0.01	0.11	0.39	0.002	0.11	0.47
5	Rangeland	0.43	0.4		0.6	0.4	
6	Trees	2.23	0.04		1.45	0.04	
7	Water	0.07	0.05		0.07	0.05	
	Total	5.3	1.9		5.3	0.6	

The increase in the runoff coefficient led to a corresponding rise in runoff discharge from 2017 to 2024, as shown in Figure 7. Although the increase is lower than that observed in Labuan Bajo Village, Gorontalo Village still shows an increasing potential for surface runoff and localized inundation, particularly during extreme rainfall events.

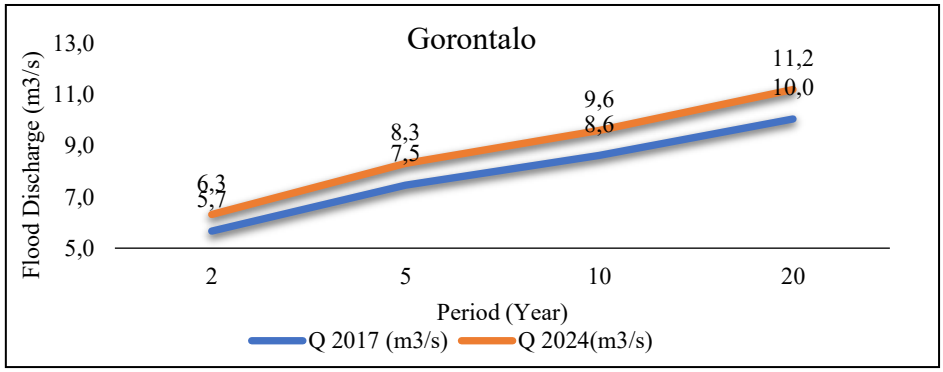

Fig. 7. Changes in runoff discharge in response to land cover conversion in gorontalo subdistrict

c. Batu Cermin Subdistrict

Batu Cermin Village covers an area of 8.0 km² and experienced considerable changes in land cover during the 2017–2024 period. The Built-up Area expanded markedly from 3.34 km² in 2017 to 4.58 km² in 2024, while Tree Cover decreased from 2.13 km² to 1.68 km², indicating a substantial conversion of vegetated land into developed areas. These land-cover changes directly influenced the runoff coefficient, as indicated by an increase in the C value from 0.73 in 2017 to 0.79 in 2024, with corresponding changes in the Ct, Cv, and Cs components, as presented in Table 5.

Table 5. Changes in runoff coefficient (C) in batu cermin subdistrict (2017–2024)

No	Topography	Area 2017 (ha)	C	Ct	C = Ct+Cs+Cv	Area 2024 (ha)	C	Ct	C = Ct+Cs+Cv
			2017				2024		
1	Flat (<1%)	0.34	0.03			0.36	0.03		
2	Wavy (1–10%)	3.36	0.08			3.38	0.08		
3	Hills (10–20%)	2.27	0.16	0.15		2.26	0.16	0.14	
4	Mountains (>20%)	2.00	0.26			1.95	0.26		
	Total	8.0	0.5			8.0	0.5		
	Soil (Cs)								
1	Sand and gravel	0	0.04			0	0.04		
2	Sandy loam	0	0.08			0	0.08		
3	Clay and silt	8.0	0.16	0.16		8.0	0.16	0.16	
4	Stone layer	0	0.26			0	0.26		
	Total	8.0	0.5			8.0	0.5		
	Vegetation (Cv)								
1	Built Area	3.34	0.7		0.73	4.58	0.7		0.79
2	Crops	0.00	0.11			0	0.11		
3	Bare Ground	0.02	0.5			0.01	0.5		
4	Flooded Vegetation	0.00	0.11	0.43		0	0.11	0.49	
5	Rangeland	2.48	0.4			1.55	0.4		
6	Trees	2.13	0.04			1.68	0.04		
7	Water	0.04	0.05			0.19	0.05		
	Total	8.0	1.9			8.0	0.6		

The increase in the runoff coefficient led to higher runoff discharge from 2017 to 2024, as illustrated in Figure 8, indicating a greater potential for surface runoff and localized inundation in Batu Cermin Village, particularly during extreme rainfall events.

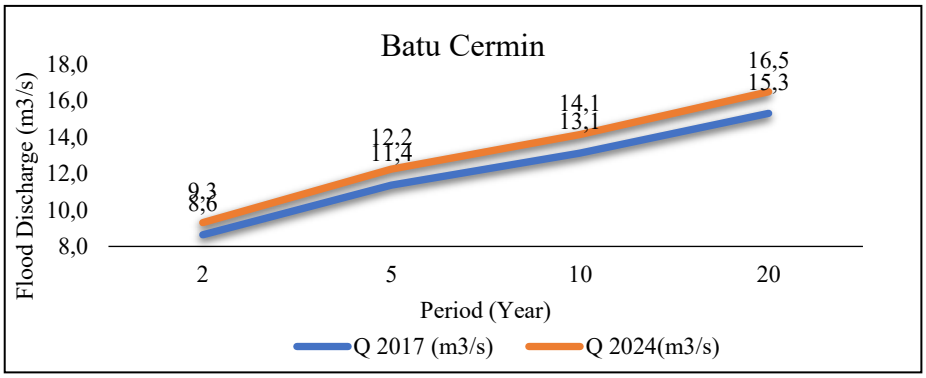

Fig. 8. Changes in runoff discharge in response to land cover conversion in batu cermin subdistrict

d. Wae Kelambu Subdistrict

Wae Kelambu Village covers an area of 22.9 km² and experienced substantial land cover changes during the 2017–2024 period. The Built-up Area increased markedly from 3.24 km² in 2017 to 4.37 km² in 2024, indicating the rapid expansion of developed land. In contrast, Trees Cover declined from 18.24 km² to 17.68 km², reflecting a significant conversion of vegetated land into built-up areas. These changes illustrate an intensifying trend in urban development in Wae Kelambu Village.

The land-cover changes had a direct impact on the runoff coefficient. In 2017, the runoff coefficient components were Ct = 0.13, Cv = 0.15, and Cs = 0.16, resulting in a total runoff coefficient (C) of 0.45. By 2024, the substantial increase in built-up areas led to a rise in the land cover component (Cv) to 0.18, while Ct slightly decreased to 0.13 and Cs remained constant at 0.16, producing a higher total runoff coefficient of C = 0.47, as presented in Table 6. This increasing trend in the runoff coefficient is consistent with findings from previous studies, which report that urban expansion and the conversion of vegetated land into impervious surfaces significantly reduce infiltration capacity and increase surface runoff. For example, a long-term study in Malang City documented a continuous increase in runoff coefficient values from 0.2468 in 2002 to 0.4119 in 2022, with an average annual increase of approximately 13.78% [10], driven by population growth, urbanization, and rising housing demand. Similar increases in runoff coefficients associated with land-cover change have also been reported in urbanizing watersheds, particularly in coastal and tourism-driven regions, where rapid development intensifies hydrological responses and increases flood risk during extreme rainfall events.

Table 6. Changes in runoff coefficient (C) in Wae Kelambu subdistrict (2017–2024)

No	Topography	Area 2017 (ha)	C	Ct	C = Ct+Cs+Cv	Area 2024 (ha)	C	Ct	C = Ct+Cs+Cv
			2017				2024		

1	Flat (<1%)	8.11	0.03			8.26	0.03		
2	Wavy (1–10%)	3.69	0.08			3.82	0.08		
3	Hills (10–20%)	3.81	0.16	0.13		3.79	0.16	0.13	
4	Mountains (>20%)	7.25	0.26			7.00	0.26		
	Total	22.9	0.5			22.9	0.5		
	Soil (Cs)								
1	Sand and gravel	0	0.04			0	0.04		
2	Sandy loam	0	0.08			0	0.08		
3	Clay and silt	22.9	0.16	0.16		22.9	0.16	0.16	
4	Stone layer	0	0.26			0	0.26		
	Total	8.0	0.5			8.0	0.5		
	Vegetation (Cv)				0.45				0.47
1	Built Area	3.24	0.7			4.37	0.7		
2	Crops	0.08	0.11			0.03	0.11		
3	Bare Ground	0.02	0.5			0.00	0.5		
4	Flooded Vegetation	0.00	0.11	0.15		0.00	0.11	0.18	
5	Rangeland	1.33	0.4			0.79	0.4		
6	Trees	18.24	0.04			17.68	0.04		
7	Water	0.01	0.05			0.03	0.05		
	Total	22.9	1.9			22.9	0.6		

The increase in the runoff coefficient resulted in a significant rise in runoff discharge from 2017 to 2024, as illustrated in Figure 9. Compared with other villages, Wae Kelambu exhibits one of the largest increases in runoff discharge, indicating an elevated risk of surface runoff and localized inundation during extreme rainfall events. These findings underscore the strong influence of rapid land-cover conversion on the hydrological response of Wae Kelambu Village.

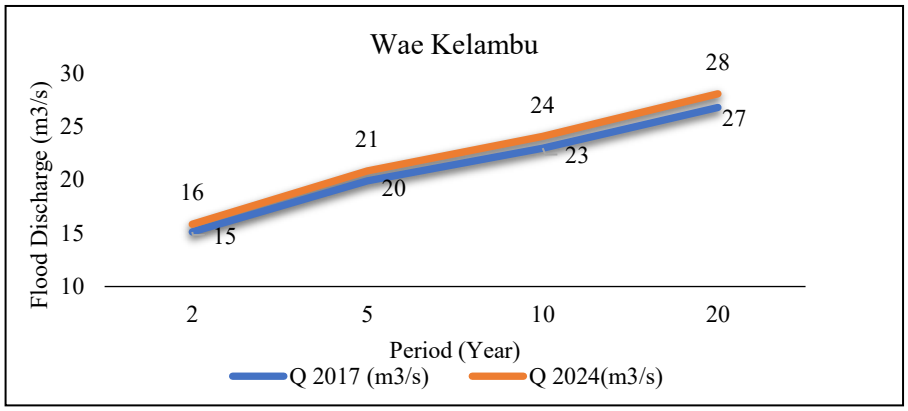

Fig. 9. Changes in Runoff Discharge in Response to Land Cover Conversion in Wae Kelambu Subdistrict

4 Conclusion

This study shows that land cover change in Komodo Regency between 2017 and 2024 was characterized by significant conversion of debtor areas to built-up and agricultural land, particularly in the villages of Labuan Bajo, Gorontalo, Batu Cermin, and Wae Kelambu. The reduction in vegetated land and the expansion of impermeable surfaces consistently increased the runoff coefficient (C) across the study area, confirming the strong influence of land-cover dynamics on surface runoff generation.

Integrating information on land cover, soil type, and slope indicates that areas characterized by clay soils, gentle slopes, and rapid urban expansion exhibit the most pronounced hydrological response. Among the villages studied, Labuan Bajo and Wae Kelambu experienced the highest increases in runoff coefficient and runoff discharge, indicating greater vulnerability to surface flooding during extreme rainfall events. These findings are consistent with hydrological theory, which links decreased infiltration capacity and increased impermeability to higher runoff potential and faster runoff response.

Although the Rational Method and additive runoff coefficient approaches address complex hydrological processes and are applied without calibration or statistical significance testing, both effectively capture relative spatial differences in runoff responses driven by land-cover change. The results highlight that even relatively small increases in built-up area can significantly alter local hydrological behavior when combined with unfavorable soil and slope conditions.

Beyond the local case study, this research contributes to a broader understanding of hydrology by demonstrating a transferable framework that integrates remotely sensed land cover data with simple hydrological modeling in data-deficient regions. This approach provides practical insights for air resource management and spatial planning in coastal areas and rapidly expanding tourism-focused areas, emphasizing the importance of controlling land cover conversion to mitigate increased runoff and flood risk.

5 Recommendations

Based on the research results, controlling land cover changes is a crucial aspect in efforts to reduce the increase in surface runoff in the Komodo District. The local government needs to integrate the results of the hydrological analysis into spatial planning, particularly by limiting the conversion of vegetation in areas with high runoff coefficients and by maintaining water catchment areas and riverbanks. Furthermore, implementing green infrastructure and sustainable drainage systems, such as infiltration wells, biopores, infiltration gardens, and porous pavements, is strongly recommended to increase infiltration and reduce runoff, particularly in urban and densely populated areas. For scientific development, further research is recommended using more comprehensive field hydrological data to enable model calibration, validation, and sensitivity analysis. The use of process-based hydrological models and more comprehensive statistical analysis is also necessary to strengthen the quantitative understanding of the relationship between land cover change and runoff response. Therefore, the approach used in this study can be replicated and developed in other areas with similar characteristics, thereby making a broader contribution to water resources management and sustainable regional development.

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