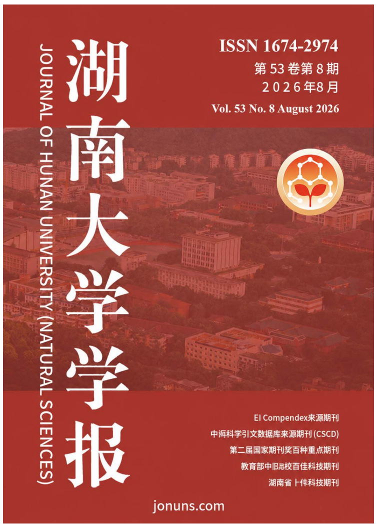

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Carrying Capacity Assessment of the Wai Samal and Wai Eti Watersheds on Seram Island, Maluku Province

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Abstract: This study aims to assess the carrying capacity of the Wai Samal and Wai Eti watersheds on Seram Island, Maluku Province, Indonesia, using an integrated multi-criteria approach adapted to small island conditions. A quantitative method was employed using **GIS-based land-unit analysis** derived from the overlay of topographic, geological, soil, and land-use maps, supported by 31 years of rainfall, hydrological, and socio-economic data. The assessment followed the Indonesian National Watershed Monitoring and Evaluation Framework (Ministerial Regulation No. P.61/Menhut-II/2014), integrating **biophysical, hydrological, socio-economic, institutional, water infrastructure, and spatial planning indicators**. The results showed that the Wai Samal Watershed achieved a carrying capacity index (DDD) of **78.75 (Good)**, whereas the Wai Eti Watershed obtained **93.25 (Moderate)**. The higher carrying capacity of the Wai Samal Watershed was associated with lower critical land extent, lower erosion and flood risk, lower water-use pressure, higher land availability, and stronger institutional performance. In contrast, the Wai Eti Watershed experienced greater environmental and socio-economic pressures, characterized by higher critical land extent, greater land degradation, and less favorable spatial land-use conditions, resulting in lower watershed resilience. These findings demonstrate that the integrated indicator-based assessment provides a scientific basis for identifying watershed-specific management priorities and supports adaptive watershed management and evidence-based spatial planning to enhance long-term sustainability in small island watersheds.

Keywords: watershed carrying capacity; GIS; erosion index; watershed evaluation; small island; integrated watershed management.

塞兰岛马鲁古省瓦伊萨马尔河与瓦伊埃蒂河流域承载力评估

摘要：本研究旨在采用适用于小岛屿环境的综合多准则方法，评估印度尼西亚马鲁古省塞兰岛瓦伊萨马尔（Wai Samal）和瓦伊埃蒂（Wai Eti）流域的承载能力。研究采用定量方法，基于地形图、地质图、土壤图和土地利用图叠加形成的基于地理信息系统（GIS）的土地单元分析，并结合31年的降雨、水文和社会经济数据开展评估。评估依据印度尼西亚国家流域监测与评价框架（林业部长条例第P.61/Menhut-II/2014号），综合考虑生物物理、水文、社会经济、制度、水利基础设施和空间规划指标。结果表明，瓦伊萨马尔流域的流域承载力指数（DDD）为78.75（良好），而瓦伊埃蒂流域的DDD为93.25（中等）。瓦伊萨马尔流域较高的承载能力主要与较低的临界土地比例、较低的土壤侵蚀和洪水风险、较低的水资源利用压力、较高的土地可利用程度以及较强的制度执行能力有关。相比之下，瓦伊埃蒂流域面临更大的环境和社会经济压力，其特征包括较高的临界土地比例、更严重的土地退化以及较不利的空间土地利用条件，从而导致较低的流域韧性。研究结果表明，这种基于综合指标的评估方法能够为识别不同流域的具体管理优先事项提供科学依据，并可支持适应性流域管理和循证空间规划，从而提升小岛屿流域的长期可持续性。

关键词：流域承载力；地理信息系统；侵蚀指数；流域评价；小岛屿；综合流域管理

1. Introduction

A watershed is an integrated environmental system in which hydrological, biophysical, ecological, and socio-economic processes interact continuously to regulate the movement, storage, and distribution of water within the hydrological cycle [1,2]. The sustainability of this system is essential for maintaining water availability, ecosystem functions, agricultural productivity, and human well-being. However, increasing anthropogenic pressures, including land-use change, population growth, and infrastructure development, have substantially altered natural watershed processes, resulting in declining environmental quality and reduced watershed resilience. These challenges are particularly pronounced in small island environments, where watersheds generally possess limited catchment areas, restricted water-storage capacity, rapid hydrological responses, and high sensitivity to environmental disturbances.

Watershed carrying capacity reflects the ability of a watershed to sustain ecological functions while supporting human activities. It is determined by the interaction of multiple components, including land condition, hydrological processes, socio-economic characteristics, institutional capacity, infrastructure investment, and spatial land-use planning [1]. Degradation in any of these components may disrupt watershed functions, leading to increased runoff, soil erosion, sedimentation, flood occurrence, water shortages, and declining ecosystem services [3]. Consequently, watershed carrying capacity has become an important indicator for evaluating watershed sustainability and guiding integrated watershed management.

Previous studies have demonstrated that watershed degradation is influenced by various environmental and socio-economic factors. Poor land management has been shown to increase the extent of critical land, reduce vegetation cover, and accelerate erosion [4]. Likewise, unstable flow regime coefficients indicate hydrological imbalance and increased flood susceptibility [5], while rapid land-use conversion has been associated with declining environmental carrying capacity and deteriorating water quality [6]. In addition, increasing population pressure intensifies land exploitation and accelerates ecosystem degradation, particularly in agricultural landscapes [7,8]. At the global scale, land degradation affects approximately 3.2 billion people and contributes significantly to biodiversity loss and climate change [9,10]. Institutional arrangements, investment in water infrastructure, and spatial planning policies have also been recognized as key determinants of watershed performance because they regulate land allocation, conservation practices, and the protection of ecosystem functions [11–14].

Although these studies have substantially advanced the understanding of watershed processes, most have evaluated biophysical, hydrological, socio-economic, or spatial components separately. Consequently, the interactions among these components that collectively determine watershed carrying capacity remain insufficiently understood. This limitation is particularly evident in small island watersheds, where limited land resources, low water-storage capacity, high erosion susceptibility, and strong socio-economic pressures require a more integrated evaluation framework. Despite their environmental vulnerability, empirical studies addressing watershed carrying capacity in small island systems remain relatively limited.

The Wai Samal and Wai Eti watersheds on Seram Island, Maluku Province, represent important small island watershed systems that support agriculture, plantations, forests, settlements, and domestic water supply [15,16]. These watersheds also exhibit contrasting environmental characteristics and development pressures, making them suitable case studies for evaluating watershed carrying capacity. Population growth continues to increase in both watersheds. In North Seram (Wai Samal), the population increased from 10,458 in 2019 to 13,922 in 2024 [17,18], while in West Seram (Wai Eti), it increased from 34,869 to 35,861 during the same period [19,20]. This increasing demographic pressure is expected to intensify land-use change and place greater stress on watershed resources.

Despite extensive watershed studies, limited attention has been given to applying an integrated, indicator-based watershed carrying capacity assessment to small island watersheds. Existing studies have generally examined individual watershed components rather than adapting the Indonesian National Watershed Monitoring and Evaluation Framework [1] to watershed systems characterized by limited catchment areas, restricted water-storage capacity, rapid hydrological response, and high sensitivity to land-use change. This study addresses this research gap by applying the national framework through the integration of biophysical, hydrological, socio-economic, institutional, infrastructure, and spatial planning indicators within a unified assessment framework. The proposed approach provides a more comprehensive evaluation of watershed carrying capacity and supports adaptive watershed management and evidence-based spatial planning in small island environments. Accordingly, this study aims to assess and compare the watershed carrying capacity of the Wai Samal and Wai Eti watersheds using this integrated framework across land condition, hydrological performance, socio-economic characteristics, institutional capacity, water infrastructure investment, and spatial land-use planning indicators.

2. Methods

2.1. Location

The research was conducted in the Wai Samal Watershed, Central Maluku Regency and the Wai Eti Watershed, West Seram Regency, Maluku Province in 2023 (Figure 1).

2.2. Material

This study employed a combination of spatial and secondary data to evaluate watershed carrying capacity. The input datasets consisted of the Critical Land Map (1:50,000) [21], Vegetation Cover Map (1:250,000) [23], DEMNAS Map of Ceram Island (1:50,000; 5–8 m spatial resolution) [24], Indonesian Topographic Map (RBI) (1:50,000) [5], Geological Map of Maluku (1:250,000) [26], Soil Classification Map of Wai Samal and Wai Eti Watershed (1:50,000) [15, 16], Watershed Boundary Map (1:50,000) [50], and the Regional Spatial Planning (RTRW) Maps of Central Maluku Regency and West Seram Regency (both 1:50,000) [27, 28]. The combination of these datasets provided an appropriate spatial basis for delineating watershed boundaries, generating land units, evaluating watershed indicators, and ensuring consistency throughout the GIS-based analysis.

Figure 1. Location Research Map

2.3. Data Processing and Analysis

The study utilized Geographic Information System (GIS) techniques to process and analyze spatial data, supported by ArcGIS 10.8 software. Spatial analysis was integrated with hydrological calculations and field observations to evaluate watershed carrying capacity using an indicator-based assessment framework.

2.3.1. Watershed Boundary Delineation

The watershed boundaries were derived from the official Maluku Province Watershed Boundary Map (scale 1:50,000), established under the [50]. The boundaries were subsequently verified and refined through DEMNAS-based hydrological analysis using the **Flow Direction**, **Flow Accumulation**, and **Stream Order** tools in ArcGIS 10.8, resulting in the final watershed boundary maps for the Wai Samal and Wai Eti watersheds.

2.3.2. Land Unit Map Generation

Land units were generated using a GIS-based overlay procedure in ArcGIS 10.8 by integrating DEMNAS (5–8 m spatial resolution), geological, soil, and land-cover maps. All spatial datasets were projected to the UTM Zone 52S coordinate system (WGS 84 datum) to ensure spatial consistency. First, DEMNAS raster data were processed to derive seven slope classes (0–3%, 3–8%, 8–15%, 15–30%, 30–45%, 45–65%, and >65%). Second, the geological, soil, and land-cover maps were clipped to the watershed boundaries and converted into polygon feature layers. Finally, the topographic, geological, soil, and land-cover layers were overlaid using the **Union** tool to generate the final land-unit maps. This procedure produced **361 land units** for the Wai Samal Watershed and **336 land units** for the Wai Eti Watershed, which served as the fundamental spatial units for all subsequent watershed carrying capacity analyses.

2.3.3.Critical Land and Vegetation Cover Classification

Critical land was classified in accordance with the Technical Guidelines for Critical Land Spatial Data Preparation issued under the [51]. Vegetation cover was classified according to the Geospatial Data and Thematic Geospatial Information Standards stipulated in the [52] Decree of the Minister of Environment of the Republic of Indonesia No. 398/2024. These standardized classification systems were used to ensure consistency and comparability in the spatial assessment of watershed carrying capacity.

2.3.4. Soil Erosion Analysis

Soil erosion for each land unit was estimated using a modified Revised Universal Soil Loss Equation (RUSLE) adapted for small-island environments in Maluku [53]: $D=0.2547\times R\times K\times LS\times CP$, where **D** is soil erosion (t ha^{-1} yr^{-1}), **R** is the rainfall erosivity factor (Lenvain equation), **K** is the soil erodibility factor derived from soil texture, organic matter, structure, and permeability, **LS** is the slope length and steepness factor derived from DEMNAS-based slope classes, and **CP** is the combined land-cover and conservation practice factor assigned according to [54].

2.3.5. Hydrological Analysis

Hydrological performance was evaluated using five indicators: the Flow Regime Coefficient (KRA), Annual Flow Coefficient (KAT), Sediment Load (MS), Flood Frequency (FB), and Water Use Index (IPA). The KRA was calculated as $KRA=(Q_{max}/Q_{min})\times 100\%$, where Q_{max} was estimated using the Rational Method with rainfall intensity derived from the Mononobe equation, while Q_{min} was obtained from field measurements using the Castelli method. The KAT was calculated as $KAT=Q_{annual}/P_{annual}$, where Q_{annual} was average annual discharge and P_{annual} was annual precipitation. Sediment load was estimated as $MS=A\times SDR$, where A is actual soil erosion calculated using the modified RUSLE model (Section 2.3.5). Flood frequency was determined from annual flood events reported through interviews with local communities and village authorities, and the Water Use Index was calculated as IPA = Water Demand/Water Availability. The analysis used 41 years (1983–2023) of rainfall records, DEMNAS-derived watershed morphometry, streamflow measurements, soil properties, land-use data, runoff coefficients, SDR values (Table 1), and standardized land-use water demand data. Field verification included slope, geology, soil, vegetation, hydrological, and sediment observations, together with stakeholder interviews to improve the reliability of the GIS analysis. All hydrological analyses followed the procedures and evaluation criteria of the Indonesian National Watershed Monitoring and Evaluation Framework [1].

2.4. Watershed Carrying Capacity Assessment Framework.

The evaluation of watershed carrying capacity was conducted using an integrated multi-criteria assessment framework adapted from [1]. This framework enables a performance-based evaluation by combining biophysical, hydrological, socio-economic, and spatial planning indicators within a unified system. The assessment consists of five main criteria, namely land conditions, water system conditions, socio-economic conditions, water infrastructure investment, and spatial land-use utilization. Each criterion is further represented by specific sub-criteria, including critical land percentage, vegetation cover, erosion index, flow regime coefficient, annual flow coefficient, sediment load, flood index, water use, population pressure, welfare level, regulatory enforcement, water infrastructure classification, and spatial land allocation (Table 2).

Table 1. **Relationship between Watershed Area and Sediment Delivery Ratio [1].**

No.	Watershed Area (Ha)	Sediment Delivery Ratio (%)
1.	10	53
2.	50	39
3.	100	35
4.	500	27
5.	1000	24
6.	5000	15
7.	10.000	13
8.	20.000	11
9.	50.000	8,5
10.	2.600.000	4,9

Table 2. Parameter Weights and Values for Monitoring and Evaluation of Watershed Carrying Capacity [1].

CRITERIA/ SUB CRITERIA	WEIGHT (%)	VALUE / SCORE				
		Very Low	Low	Moderate	High	Very High
		Score = 0.5	Score = 0.75	Score = 1.0	Score = 1.25	Score = 1.5
A. Land Condition	40					
1. Percentage of critical land (PLK)	20	PLK ≤ 5	5 < PLK ≤ 10	10 < PLK ≤ 15	15 < PLK ≤ 20	PLK > 20
2. Percentage of vegetation cover (PPV)	10	PPV > 80	60 < PPV ≤80	40 < PPV ≤ 60	20 < PPV ≤ 40	PPV ≤ 20
3. Index of eros (IE)	10	IE ≤ 0.5	0.5 < IE ≤ 1.0	1.0 < IE ≤ 1.5	1.5 < IE ≤ 2.0	IE > 2.0
A. Water System Condition	20					
1. Flow regime coefficient (KRA)	5	KRA ≤ 20	20 < KRA ≤ 50	50 < KRA ≤ 80	80 < KRA ≤110	KRA > 110
2. Annual flow coefficient (KAT)	5	KAT ≤ 0.2	0.2 < KAT ≤0.3	0.3 < KAT ≤ 0.4	0.4 < KAT ≤0.5	KAT > 0.5
3. Sediment load (MS)	4	MS ≤ 5	5 < MS ≤ 10	10 < MS ≤ 15	15 < MS ≤ 20	MS > 20
4. Flood	2	Never	1 time in 5 years	1 time in 2 years	1 time in 1 year	More than 1 x in 1 year
5. Water use index (IPA)	4	IPA ≤ 0.25	0.25 < IPA≤0.5	0.5<IPA≤0.75	0.75<IPA≤1.0	IPA > 1.0
B. Socio-Economic Conditions	20					
1. Population pressure (IKL)	10	IKL > 4.0	2.0 < IKL ≤ 4.0	1.0 < IKL ≤ 2.0	0.5 < IKL≤ 1.0	ICL < 0.5
2. Level of population welfare (TKP)	3	TKP ≤ 5	5 < TKP ≤ 10	10 < TKP ≤ 20	20 < TKP ≤ 30	TKP > 30
3. Existence and enforcement of regulations (norms)	7	Exists, it is widely practiced	Exists, limited practiced	Exists, but not practiced	There are no rules	There are rules but they are against conservation
C. Building Investment	10					
1. City classification	5	There is no city	Small city/town	Municipality	Big city	Metropolitan City
2. Classification of water structures (IBA)	5	IBA ≤15 billion rupiahs	15< IBA ≤30 billion rupiahs	30< IBA ≤45 billion rupiahs	45< IBA ≤60 billion rupiahs	IBA >60 billion rupiahs
D. Utilization of Regional Space	10					
1. Protected area (KL)	5	KL > 70	45 < KL ≤ 70	30 < KL ≤ 45	15 < KL ≤30	KL ≤ 15
2. Cultivation area (KB)	5	KB > 70	45 < KB ≤ 70	30 < KB ≤ 45	15 < KB ≤ 30	KB ≤ 15

2.5. Scoring and Classification Procedure

The assessment procedure was carried out through a systematic scoring and weighting process. Initially, each sub-criteria value was calculated based on the available data. These values were then classified into performance categories according to predefined thresholds. Subsequently, scores were assigned to each sub-criteria and multiplied by their respective weights to reflect their relative importance. The weighted scores of all fifteen sub-criteria were aggregated to obtain a composite index representing the overall carrying capacity of each watershed. Finally, the resulting index values were classified into watershed carrying capacity categories to determine the performance level of each watershed system (Table 3).

Table 3. Classification of Watershed Carrying Capacity (DDD) [1].

No.	Value	Category
1.	DDD ≤ 70	Very good
2.	70 < DDD ≤ 90	Good
3.	90 < DDD ≤ 110	Moderate
4.	110 < DDD ≤ 130	Poor
5.	DDD > 130	Very Poor

3. Result and Discussion

3.1. Land Condition

3.1.1. Critical Land

The analysis of critical land conditions indicates that the total area classified as critical and very critical land in the Wai Samal and Wai Eti watersheds reaches 1,415.13 ha and 1,021.87 ha, respectively. Considering the total watershed areas of 34,473.37 ha (Wai Samal) and 14,452.44 ha (Wai Eti), the proportion of degraded land remains relatively limited (Table 4). The calculated percentage of critical land (PLK) is 4.10% for the Wai Samal Watershed and 7.07% for the Wai Eti Watershed. Based on the classification criteria, the Wai Samal

Watershed falls into the very low (very good) category (PLK $\leq$ 5), with a score of 0.5, while the Wai Eti Watershed is categorized as low (good) (5 < PLK $\leq$ 10), with a score of 0.75 (Figure 2, 3).

Table 4. Components of the Critical Land Assessment in the Wai Samal and Wai Eti Watersheds

No.	Indicator of Land Criticality Level	Wai Samal Watershed (ha)	Wai Eti Watershed (ha)
1.	Not Critical	9231.75	1395.50
2.	Critical Potential	5666.09	113.48
3.	Slightly Critical	18160.40	11921.59
4.	Critical	597.64	256.20
5.	Very Critical	817.49	765.67
	Total	34473.37	14452.44

Figure 2. Critical land conditions in the Wai Samal Watershed showing sheet and rill erosion.

Figure 3. Critical land conditions in the Wai Eti Watershed showing secondary shrub vegetation following logging and shifting cultivation.

From a comparative perspective, the Wai Eti Watershed exhibits a higher proportion of critical land despite its smaller spatial extent, indicating greater environmental pressure on the watershed system (Figure 4, 5). This finding is particularly important in the context of small island watersheds, where limited land area and restricted ecological buffering capacity can amplify the impacts of land degradation. Under such conditions, even relatively small increases in critical land may significantly alter hydrological responses by increasing surface runoff, reducing infiltration capacity, accelerating erosion processes, and decreasing overall watershed stability. Although both watersheds remain within acceptable carrying capacity categories, the higher PLK value observed in the Wai Eti Watershed indicates a greater susceptibility to environmental disturbance and watershed degradation. This condition is likely associated with differences in land-use intensity, vegetation cover, and topographic characteristics, which collectively influence watershed performance and therefore require greater attention in future watershed management strategies.

These findings are consistent with [29], who reported that the expansion of critical land within a watershed can accelerate erosion, reduce permanent vegetation cover, and intensify land degradation processes, ultimately threatening both the hydrological and ecological carrying capacity of the watershed. Similarly, [30] demonstrated that although the Bodri Watershed had a relatively low proportion of critical land (6.34%; good category), this indicator still played an important role in determining overall watershed carrying capacity performance.

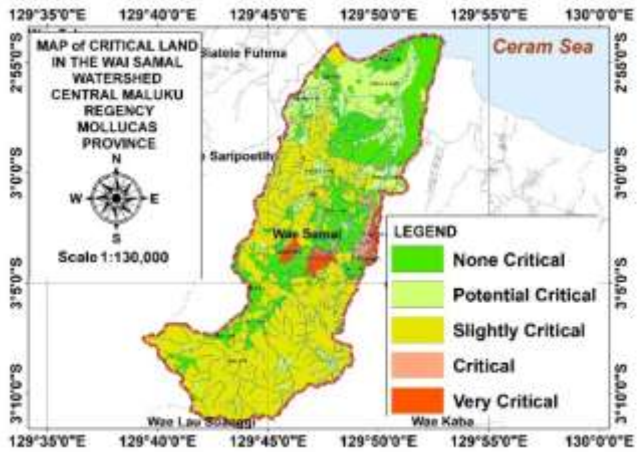

Figure 4. Map of Land Critical Map of Wai Samal Watershed

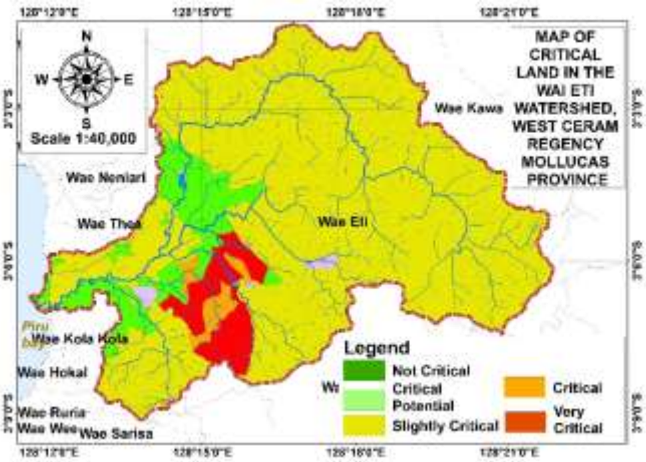

Figure 5. Map of Land Critical Map of Wai Eti Watershed

3.1.2. Vegetation Coverage

The analysis of permanent vegetation cover indicates that the Wai Samal Watershed has a total vegetated area of 29,185.21 ha, consisting of secondary dryland forest, primary and secondary mangrove forests, primary swamp forest, plantations, shrubs, and savanna/grassland. Similarly, the Wai Eti Watershed has a vegetated area of 12,344.81 ha, including primary and secondary forests, secondary mangrove forest, shrubs, and savanna/grassland. Given the total watershed areas of 34,473.37 ha (Wai Samal) and 14,452.44 ha (Wai Eti), the proportion of permanent vegetation cover in both watersheds is classified as very high (>80%), placing them in the very good category with a score of 0.5 (Table 5; Figures 6 and 7).

Table 5. Land Cover Components in the Wai Samal Watershed and Wai Eti Watershed

No.	Land Cover Area (ha)	Wai Samal Watershed	Wai Eti Watershed
1.	Primary Dryland Forest	0.00	476.59
2.	Secondary Dryland Forest	17662.99	10136.82
3.	Primary Mangrove Forest	2.15	0.0
4.	Secondary Mangrove Forest	1192.12	37.95
5.	Primary Swamp Forest	51.26	0.00
6.	Plantation	5048.12	0.00
7.	Dryland Farming	118.35	1135.96
8.	Mixed Dryland Agriculture	2408.90	900.06
9.	Ricefield	1904.19	0.00
10.	Bush / Bush	3688.50	1638.44
11.	Savanna / Grassland	1540.07	55.01
12.	Transmigration / Village	359.26	0.00
13.	Settlement	21.82	71.61
14.	Open Land	409.05	0.00
15.	Lake	66.58	0.00
	Total	34473.37	14452.44

The analysis results show that the percentage of permanent vegetation cover (PPV) in the Wai Samal and Wai Eti watersheds reached 84.66% and 85.42%, respectively (Figures 6 and 7). Based on the watershed carrying capacity classification, both watersheds fall within the very good category (PPV > 80) with a score of 0.5. These findings indicate that both watersheds still maintain relatively extensive permanent vegetation cover, which plays an important role in supporting watershed stability and sustaining hydrological functions.

High vegetation cover, particularly forest vegetation, contributes significantly to improving watershed carrying capacity by enhancing infiltration, reducing surface runoff, and minimizing soil erosion. In hydrological terms, greater forest cover reduces the cover-management factor (C factor), thereby lowering erosion rates and sediment transport. Conversely, the expansion of non-permanent land uses, such as dryland agriculture and mixed dryland farming, tends to increase soil exposure and accelerate erosion processes, particularly on sloping land. This condition is especially important in small island watersheds, where limited spatial extent and high environmental sensitivity can intensify the impacts of land-cover change on watershed performance.

These findings are consistent with the Regulation of the [1], which states that uncontrolled land-use change without adequate soil and water conservation measures can increase erosion and sedimentation, reduce vegetation cover, and accelerate land degradation. Similarly, [31] reported in the Wai Tala Watershed that vegetation and land-use factors significantly influence erosion rates (p-value = 0.000; r = 0.72), indicating that higher C-factor values are associated with increased erosion intensity. [32] further demonstrated that wider forest vegetation cover, particularly primary forest, contributes to lower levels of soil degradation due to erosion in Kairatu District. In contrast, [33] found that mixed dryland agricultural areas in the Wai Ruhu Watershed experienced high erosion rates reaching 70.58 tons ha^{-1} $year^{-1}$ using field indicators and 106.29 tons ha^{-1} $year^{-1}$ using the RUSLE method, as indicated by exposed plant root systems resulting from severe soil loss.

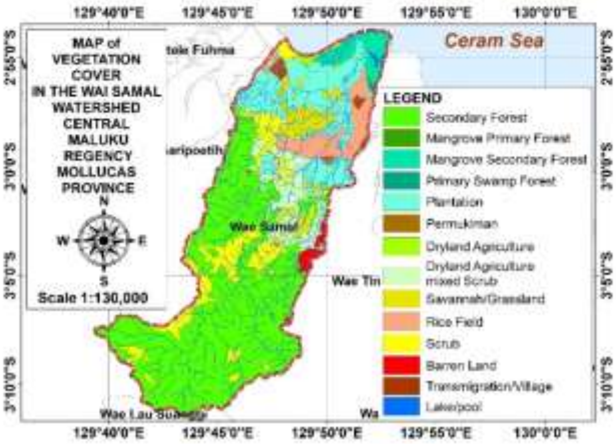

Figure 6. Map of Vegetation Cover of Wai Samal Watershed

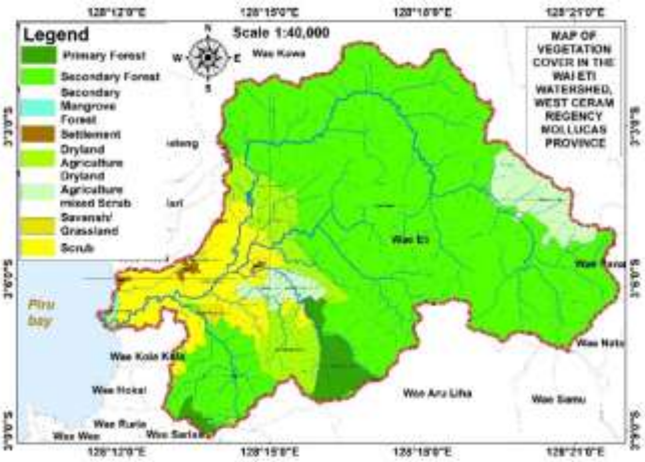

Figure 7. Map of Vegetation Cover of Wai Eti Watershed

3.1.3. Erosion Index

The analysis of erosion characteristics indicates a significant disparity between tolerable erosion and actual erosion rates in both watersheds. The average tolerable erosion was estimated at 26.10 ton·ha^{-1}·year^{-1} for the Wai Samal Watershed and 19.66 ton·ha^{-1}·year^{-1} for the Wai Eti Watershed. In contrast, the actual erosion rates were substantially higher, reaching 290.26 ton·ha^{-1}·year^{-1} and 71.03 ton·ha^{-1}·year^{-1}, respectively (Table 6). As a consequence, the calculated erosion index (IE), defined as the ratio between actual and tolerable erosion, was 4.69 for the Wai Samal Watershed and 7.08 for the Wai Eti Watershed. Based on the classification criteria, both watersheds fall into the **very** high category (IE > 2.0), with a score of 1.5 (Figures 8–11). These values indicate that erosion rates in both watersheds far exceed sustainable thresholds, reflecting severe land degradation processes.

Table 6. Components of Erosion Index in Wai Samal Watershed and Wai Eti Watershed

No.	Erosion Index Components	Wai Samal Watershed	Wai Eti Watershed
1.	Mean erosion tolerance (tons/ha/yr)	26.10	19.66
2.	Mean actual erosion (tons/ha/yr)	290.26	71.03
3.	Average erosion index	4.69	7.08

Figure 8. Land degradation due to soil erosion in Wai Samal Watershed

Figure 9. Land degradation due to soil erosion in Wai Eti Watershed

Despite both watersheds being classified within the same erosion index category, the Wai Eti Watershed exhibits a considerably higher IE value compared to the Wai Samal Watershed. This suggests that the Wai Eti Watershed is subject to more intense erosion pressure, which contributes to a reduction in its overall carrying capacity, categorized as moderate. In contrast, the relatively lower erosion index in the Wai Samal Watershed supports a better carrying capacity classification.

These findings are consistent with [4], who reported that an erosion index value of 2.00 in the Wanggu Watershed was already categorized as high and contributed to poor watershed carrying capacity. Similarly, [1] emphasizes that uncontrolled land use without adequate soil and water conservation measures can accelerate erosion, increase sedimentation, and degrade watershed conditions. Therefore, the high erosion index observed in both watersheds highlights the need for improved land management practices, particularly soil and water conservation strategies, to maintain and enhance watershed carrying capacity. This is especially critical in small island environments, where the threshold for ecological degradation is relatively low and the recovery capacity is limited.

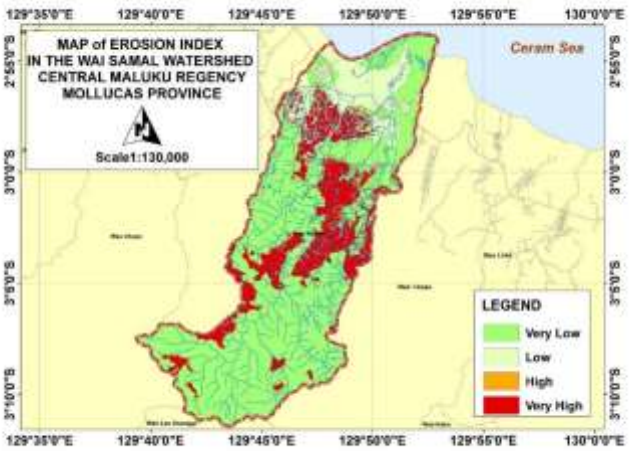

Figure 10. Map of Erosion Index of Wai Samal Watershed

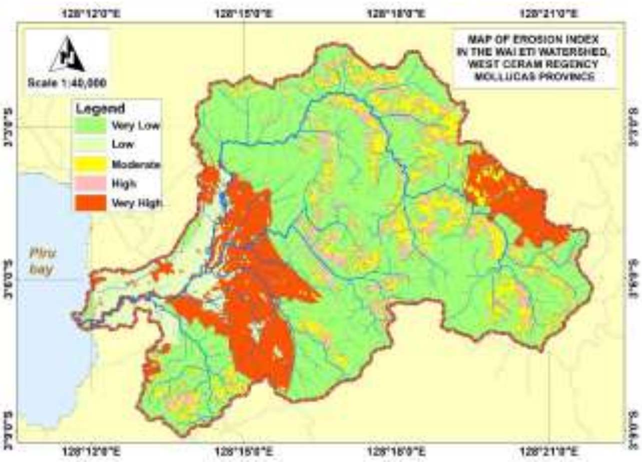

Figure 11. Map of Erosion Index of Wai Eti Watershed

3.2. Water System Condition

3.2.1. Flow Regime Coefficient

The hydrological analysis reveals significant differences in flow variability between the two watersheds. The Wai Samal Watershed exhibits an average maximum discharge (Qmax) of 212.71 $m^3 \cdot s^{-1}$ and a minimum discharge (Qmin) of 3.79 $m^3 \cdot s^{-1}$. In contrast, the Wai Eti Watershed shows a lower maximum discharge of 79.18 $m^3 \cdot s^{-1}$ but a slightly higher minimum discharge of 3.85 $m^3 \cdot s^{-1}$ (Table 7).

These values result in a flow regime coefficient (KRA) of 56.12 for the Wai Samal Watershed and 20.57 for the Wai Eti Watershed. Based on the classification criteria, the Wai Samal Watershed falls into the moderate category ($50 < KRA \leq 80$) with a score of 1.0, whereas the Wai Eti Watershed is classified as low ($20 < KRA \leq 50$) with a score of 0.75. The higher KRA value in the Wai Samal Watershed indicates greater variability between peak and low flows, suggesting a less stable flow regime. This condition reflects limited water retention capacity, where a significant portion of rainfall is rapidly converted into surface runoff rather than being stored within the soil or groundwater system. As a result, the watershed tends to experience higher peak flows during the rainy season and reduced water availability during the dry season.

Table 7. Flow Regime Components in the Wai Samal and Wai Eti Watersheds

No.	Flow Regime Components	Wai Samal Watershed	Wai Eti Watershed
1.	Average maximum discharge (Qmax) (m3/sec)	212.71	79.18
2.	Average minimum discharge (Qmin) (m3/sec)	3.79	3.85
3.	Average Flow Regime Coefficient	56.12	20.57

In contrast, the lower KRA value in the Wai Eti Watershed indicates a relatively more stable flow regime, with smaller differences between maximum and minimum discharge. This suggests better water storage and regulation capacity, allowing for more sustained baseflow during dry periods. Consequently, despite its smaller size, the Wai Eti Watershed demonstrates a relatively better hydrological buffering capacity compared to the Wai Samal Watershed. These findings are consistent with [34], who reported that very high KRA values (e.g., 175.46 in the Bulok Sub-watershed) indicate severe land degradation, where most rainfall is converted into surface runoff rather than being stored. Similarly, [35] observed that high KRA values are associated with steep slopes, reduced vegetation cover, and inadequate soil conservation practices, leading to extreme hydrological fluctuations such as flooding during the rainy season and drought during the dry season.

In small island watersheds, unstable flow regimes pose a critical challenge due to limited catchment area and water storage capacity. Under these conditions, increases in KRA can rapidly reduce water availability and intensify vulnerability to hydrological extremes. Therefore, improving vegetation cover and strengthening soil and water conservation are essential to enhance water retention and maintain watershed stability.

3.2.2. Annual Flow Coefficient (KAT)

The analysis of annual hydrological balance shows that the Wai Samal Watershed has an average annual flow volume (Q annual) of 3.41 M m³ and an annual rainfall volume (P annual) of 1.33 M m³. Similarly, the Wai Eti Watershed records an annual flow volume of 0.94 M m³ and an annual rainfall volume of 0.31 M m³ (Table 8). Based on these values, the calculated KAT, defined as the ratio between annual flow and annual rainfall, is 3.63 for the Wai Samal Watershed and 4.29 for the Wai Eti Watershed. According to the classification criteria, both watersheds fall into the very high (very poor) category (KAT > 0.5), with a score of 1.5.

Table 8. Annual Flow Components in the Wai Samal and Wai Eti Watersheds

No.	Annual Flow Components	Wai Samal Watershed	Wai Eti Watershed
1.	Average annual flow volume (Q annual) (M m^3)	3.41	0.94
2.	Average annual rainfall volume (P annual) (M m^3)	1.33	0.31
3.	Average annual flow coefficient	3.63	4.29

These high KAT values indicate that a large proportion of rainfall is rapidly converted into surface runoff, reflecting limited infiltration and low water storage capacity. Consequently, both watersheds are more vulnerable to flooding during the rainy season and reduced water availability during the dry season. The higher KAT value observed in the Wai Eti Watershed further indicates lower hydrological regulation capacity and greater susceptibility to runoff-driven processes, which may contribute to declining watershed carrying capacity. In contrast, the lower KAT value in the Wai Samal Watershed reflects relatively better infiltration and water retention capacity. The relatively high KAT values reflect the hydrological characteristics of the study watersheds, particularly their high annual rainfall and rapid runoff response, which are typical of small island watersheds characterized by relatively small catchment areas and limited water storage capacity.

These findings are consistent with [35], who reported that lower annual flow coefficient values are associated with better infiltration capacity and more stable hydrological conditions, thereby reducing drought risk. Similarly, [36] found that a very low KAT value (0.055) in the Dodokan Watershed reflects minimal surface runoff and well-maintained watershed conditions. [37] further emphasized that land use based on soil and water conservation principles tends to reduce KAT values, whereas land degradation increases surface runoff and reflects declining watershed biophysical conditions. A low KAT value indicates that the watershed's biophysical condition is still in a good category, and a high KAT value indicates that the watershed's biophysical condition is damaged, resulting in most of the rainwater flowing as surface flow.

In the context of small island watersheds, high KAT can intensify vulnerability to hydrological extremes and seasonal water scarcity. Therefore, improving infiltration through vegetation management and soil and water conservation practices is essential to enhance watershed carrying capacity and sustain water availability.

3.2.3. Sediment Load (MS)

The analysis of sediment dynamics indicates substantial differences between the two watersheds. The Wai Samal Watershed recorded a much higher actual erosion total (42330.01 ton·ha^{-1}·year^{-1}) with an SDR value of 0.098, compared to 23866.78 ton·ha^{-1}·year^{-1} and an SDR of 0.12 in the Wai Eti Watershed (Table 9). Consequently, the average sediment load (MS) in the Wai Samal Watershed reached 4148.34 ton·ha^{-1}·year^{-1}, classified as very high (MS > 20) with a score of 1.5, similarly, Wai Eti Watershed recorded a very high sediment load of 2864.02 ton·ha^{-1}·year^{-1}, classified as very high (MS > 20) with a score of 1.5 (Figures 12 and 13).

Table 9. Sediment Load Components in the Wai Samal and Wai Eti Watersheds

No.	Sediment Load Components	Wai Samal Watershed	Wai Eti Watershed
1.	Total actual erosion (tons/ha/yr)	42330.01	23866.78
2.	Average sediment delivery ratio (SDR)	0.098	0.12
3.	Total sediment load (MS) (tons/ha/yr)	4148.34	2864.02

Figure 12. Sedimen load condition in the downstream of Wai Samal Watershed

Figure 13. Sedimen load condition in the downstream of Wai Eti Watershed

These findings indicate that, despite being classified within the good carrying capacity category, the Wai Samal Watershed remains highly vulnerable to sediment-related degradation processes. The high sediment load reflects intensive erosion, suggesting that soil loss remains a major challenge for watershed sustainability. In contrast, the lower sediment load observed in the Wai Eti Watershed indicates relatively lower sediment transport pressure.

The results further suggest that erosion intensity plays a more dominant role in controlling sediment yield than the sediment delivery ratio. In small island watersheds, where river systems and catchment areas are relatively limited, high sediment loads can rapidly accelerate river sedimentation, reduce water quality, increase turbidity, and disrupt downstream ecosystem functions and water resource utilization. Consequently, the Wai Samal Watershed exhibits greater vulnerability to sediment-related degradation despite its overall good carrying capacity classification.

[35] also reported that high sediment loads in tropical watersheds are closely associated with severe erosion, steep slopes, and poor conservation practices, which collectively reduce watershed performance. Similarly, [38] found that high erosion, declining vegetation cover, cultivation on steep slopes, settlement expansion, and mining activities significantly increased sediment loads and reduced watershed carrying capacity in the Tallo Watershed. [39] further emphasized that sediment deposition from surface runoff contributes substantially to declining river water quality and ecosystem

3.2.4. Flood

The results show that flooding occurs once per year in the Wai Samal Watershed and more than once per year in the Wai Eti Watershed. Based on the flood classification criteria, the Wai Samal Watershed is classified as high with a score of 1.25, whereas the Wai Eti Watershed is classified as very high with a score of 1.5. These findings indicate that the lower flood frequency in the Wai Samal Watershed contributes to more stable hydrological conditions and better watershed carrying capacity. In contrast, the higher flood frequency in the Wai Eti Watershed reflects greater hydrological pressure and reduced watershed resilience, which collectively contribute to declining watershed carrying capacity.

In small island watersheds, high flood frequency represents a critical indicator of hydrological instability because limited catchment area and storage capacity can accelerate runoff concentration during intense rainfall events. Frequent flooding also indicates reduced infiltration capacity and weakened natural water regulation functions, which may further increase watershed vulnerability to environmental degradation.

These findings are consistent with [38], who reported that frequent flooding significantly contributed to declining watershed carrying capacity in the Tallo Watershed. Similarly, [35] found that high flood frequency in the Ambang Watershed was associated with inundation and flash flood events linked to poor watershed conditions. [40] further emphasized that land-use change and the conversion of forested areas into agricultural and urban land increase surface runoff and reduce groundwater retention capacity, thereby intensifying flood risk and hydrological disturbance.

3.2.5. Water Use Index (IPA)

The analysis of water availability and demand indicates that the Wai Samal Watershed has a total water demand of 411.62 million m³ and a water supply of 942.21 million m³. In comparison, the Wai Eti Watershed has a water demand of 156.02 million m³ and a water supply of 307.54 million m³ (Table 10).

The calculated Water Use Index (IPA) values for the Wai Samal and Wai Eti watersheds are 0.44 and 0.51, respectively. Based on the classification criteria, the Wai Samal Watershed is categorized as low ($0.25 < IPA \leq 0.50$) with a score of 0.75, whereas the Wai Eti Watershed is categorized as moderate ($0.50 < IPA \leq 0.75$) with a score of 1.0. These results indicate that water availability in the Wai Samal Watershed is still relatively sufficient to meet water demand, while the higher IPA value in the Wai Eti Watershed reflects increasing pressure on water resources and lower hydrological resilience.

Table 10. Components of the Water Use Index in the Wai Samal Watershed and Wai Eti Watershed

No.	Land Use	Annual Water Requirements (million m^3/thn		Annual Water Supply (million m^3/thn)		Water Use Index (IPA)	
		Wai Samal	Wai Eti	Wai Samal	Wai Eti	Wai Samal	Wai Eti
1.	Primary Forest	-	0.157	-	10.1416	-	0.015
2.	Secondary Forest	90.499193	71.099	482.76	215.7075	0.18746	0.330
3.	Primary Mangrove Forest	0.000001	-	0.06	-	0.00002	-
4.	Secondary Mangrove Forest	0.412246	0.001	32.58	0.8076	0.01265	0.001
5.	Primary Swamp Forest	0.000762	-	1.40	-	0.00054	-
6.	Plantation	8.870679	-	137.97	-	0.06429	-
7.	Dryland Agriculture	0.004876	1.071	3.23	24.1728	0.00151	0.044
8.	Dryland Agriculture mixed scrub	2.272415	0.757	65.84	19.1529	0.03451	0.040
9.	Rice field	2.524341	-	52.04	-	0.04850	-
10.	Scrub	5.327821	2.508	100.81	34.8653	0.05285	0.072
11.	Savanna / Grassland	0.928819	0.003	42.09	1.1706	0.02207	0.002
12.	Transmigration / Village	0.044928	-	9.82	-	0.00458	-
13.	Settlement	0.000166	0.004	0.60	1.5238	0.00028	0.003
14.	Bare Land	0.084939	-	11.18	-	0.00760	-
	Total	411.62	156.02	942.21	307.54	0.44	0.51

The lower IPA value in the Wai Samal Watershed indicates that water availability still exceeds demand by a considerable margin, suggesting relatively favorable conditions for sustaining water use and supporting watershed carrying capacity. In contrast, the higher IPA value in the Wai Eti Watershed reflects a narrower gap between water supply and demand, indicating increasing pressure on available water resources and reduced hydrological resilience. In small island watershed systems, this condition is particularly critical because limited catchment area and water storage capacity can accelerate the onset of water stress during periods of prolonged drought or increasing water demand.

These findings are consistent with [4], who reported that a moderate Water Use Index (IPA=0,69) contributed to declining watershed carrying capacity in the Wanggu Watershed. Similarly, [41] emphasized that water availability exceeding water demand is a key indicator of good watershed carrying capacity and sustainable hydrological conditions.

However, it is important to note that water availability alone does not fully guarantee water security. In the context of the Wai Samal and Wai Eti watersheds, previously identified hydrological conditions such as high flow variability (KRA), elevated annual flow coefficients (KAT), and frequent flooding indicate that a significant portion of water is rapidly lost as surface runoff. This suggests that although total water supply appears sufficient on an annual basis, effective water storage and distribution remain limited. This condition is particularly critical in small island watersheds, where limited storage capacity and high hydrological variability can lead to temporal mismatches between water availability and demand. As a result, water surplus during the rainy season may not translate into adequate water availability during the dry season.

3.3 Socio-Economic Condition

3.3.1. Population Pressure (Land Availability Index)

The analysis of population pressure on land, represented by the Land Availability Index (IKL), shows notable differences between the two watersheds. In the Wai Samal Watershed, the available agricultural land area reaches 9,479.57 ha, supporting 934 farming households. In contrast, the Wai Eti Watershed has a significantly smaller agricultural land area of 2,036.02 ha with 708 farming households (Table 11). Based on these values, the calculated IKL is 10.14 for the Wai Samal Watershed and 2.88 for the Wai Eti Watershed. According to the classification criteria, the Wai Samal Watershed falls into the very high category (IKL > 4.0) with a score of 0.5, indicating very low population pressure on land. Meanwhile, the Wai Eti Watershed is classified as high (2.0 < IKL ≤ 4.0) with a score of 0.75, reflecting relatively greater pressure on available agricultural land and a lower capacity to support population needs sustainably.

Table 11. Population Pressure Components (Land Availability) at Wai Samal Watershed and Wai Eti Watershed

No.	Population Pressure Components	Wai Samal Watershed	Wai Eti Watershed
1.	Available Agricultural Land Area (Ha)	9,479.57	2,036.02
2.	Number of Farmer Households	934	708
3.	Land Availability Index (IKL)	10.14	2.88

A higher IKL value indicates greater land availability relative to population demand, thereby reducing pressure on land resources and supporting more sustainable land use. The very high IKL value in the Wai Samal Watershed suggests that agricultural land availability remains sufficient to support local community needs, contributing positively to watershed carrying capacity. In contrast, the lower IKL value in the Wai Eti Watershed reflects increasing pressure on available land resources, which may encourage more intensive land use and expansion into environmentally sensitive areas, potentially accelerating land degradation and reducing watershed performance.

These findings are consistent with [42], who reported that moderate population pressure reflects relatively adequate land availability to support community needs sustainably. Conversely, [8] found that high population pressure indicates an imbalance between population growth and land availability, which may contribute to environmental degradation.

In small island watershed systems, population pressure on land becomes particularly critical because limited spatial capacity restricts opportunities for land expansion. Increasing demand for land can therefore intensify land-use pressure and negatively affect hydrological functions through increased runoff, reduced infiltration, and accelerated erosion. Therefore, maintaining a balance between population demand and land availability is essential for sustaining watershed carrying capacity in small island environments.

3.3.2. Population Welfare Level (TKP)

The assessment of population welfare reveals substantial disparities between the two watersheds. In the Wai Samal Watershed, the number of poor households (pre-prosperous and prosperous I categories) is 156 out of a total of 1,000 households. In contrast, the Wai Eti Watershed records 2,823 poor households out of 3,002 households (Table 12). These figures correspond to population welfare levels (TKP) of 15.60% in the Wai Samal Watershed and 94.04% in the Wai Eti Watershed. Based on the classification criteria, the Wai Samal Watershed falls into the moderate category (10 < TKP ≤ 20) with a score of 1.0, while the Wai Eti Watershed is classified as very poor (TKP > 30) with a score of 1.5.

Table 12. Components of Population Welfare Level (Land Availability) at Wai Samal Watershed and Wai Eti Watershed

No.	Components of Population Welfare Level	Wai Samal Watershed	Wai Eti Watershed
1.	Number of poor families (pre-prosperous and prosperous families I)	156	2823
2.	Total number of families	1000	3002
3.	Population Welfare Level (TKP) (%)	15.60	94.04

The lower TKP values indicate better socio-economic conditions and greater community capacity to manage natural resources sustainably. The relatively moderate TKP value in the Wai Samal Watershed suggests that local communities still possess a better ability to support environmental management and maintain watershed functions. In contrast, the extremely high TKP value in the Wai Eti Watershed reflects severe socio-economic limitations and greater dependence on natural resources, which may encourage unsustainable land-use practices and increase pressure on watershed systems. These findings are consistent with [43], who reported that better community welfare is associated with improved watershed carrying capacity due to stronger environmental management capacity. Conversely, [30] found that high poverty levels contribute to increased environmental vulnerability and declining watershed conditions. In small island watershed systems, socio-economic pressure becomes particularly critical because limited land and economic opportunities intensify dependence on natural resources. Under such conditions, low community welfare can accelerate land degradation, increase runoff and erosion, and reduce watershed resilience. Therefore, improving community welfare should be considered an integral component of sustainable watershed management in small island environments.

3.3.3. Existence and Enforcement of Rules

The analysis of institutional aspects reveals clear differences in the effectiveness of soil and water conservation regulations between the two watersheds. Based on the classification criteria, the Wai Samal Watershed is categorized as very good with a score of 0.5, reflecting stronger institutional capacity and more effective enforcement of conservation regulations. In contrast, the Wai Eti Watershed is classified as good with a score of 0.75, indicating that although conservation regulations are present, their implementation remains relatively limited. In the Wai Samal Watershed, regulations governing soil and water conservation are not only formally established but are also widely implemented, particularly in the protection of irrigation water sources (Figure 14). In contrast, although similar conservation regulations exist in the Wai Eti Watershed, their implementation remains limited. One example is the *sasi* system, a traditional community-based practice reinforced through local church institutions, which regulates the harvesting period of natural resources such as coconuts through temporary harvesting restrictions (3–6 months). Although *sasi* reflects strong local wisdom in resource management, its implementation remains limited in scope and has not yet comprehensively addressed broader soil and water conservation issues (Figure 15).

Figure 14. Local regulations for protecting irrigation water sources in the Wai Samal watershed.

Figure 15. Church Sasi regulations protecting coconut plantation areas in the Wai Eti Watershed.

This study shows that effective institutional enforcement is essential for maintaining watershed functions through land-use regulation, water resource protection, and the implementation of conservation practices. The stronger institutional performance in the Wai Samal Watershed contributes positively to its carrying capacity, whereas the weaker implementation of conservation rules in the Wai Eti Watershed reduces management effectiveness and watershed performance. These findings are consistent with [43], who reported that effective institutional performance and law enforcement positively influence watershed carrying capacity. Similarly, [30] emphasized that local cultural practices and collective social systems strengthen environmental management and community participation in watershed conservation.

In small island watersheds, institutional capacity and local governance are particularly important due to limited natural resources and high environmental sensitivity. Integrating formal regulations with local wisdom systems such as *sasi* can support more adaptive and context-specific watershed management. Therefore, strengthening institutional effectiveness and community participation is essential for improving watershed carrying capacity and long-term environmental sustainability.

3.4. Water Infrastructure Investment

3.4.1. Urban Classification

The results show that the population within the Wai Samal Watershed is 3,001 people, whereas the Wai Eti Watershed has a population of 13,239 people. Based on the classification criteria, both watersheds are categorized as small urban areas. After weighting and scoring the urban classification indicators, both watersheds fall into the low category with a score of 0.75. Although both watersheds are classified within the same urban category, differences in population size indicate varying levels of anthropogenic pressure on watershed systems. The smaller population in the Wai Samal Watershed suggests relatively lower pressure on land and water resources, which contributes positively to watershed carrying capacity. In contrast, the larger population in the Wai Eti Watershed may increase pressure on natural resources and spatial utilization, potentially reducing watershed performance.

These findings are consistent with [30], who reported that increasing urban development contributed to declining watershed carrying capacity in the Bodri Watershed. Similarly, [44] identified urban development, together with high critical land extent, flooding, erosion, and poor spatial planning, as important factors contributing to degraded watershed conditions.

In small island watershed systems, urban expansion and population concentration can rapidly intensify environmental pressure due to limited land availability and restricted ecological carrying capacity. Therefore, spatial planning and controlled urban development are essential to maintain sustainable watershed functions and long-term environmental resilience.

3.4.2. Water Infrastructure Investment Value (IBA)

The assessment of water infrastructure investment reveals contrasting conditions between the two watersheds. In the Wai Samal Watershed, the total investment value of water structures ranges from 1 to 5 billion IDR, primarily allocated to dam maintenance and irrigation network repairs. In contrast, the Wai Eti Watershed exhibits a substantially higher investment value of approximately 22.5 billion IDR, including the construction of check dams, riverbank protection structures, and other water resource infrastructure.

Based on the classification criteria, the Wai Samal Watershed is categorized as very low investment with a score of 0.5, whereas the Wai Eti Watershed is classified as low investment with a score of 0.75.

The higher infrastructure investment reflects increasing environmental degradation and greater dependence on structural approaches to mitigate hydrological risks. In contrast, the lower investment value observed in the Wai Samal Watershed suggests relatively better natural watershed functioning and lower reliance on engineered interventions, which contributes positively to watershed carrying capacity. According to [45], water infrastructure investment reflects the magnitude of watershed assets that require protection from degradation. Similarly, [46] demonstrated that very high infrastructure investment in the Upper Ciliwung Watershed was associated with lower watershed carrying capacity and increasing dependence on reactive structural management approaches.

In small island watershed systems, excessive reliance on structural infrastructure may indicate declining ecosystem resilience and limited natural hydrological regulation capacity. Therefore, watershed management should prioritize preventive and ecosystem-based approaches alongside infrastructure development to improve long-term watershed sustainability.

3.5. Regional Spatial Land Use

3.5.1. Protected Areas (KL)

Analysis of the 2013–2033 Regional Spatial Planning Maps (RTRW) of Central Maluku Regency and West Seram Regency indicates that the Wai Samal Watershed contains 3,857.52 ha of protected area, of which 3,834.35 ha are covered by permanent vegetation, including primary mangrove forest, secondary dryland forest, and shrubs. In contrast, the Wai Eti Watershed has a much smaller protected area of 97.77 ha, entirely dominated by shrub vegetation (Table 13). Despite the large difference in absolute area, both watersheds exhibit very high proportions of protected areas with permanent vegetation (KL), reaching 99.40% in the Wai Samal Watershed and 100% in the Wai Eti Watershed. Based on the classification criteria, both watersheds are categorized as very good (KL > 70) with a score of 0.5 (Figures 16 and 17). However, the contribution of protected areas to watershed carrying capacity is determined not only by their proportion but also by their spatial extent, vegetation quality, and ecological function. The Wai Samal Watershed benefits from a larger protected area with more diverse and structurally complex vegetation, which enhances hydrological regulation, soil stability, and erosion control. In contrast, although the Wai Eti Watershed exhibits a higher percentage of protected area, its limited extent and dominance of shrub vegetation likely provide lower ecological protection capacity than forest-based ecosystems. In small island watersheds, where land resources and hydrological storage are inherently limited, such differences can substantially influence watershed stability and environmental resilience.

Table 13. Components of Protected Areas in the Wai Samal Watershed and Wai Eti Watershed

No.	Protected Area Components	Wai Samal Watershed	Wai Eti Watershed
1.	Area of protected area (ha)	3857.52	97.77
2.	Permanent vegetation area in protected areas (ha)	3834.35	97.77
3.	Percentage of Protected Areas (KL)	99.40	100.00

These findings are consistent with [47], who reported that watersheds with a high proportion of protected areas exhibit better carrying capacity due to the maintenance of ecological and hydrological functions. Similarly, [45] emphasized that protected areas with steep slopes and erosion-sensitive soils require strong protection to prevent ecosystem degradation and maintain watershed stability.

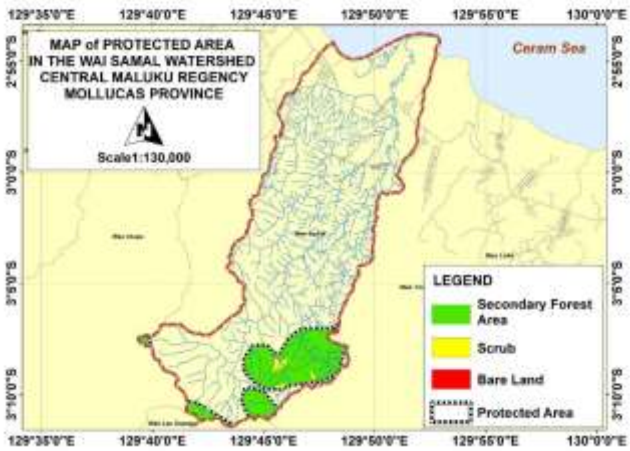

Figure 16. Map of Protected Area of Wai Samal Watershed

Figure 17. Map of Protected Area of Wai Eti Watershed

3.5.2. Cultivation Area (KB)

The analysis of cultivated areas based on the Regional Spatial Plans (RTRW) of Central Maluku Regency (2013–2033) and West Seram Regency (2013–2033) shows notable differences between the two watersheds. The Wai Samal Watershed has a cultivated area of 10,006.99 ha, of which 9,937.16 ha is located on land with slopes of 0–25%. In contrast, the Wai Eti Watershed has a larger cultivated area of 14,354.66 ha, but only 8,522.15 ha falls within the 0–25% slope category (Table 14, Figure 18, Figure 19). These conditions result in cultivated area percentages (KB) of 99.30% for the Wai Samal Watershed and 59.37% for the Wai Eti Watershed (Figure 18, 19). Based on the classification criteria, the Wai Samal Watershed is categorized as very high (KB > 70) with a score of 0.5, whereas the Wai Eti Watershed is classified as high (45 < KB ≤ 70) with a score of 0.75.

Table 14. Components of Cultivation Areas in the Wai Samal Watershed and Wai Eti Watershed

No.	Cultivation Area Components	Wai Samal Watershed	Wai Eti Watershed
1.	Cultivation area (ha)	10006.99	14354.66
2.	Land area with a slope of 0-25% in the cultivation area (ha)	9937.16	8522.15
3.	Percentage of Cultivation Area (KB)	99.30	59.37

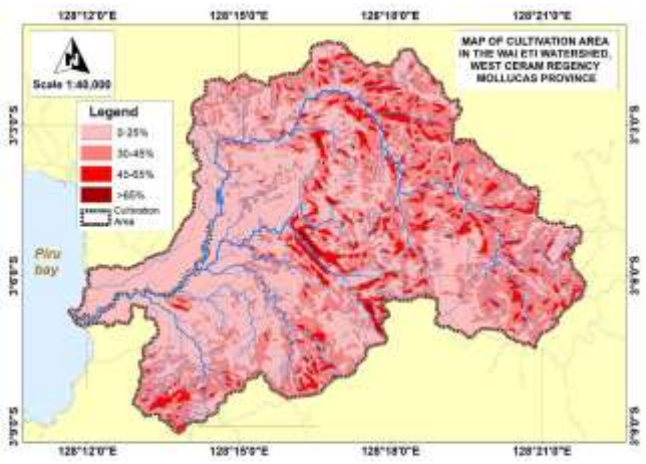

Figure 18. Map of Cultivation Area of Wai Samal Watershed

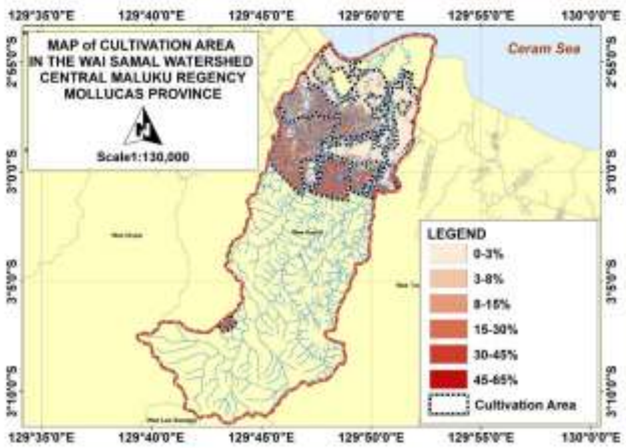

Figure 19. Map of Cultivation Area of Wai Eti Watershed

The higher proportion of cultivated areas on gentle slopes (0–25%) in the Wai Samal Watershed indicates better alignment between land capability and land use, thereby reducing erosion risk and supporting watershed carrying capacity. In contrast, the lower KB percentage in the Wai Eti Watershed reflects greater cultivation pressure on steeper and more erosion-prone land, which may increase runoff, soil loss, and sediment transport, ultimately reducing watershed performance. However, high cultivation suitability alone does not guarantee sustainable watershed conditions, as long-term sustainability also depends on the implementation of effective soil and water conservation practices. These findings are consistent with [30] and [48], who reported that cultivated areas located on suitable slopes contribute positively to watershed performance and carrying capacity when supported by appropriate land management practices. In small island watersheds, where cultivable land is inherently limited, optimizing land use must be balanced with soil and water conservation measures to prevent degradation and maintain long-term watershed sustainability.

3.6. Carrying Capacity of Wai Samal Watershed and Wai Eti Watershed

The carrying capacity of the Wai Samal and Wai Eti watersheds was evaluated using an integrated framework comprising five major criteria: land condition, water system performance, socio-economic factors, water infrastructure investment, and spatial planning. The final watershed carrying capacity index (DDD) was calculated by multiplying the score of each of the 15 sub-criteria by its corresponding weighting factor, as specified in the Indonesian National Watershed Monitoring and Evaluation Framework [1]. The weighted scores were then summed to obtain the final DDD value for each watershed and classified into the corresponding carrying capacity category according to the criteria established in the regulation (Table 15).

The assessment shows that the Wai Samal Watershed has a DDD value of 78.75, classified as good (70 < DDD ≤ 90), whereas the Wai Eti Watershed has 93.25, classified as moderate (90 < DDD ≤ 110). These results indicate that the Wai Samal Watershed has better overall watershed performance and resilience than the Wai Eti Watershed (Figure 20).

The higher carrying capacity of the Wai Samal Watershed was associated with lower environmental pressure and more favorable watershed conditions, including a lower percentage of critical land (4.11%), lower flood frequency (once per year), lower Water Use Index (IPA = 0.44), higher Land Availability Index (IKL = 10.14), lower poverty level (15.62%), more effective implementation of conservation regulations, lower water infrastructure investment (1–5 billion rupiah), and a higher proportion of suitable cultivated land (99.30%). In contrast, the Wai Eti Watershed exhibited greater environmental and socio-economic pressure, characterized by a higher proportion of critical land (7.07%), more frequent flooding, higher IPA (0.52), lower IKL (2.88), a higher poverty level (94.04%), weaker implementation of conservation regulations, higher water infrastructure investment (22.5 billion rupiah), and a lower proportion of suitable cultivated land (59.37%). These differences indicate lower watershed resilience and greater dependence on management interventions in the Wai Eti Watershed.

Table 15. Summary of watershed carrying capacity (DDD) assessment results for the Wai Samal and Wai Eti watersheds

Criteria/Sub Criteria of Watershed Carrying Capacity Indicator (DDD)	Weight	WAI SAMAL WATERSHED				WAI ETI WATERSHED			
		Results	Value / Class	Scores	Weighted x Scores	Results	Class	Scores	Weighted x Scores
A. Land Conditions	40								
1. Percentage of critical land (PLK)	20	4.11 %	PLK ≤ 5 Very Low (Very Good)	0.5	10	7.07%	5<PLK≤ 10 Low (Good)	0.75	15
2. Percentage of vegetation cover (PPV)	10	84.66 %	PPV > 80 Very good	0.5	5	85.42%	PPV > 80 Very good	0.5	5
4. Index of eros (IE)	10	4.69	IE > 2.0 Very high (Very bad)	1.5	15	7.08	IE > 2.0 Very high (Very bad)	1.5	15
B. Water System Condition	20								
1. Flow regime coefficient (KRA)	5	56.12	50< KRA≤80 Moderate	1.0	5	20.57	20<KRA≤50 Low (Good)	0.75	3.75
2. Annual flow coefficient (KAT)	5	3.63	KAT > 0.5 Very high (Very bad)	1.5	7.5	4.29	KAT > 0.5 Very high (Very bad)	1.5	7.5
3. Sediment load (MS)	4	4148.34 t/ha/yr	MS > 20 Very high (Very bad)	1.5	6.0	2864.02	MS > 20 Very high (Very bad)	1.5	6.0
4. Flood	2	1 time per year	High (Bad)	1.25	2.5	More than 1 time in 1 year	Very high (Very bad) (1.5)	1.5	3.0
5. Water use index (IPA)	4	0.44	0.25<IPA≤0.5 Low (Good)	0.75	3	0.52	0.5<IPA≤0.75 Moderate	1.0	4.0
C. Socio-Economic Conditions	20								
1. Population pressure (IKL)	10	10.14	Very high (Very good)	0.5	5	2.88	2.0<IKL≤4.0 High (Good)	0.75	7.5
2. Level of population welfare (TKP)	7	15.62	10<TKP≤20 Moderate	1.0	7	94.04	TKP > 30 Very bad	1.5	10.5
3. Existence and enforcement of regulations (norms)	3	Yes, it is widely	Very Good	0.5	1.5	Yes, it is practiced on a limited basis.	Good	0.75	2.25

Criteria/Sub Criteria of Watershed Carrying Capacity Indicator (DDD)	Weight	WAI SAMAL WATERSHED				WAI ETI WATERSHED			
		Results	Value / Class	Scores	Weighted x Scores	Results	Class	Scores	Weighted x Scores
		practiced							
D. Building Investment	10								
1. City classification	5	Small town	Low (Good)	0.75	3.75	Small town	Low (Good)	0.75	3.75
2. Building value classification (BBA)	5	1 – 5 M rupiah	IBA ≤15 billion rupiahs Very Low (Very Good)	0.5	2.5	22.5 M rupiahs	15< IBA ≤30 billion rupiahs Low (Good)	0.75	3.75
E. Utilization of Regional Space	10								
1. Protected area (KL)	5	99.40 %	KL > 70 (Very Good	0.5	2.5	100%	KL > 70 Very good	0.5	2.5
2. Cultivation area (KB)	5	99.30 %	KB > 70 Very Low (Very Good)	0.5	2.5	59.37%	45 < KB ≤70 Low (Good)	0.5	3.75
Total = DDD Value					**78.75**				**93.25**

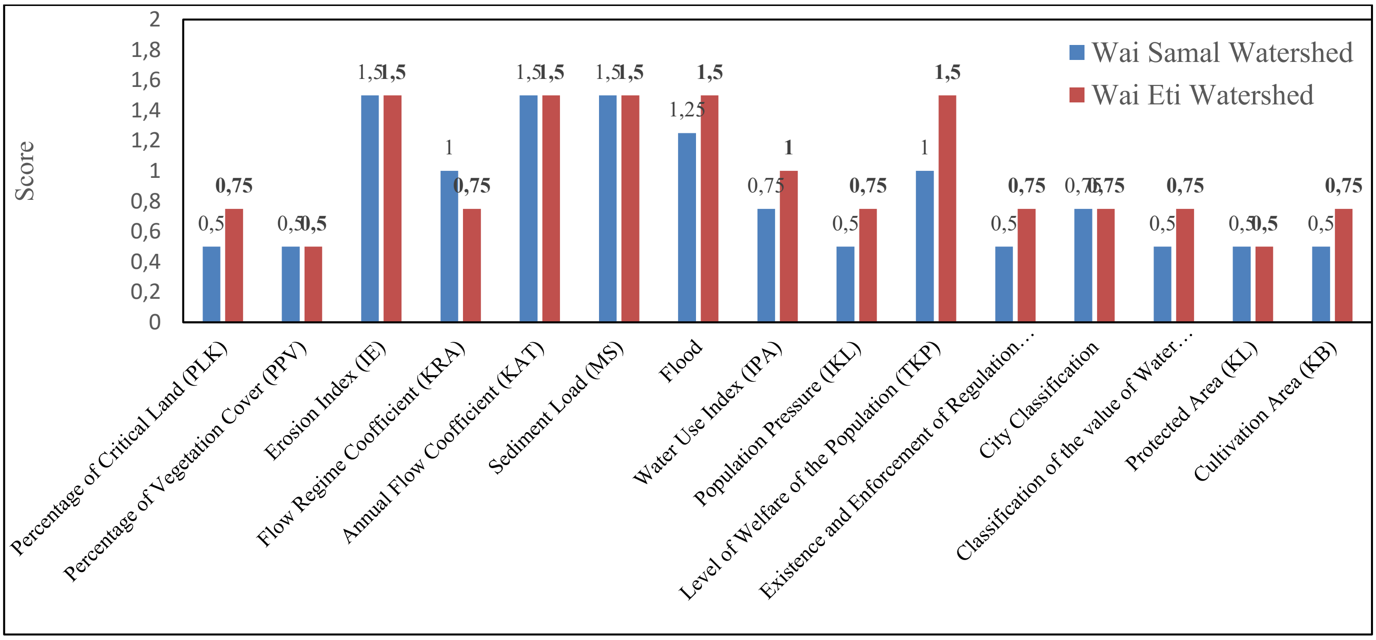

Figure 20. Key Factors Influencing the Carrying Capacity of the Wai Samal and Wai Eti Watersheds

3.7. Comparative Assessment of Watershed Carrying Capacity

Table 15 synthesizes the watershed carrying capacity assessment by integrating the results of all fifteen indicators. Overall, the Wai Samal Watershed (DDD = 78.75) exhibited better carrying capacity than the Wai Eti Watershed (DDD = 93.25). However, these composite classifications should be interpreted together with the individual assessment indicators rather than as evidence of uniformly favorable watershed conditions.

Despite its higher overall carrying capacity, Wai Samal remained constrained by a very high Erosion Index (IE), high Annual Flow Coefficient (KAT), and high sediment load, indicating persistent risks of land degradation and rapid runoff. Conversely, the lower carrying capacity of Wai Eti reflected less favorable land, hydrological, and spatial planning conditions together with a high Annual Flow Coefficient, characteristic of small island watersheds with limited catchment area and water-storage capacity.

These findings demonstrate that watershed carrying capacity is governed by the combined effects of biophysical conditions, hydrological response, socio-economic pressure, institutional effectiveness, and spatial land-use suitability rather than by individual indicators alone. The integrated indicator-based framework therefore provides a more comprehensive evaluation than the composite DDD index by identifying watershed-specific environmental constraints that require priority management. These results are consistent with previous studies showing that lower critical land extent, better vegetation cover, appropriate spatial planning, and stronger institutional capacity enhance watershed carrying capacity, whereas high erosion, rapid runoff, and socio-economic pressures accelerate watershed degradation [48,44,49].

3.7. Integrated Watershed Management Strategies for Small Island Watersheds

The integrated assessment indicates that improving watershed carrying capacity in small island watersheds requires integrated management addressing land degradation, hydrological instability, and socio-economic pressure.

Land and forest rehabilitation should be prioritized in degraded and erosion-prone areas, including abandoned land, former cultivation areas, logged-over forests, and scrublands. Although the proportion of critical land is relatively low, the high erosion index indicates ongoing land degradation. Therefore, reforestation and agroforestry are essential to strengthen vegetation cover, reduce erosion, enhance infiltration, and improve hydrological stability.

Hydrological management should prioritize retention ponds, infiltration structures, check dams, and riparian restoration to reduce runoff, flood risk, sediment transport, and improve dry-season water availability. These measures are particularly important in the Wai Eti Watershed because of its higher flood frequency and greater hydrological pressure.

Sediment management and institutional strengthening are also essential for watershed sustainability. The very high sediment load in the Wai Samal Watershed requires regular monitoring and maintenance of hydraulic infrastructure, whereas the limited implementation of conservation regulations in the Wai Eti Watershed highlights the need to strengthen governance and integrate local wisdom (*sasi*) into watershed management.

Reducing socio-economic pressure on land resources is particularly important in the Wai Eti Watershed, where high poverty levels increase dependence on fragile land systems. Promoting agroforestry and sustainable agriculture can reduce land-use pressure while improving community livelihoods. Strengthening community participation and environmental awareness is also essential to enhance long-term watershed resilience in small island environments.

3.8. Study Limitations.

This study provides a comprehensive watershed carrying capacity assessment using the Indonesian National Watershed Monitoring and Evaluation Framework. Nevertheless, several limitations should be acknowledged. The analysis relied partly on secondary spatial and socio-economic datasets with different map scales, while erosion and sediment estimates were derived from empirical models that involve inherent uncertainty. Field validation was conducted at representative locations to verify the main spatial and hydrological characteristics rather than every land unit. Despite these limitations, the integrated indicator-based framework provides a robust and reproducible approach for evaluating watershed carrying capacity in small island watersheds.

4. Conclusion

This study demonstrates that the Wai Samal Watershed exhibits higher watershed carrying capacity (78.75; good category) than the Wai Eti Watershed (93.25; moderate category), reflecting differences in system pressure and resilience. These differences are driven by the interaction of biophysical, hydrological, socio-economic, institutional, and spatial factors rather than by individual indicators. The Wai Samal Watershed is characterized by lower critical land extent, lower flood frequency, lower water use pressure, higher land availability, stronger institutional performance, and more suitable spatial land use, all of which contribute positively to hydrological stability and watershed sustainability. In contrast, the Wai Eti Watershed experiences greater environmental and socio-economic pressure, reflected in higher flooding frequency, higher water use intensity, lower community welfare, weaker implementation of conservation regulations, and greater pressure on cultivated land, which collectively reduce watershed performance and resilience.

The findings indicate that lower environmental pressure characterized by reduced critical land extent, lower flood frequency, efficient water use, and stronger institutional capacity supports higher watershed performance, even with limited structural intervention. In contrast, higher pressure conditions, including increased flooding, land-use intensity, lower community welfare, and reliance on reactive infrastructure, reduce watershed carrying capacity. In small island watershed systems, where land resources, catchment area, and hydrological storage capacity are inherently limited, environmental disturbances can more rapidly disrupt hydrological regulation and ecological stability. Therefore, watershed sustainability depends not only on maintaining vegetation cover and suitable land use, but also on strengthening hydrological regulation, sediment control, socio-economic resilience, and institutional effectiveness.

This study demonstrates the applicability of the Indonesian National Watershed Monitoring and Evaluation Framework for integrated watershed carrying capacity assessment in small island environments. By integrating biophysical, hydrological, socio-economic, institutional, infrastructure, and spatial planning indicators, the framework provides a comprehensive scientific basis for adaptive watershed management and evidence-based spatial planning to enhance long-term watershed resilience.

Declarations

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Conflict of Interest

The authors declare that they have no competing interests or conflicts of interest related to this study.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Author Contributions

SMT conceived and designed the study, conducted the field investigations, performed the GIS and statistical analyses, interpreted the results, and prepared the original manuscript. RMO and JMT contributed to the study methodology, data validation, supervision, and critical revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

Ethics Statement

This study involved interviews with local communities and village officials as part of the watershed assessment. Participation was voluntary, and informed consent was obtained from all participants prior to data collection. The information was used exclusively for research purposes, and no personal or sensitive information is disclosed in this manuscript.

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