JPPIPA 12(4) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

Carrying Capacity Assessment for Strengthening Landscape Conservation Governance: A Case Study of the Sentarum Lake Sub-Watershed

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Received: February 09, 2026
Revised: March 29, 2026
Accepted: April 25, 2026
Published: April 30, 2026

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DOI: 10.29303/jppipa.v12i4.14550

Abstract: A landscape carrying capacity assessment serves as a critical tool for strengthening sustainable natural resource governance within socio-ecological systems. This study aimed to evaluate the carrying capacity status of the Sentarum Lake Catchment Area and identify key ecological and socioeconomic vulnerabilities. The analysis was conducted using a multi-criteria index-based approach aligned with the Indonesian Minister of Forestry Regulation No. P.61/Menhut-II/2014, integrating cross-sectoral data across five dimensions: land condition, water regime, socioeconomic conditions, water infrastructure, and land use patterns. The results showed that the carrying capacity was classified as "good," with an index value of 78.00. Nevertheless, a phenomenon of pseudo-hydrological stability was identified, in which stable flow regimes (flow regime coefficient = 0.50) and high water availability (water use index = 0.50) masked functional degradation within the system. This condition was reflected in a high annual runoff coefficient (1.50) and increasing flood frequency (1.25), indicating declining infiltration capacity. These pressures were further exacerbated by the limited proportion of natural vegetation within protected areas (45.10%) and high socioeconomic vulnerability (poverty level index = 1.50). Overall, the findings indicate a fragile equilibrium in which apparent ecological stability conceals emerging hydrological and socioeconomic risks. Without adaptive and integrated management interventions, the system is likely to shift toward structural degradation. Therefore, strengthening landscape governance requires ecosystem-based spatial planning, nature-based mitigation strategies, and inclusive local economic development to enhance long-term resilience.

Keywords: Carrying capacity; Ecosystem resilience; Hydrological integrity; Social-ecological system; Watershed management

Introduction

The Sentarum Lake Catchment Area constitutes a complex ecological landscape in Kapuas Hulu Regency, composed of tropical rainforests, ancient peat swamp forests, and interconnected seasonal lake systems (Giesen et al., 2016a; Hidayat et al., 2021). This area possesses high ecological value due to the uniqueness of its wetland ecosystems and the ancient age of its peatland systems, which have developed over long geological timescales (Anshari et al., 2004; Giesen et al., 2016a; Roslinda, 2019; Utami et al., 2025). The Sentarum Lake Catchment Area provides essential ecosystem services, including regulating functions such as carbon

How to Cite:
Kumara, I., Soekmadi, R., Prasetyo, L. B., Sunkar, A., & Kusharyono, D. (2026). Carrying Capacity Assessment for Strengthening Landscape Conservation Governance: A Case Study of the Sentarum Lake Sub-Watershed. *Jurnal Penelitian Pendidikan IPA*, *12*(4), 124–137. https://doi.org/10.29303/jppipa.v12i4.14550

storage and hydrological regulation of the Kapuas River (Onrizal et al., 2005), habitat functions supporting important and endangered wildlife species (Roslinda, 2019; Yuniarti et al., 2018), provisioning functions in the form of timber, medicinal plants, and forest honey (Agustini et al., 2023; Onrizal et al., 2005; Roslinda, 2019), as well as cultural services through its potential for recreation and ecotourism (Agustini et al., 2023; Astari et al., 2023; Yuniarti et al., 2018).

These ecosystem functions have long supported local community livelihoods (Agustini et al., 2023), with evidence of human activities dating back to before the sixteenth century (Giesen et al., 2016b). However, population growth and the intensification of economic activities have increasingly exerted pressure on the ecosystems of the Sentarum Lake Catchment Area (Hidayat et al., 2021; Roslinda, 2019). Previous studies have documented the emergence of complex challenges, including biophysical degradation such as the expansion of degraded lands and increased sedimentation (Andryannur et al., 2022; Onrizal et al., 2005), social conflicts and unequal access to natural resources (Yasmi et al., 2007), weak institutional capacity for ecosystem management (Hasudungan, 2010; Roslinda, 2019), and limited provision of basic infrastructure services (Astari et al., 2023; Onrizal et al., 2005). In the absence of development planning that integrates environmental carrying capacity considerations, these pressures may accelerate the decline of key ecosystem functions, particularly within lake and peatland areas.

The integration of environmental carrying capacity assessments into development planning has become a critical instrument to ensure that economic development does not exceed the ecological limits of resource availability and environmental services (Cai et al., 2024; Rojikhah et al., 2024). Carrying capacity information provides a scientific basis for spatial zoning, investment direction, and the formulation of priority development programs aligned with ecosystem resilience, while also contributing to disaster risk mitigation (Kementerian Lingkungan Hidup, 2014). A growing body of research demonstrates that carrying capacity analysis has been widely applied in agricultural land-use planning (Alifatri et al., 2017), fisheries management (Nurlukman et al., 2025), and settlement development control (Cahyono et al., 2022; Djalil et al., 2023).

The concept of carrying capacity is closely linked to the socio-ecological systems framework, which emphasizes the dynamic interactions between ecological processes and human systems (Wenpeng et al., 2018). Within this framework, resilience theory highlights the capacity of ecosystems to absorb disturbances while maintaining their core functions and structures (Dakos et al., 2022). In watershed systems, this resilience is strongly influenced by hydrological integrity, vegetation cover, and adaptive land-use management (Lane et al., 2023; Shiferaw et al., 2025). Therefore, carrying capacity should not be interpreted solely as a static indicator but also as a reflection of the system's ability to sustain ecological functions under increasing anthropogenic pressure (del Monte-Luna et al., 2004).

Despite its growing application, existing studies on carrying capacity have largely relied on aggregated indicators that may overlook hidden functional degradation within complex watershed systems, particularly in wetland-dominated areas. In the Sentarum Lake Catchment Area, the application of carrying capacity evaluation is further constrained by limited cross-sectoral data integration, as existing datasets remain fragmented and have been used only partially. This limitation creates a critical gap in understanding the reliability of carrying-capacity indicators in capturing actual ecosystem conditions and emerging risks. Therefore, this study aimed to evaluate the carrying capacity status of the Sentarum Lake Catchment Area using a watershed carrying capacity index approach in accordance with the Regulation of the Minister of Forestry No. P.61/Menhut-II/2014, by integrating official cross-sectoral data. In addition, this study seeks to identify hidden vulnerabilities within the system. The primary contribution of this study is providing an operational carrying capacity database and bridging scientific evaluation outcomes with cross-sectoral decision-making needs for development planning at the regency level.

Method

Time and Study Area

This study was conducted from September to December 2025 and was located in the Tawang–Gundal–Sentarum Sub-Watershed, situated in Kapuas Hulu Regency, West Kalimantan Province, Indonesia (Figure 1). According to West Kalimantan Provincial Regulation No. 2 of 2018 on Integrated Watershed Management, the area covers approximately 451,429 hectares and constitutes an important component of the Sentarum Lake hydrological system. Geographically, the study area is located between 00°35′42.21″ and 01°21′40.54″ North Latitude and between 111°37′12.65″ and 112°34′47.05″ East Longitude. The landscape represents upstream-to-midstream watershed characteristics, dominated by wetland ecosystems, peat swamp forests, and seasonal lake waters that play a strategic role in regulating regional hydrological processes.

Administratively, the Tawang–Gundal–Sentarum Sub-Watershed lies entirely within Kapuas Hulu Regency and encompasses 11 districts and 73 villages. To the north, the study area directly borders the State of

Sarawak, Malaysia, while to the west it borders Sintang Regency. To the east, it is bounded by Embaloh Hulu and Embaloh Hilir Districts, whereas to the south it borders the districts of Bunut Hilir, Jongkong, Selimbau, Suhaid, and Semitau. This administrative and geographical configuration positions the Tawang–Gundal–Sentarum Sub-Watershed as a multi-functional and multi-stakeholder area, making it a relevant unit of analysis for environmental carrying capacity assessment and ecosystem-based regional management planning.

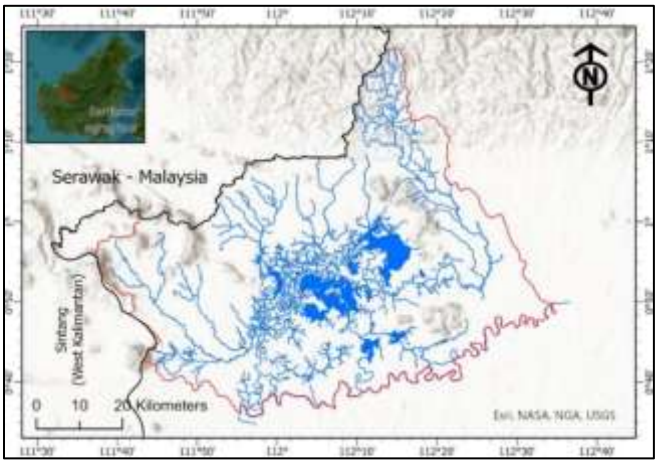

Figure 1. Location of the Sentarum Lake Catchment area in Kapuas Hulu Regency, West Kalimantan Province, Indonesia

Data Collection

This study employed a cross-sectoral secondary data integration approach, utilizing datasets obtained from central and local government agencies responsible for watershed and natural resource management in Kapuas Hulu Regency and West Kalimantan Province, Indonesia. The datasets represent the most recent and authoritative information available at the time of the study and encompass five major aspects: biophysical conditions, hydrological characteristics, socioeconomic aspects, water resource infrastructure, and land use.

Data were collected through a systematic review of technical reports, official statistical publications, geospatial databases, and relevant regulatory and policy documents from the respective institutions. To enhance data reliability and ensure consistency in interpretation, the compilation of secondary data was complemented by semi-structured interviews with key informants to clarify data acquisition procedures, technical assumptions, and temporal and spatial limitations, as well as to support triangulation for data validation (Kallio et al., 2016; Shoozan et al., 2024). For discharge data, field measurements were conducted using the velocity-area method (SNI 8066:2015) by dividing the Tawang River Estuary cross-section into 10 segments. The total discharge (Q total) was calculated by summing the discharge of each segment (Qi-n), where the cross-sectional area of each ($Ai\text{-}n$) was determined using the trapezoidal formula based on depth data from the depth sounder. The surface flow velocity ($Vi\text{-}n$) at one point was measured using a current meter and multiplied by a correction factor of 0.85 to obtain the average velocity (Vi). The discharge of each segment was determined through the equation $Qi\text{-}n\ (m^3/s) = Ai\text{-}n \times (Vi\text{-}n \times 0.85)$. All spatial and non-spatial datasets were subsequently harmonized, standardized, and integrated into a unified database, which served as the primary input for the watershed carrying capacity analysis of the Sentarum Lake Sub-Watershed. Detailed information on the data types, sources, and their respective roles in the analysis are presented in Table 1.

Table 1. Types of Data, Data Sources, and Their Use for Carrying Capacity Criteria

Type of Data	Data Source	Use in Criteria
Critical land map Erosion map Water structure value	Kapuas Watershed Management Agency (Balai Pengelolaan Daerah Aliran Sungai Kapuas)	a. Percentage of critical land b. Land management value c. Water structure value
Sentarum Lake Sub-watershed boundary	Department of Housing, Settlement Areas, Land Affairs, and Environment of Kapuas Hulu Regency (Dinas Perumahan Rakyat dan Kawasan Permukiman, Pertanahan dan Lingkungan Hidup Kabupaten Kapuas Hulu)	Spatial basis of Sentarum Lake Catchment Area
Reliable discharge	Kalimantan I River Basin Authority (Balai Wilayah Sungai Kalimantan I)	Water availability
Population data	Department of Population and Civil Registration of Kapuas Hulu Regency (Dinas Kependudukan dan Catatan Sipil Kabupaten Kapuas Hulu)	Water availability
a. Forest cover b. Forest area	Regional Office of Forestry Planning Region III (Balai Pemantapan Kawasan Hutan Wilayah III Pontianak)	a. Vegetation cover percentage b. Protected areas c. Cultivation areas
Urban classification	Central Statistics Agency of Indonesia(Badan Pusat Statistik Indonesia)	Urban classification

Type of Data	Data Source	Use in Criteria
Flood	Regional Disaster Management Agency of Kapuas Hulu Regency (Badan Penanggulangan Bencana Daerah Kabupaten Kapuas Hulu)	Flood frequency
Local community watershed regulations	Department of Housing, Settlement Areas, Land Affairs, and Environment of Kapuas Hulu Regency (Dinas Perumahan Rakyat dan Kawasan Permukiman, Pertanahan dan Lingkungan Hidup Kabupaten Kapuas Hulu) Betung Kerihun and Sentarum Lake National Park Authority (Balai Besar Taman Nasional Betung Kerihun dan Danau Sentarum)	Existence and enforcement of local regulations
Community welfare	Village and sub-district profile database, Ministry of Home Affairs (Kementerian Dalam Negeri)	Community welfare level
Annual rainfall	Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)	Annual runoff coefficient
Runoff discharge	Field data collection (velocity-area method)	a. Flow regime coefficient b. Annual runoff coefficient

Data Analysis

Data analysis commenced with spatial validation and synchronization to ensure consistency between thematic datasets and the administrative boundary of Kapuas Hulu Regency. Geospatial analysis was performed using overlay techniques to integrate thematic layers with the Sentarum Lake Sub-Watershed boundary, enabling the extraction of variables, including the percentage of critical land, vegetation cover, land management performance, and extent of protected and cultivated areas. In parallel, tabular data were processed using arithmetic operations and descriptive statistical analyses to derive the hydrological and socioeconomic parameters.

Table 2. Calculation and Assessment of Criteria and Carrying Capacity

Criteria – Sub-Criteria (Weight and Parameter)	Sub-Criteria Value Range	Classification	Score
I. Land Condition (Total Weight = 20)			
a. Percentage of Critical Land (Weight = 20)			
$PCL = \frac{Critical\ Land\ Area}{Sentarum\ Catchment\ Area}\ x\ 100\%$	PCL ≤ 5	Very Low	0.50
	5 < PCL ≤ 10	Low	0.75
	10 < PCL ≤ 15	Moderate	1.00
	15 < PCL ≤ 20	High	1.25
	PCL > 20	Very High	1.50
b. Percentage of Vegetation Cover (Weight = 10)			
$PVC = \frac{Vegetation\ Cover\ Area}{Sentarum\ Catchment\ Area}\ x\ 100\%$	PVC > 80	Very Good	0.50
	60 < PVC ≤ 80	Good	0.75
	40 < PVC ≤ 60	Moderate	1.00
	20 < PVC ≤ 40	Poor	1.25
	PVC ≤ 20	Very Poor	1.50
c. Land Use Value (Weight = 10)			
	CP ≤ 0.10	Very Low	0.50
$LUV = C\ x\ P$	0.10 < CP ≤ 0.30	Low	0.75
	0.30 < CP ≤ 0.50	Moderate	1.00
$C\ x\ P = \Sigma\,(Ai\ x\ CPi)/A$	0.50 < CP ≤ 0.70	High	1.25
	IE > 0.70	Very High	1.50
II. Water System Condition (Total Weight = 20)			
a. Flow Regime Coefficient (Weight = 5)			
$FRC = \frac{Q\ max}{Q\ min}$	FRC ≤ 5	Very Low	0.50
	5 < FRC ≤ 10	Low	0.75
	10 < FRC ≤ 15	Moderate	1.00
	15 < FRC ≤ 20	High	1.25
	FRC > 20	Very High	1.50
b. Annual Runoff Coefficient (Weight = 5)			
$ARC = \frac{Q\ annual}{P\ annual}$	ARC ≤ 0.20	Very Low	0.50
	0.20 < ARC ≤ 0.30	Low	0.75
	0.30 < ARC ≤ 0.40	Moderate	1.00

Criteria – Sub-Criteria (Weight and Parameter)	Sub-Criteria Value Range	Classification	Score
	0.40 < ARC ≤ 0.50	High	1.25
	ARC > 0.50	Very High	1.50
c. Sediment Load (Weight = 4)			
	SL ≤ 5	Very Low	0.50
SL = Actual erosion value (A) x Sediment Delivery Ratio (SDR)	5 < SL ≤ 10	Low	0.75
	10 < SL ≤ 15	Moderate	1.00
	15 < SL ≤ 20	High	1.25
	SL > 20	Very High	1.50
d. Flood Frequency (Weight = 2)			
	Never	Very Low	0.50
Flood Frequency	Once in 5 years	Low	0.75
	Once in 2 years	Moderate	1.00
	Once every year	High	1.25
	More than once a year	Very High	1.50
e. Water Use Index (Weight = 4)			
	WUI > 6,800	Very Good	0.50
$WUI = \frac{Amount\ of\ water\ (Q\ m3/year)}{Number\ of\ inhabitants\ (people)}$	5,100 < WUI ≤ 6,800	Good	0.75
	3,400 < WUI ≤ 5,100	Moderate	1.00
	1,700 < WUI ≤ 3,400	Poor	1.25
	WUI < 1,700	Very Poor	1.50
III. Socio-Economic Condition (Total Weight = 20)			
a. Population Pressure (Weight = 10)			
	PP > 4.00	Very High	0.50
$PP = \frac{Agricultural\ land\ area}{Number\ of\ farmer\ families}$	2.00 < PP ≤ 4.00	High	0.75
	1.00 < PP ≤ 2.00	Moderate	1.00
	0.50 < PP ≤ 1.00	Low	1.25
	PP < 0.50	Very Low	1.50
b. Community Welfare Level (Weight = 7)			
	CWL ≤ 5	Very High	0.50
$CWL = \frac{Number\ of\ Poor\ Households}{Total\ Number\ of\ Households}$	5 < CWL ≤ 10	High	0.75
	10 < CWL ≤ 20	Moderate	1.00
	20 < CWL ≤ 30	Low	1.25
	CWL >30	Very Low	1.50
c. Regulatory Presence and Enforcement (Weight = 3)			
	Yes, widely practiced	Very Good	0.50
Whether or not there are community rules in the watershed relating to conservation	Yes, limited practice	Good	0.75
	Yes, not practiced	Moderate	1.00
	No regulations	Poor	1.25
	Regulations exist but are counter-conservative	Very Poor	1.50
IV. Infrastructure Investment (Total Weight = 10)			
a. Urban Classification (Weight = 5)			
	No cities	Very Low	0.50
	Small cities	Low	0.75
The existence and status of the city	Municipalities	Moderate	1.00
	Large cities	High	1.25
	Metropolitan cities	Very High	1.50
b. Water Infrastructure Value (Weight = 5)			
	WIV ≤ Rp. 15 Billion	Very Low	0.50
Current value of water structure investments (reservoirs, dams, barrages, irrigation channels)	15 < WIV ≤ Rp. 30 Billion	Low	0.75
	30 < WIV ≤ Rp. 45 Billion	Moderate	1.00
	45 < WIV ≤ Rp. 60 Billion	High	1.25
	WIV > Rp. 60 Billion	Very High	1.50
V. Spatial Utilization (Total Weight = 10)			
a. Protected Areas (Weight = 5)			
	PA > 70	Very Good	0.50
$PA = \frac{Vegetation\ coverage\ area}{Protected\ area\ in\ watershed}$	45 < PA < 70	Good	0.75
	30< PA < 45	Moderate	1.00
	15 < PA < 30	Poor	1.25

Criteria – Sub-Criteria (Weight and Parameter)	Sub-Criteria Value Range	Classification	Score
	PA < 15	Very Poor	1.50
b. Cultivated Areas (Weight = 5)			
$CA = \frac{Land\ area\ with\ a\ slope\ of\ 0{-}25\%}{Protected\ area\ in\ watershed}$	CA >70	Very Low	0.50
	45 < CA < 70	Low	0.75
	30 < CA < 45	Moderate	1.00
	15 < CA < 30	High	1.25
	CA < 15	Very High	1.50

Table 3. Classification of Watershed Carrying Capacity Status

Watershed Carrying Capacity (WCC) Value	Category
WCC ≤ 70	Very Good
70 < WCC ≤ 90	Good
90 < WCC ≤ 110	Moderate
110 < WCC ≤ 130	Poor
WCC > 130	Very Poor

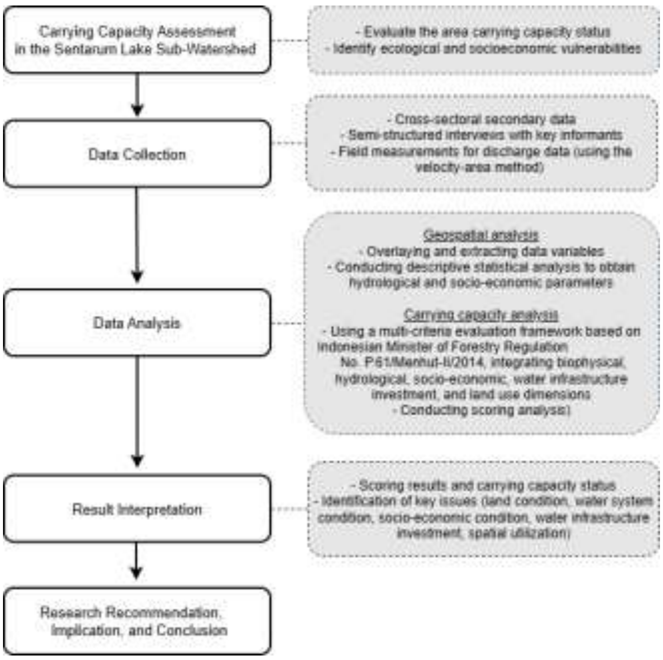

Figure 2. Research flowchart of the carrying capacity assessment process in the Sentarum Lake Sub-Watershed

The watershed carrying capacity was assessed using a multi-criteria evaluation framework in accordance with the Indonesian Minister of Forestry Regulation No. P.61/Menhut-II/2014. This framework integrates biophysical, hydrological, socio-economic, water infrastructure investment, and land-use dimensions into a single composite index that represents the overall condition and stability of the watershed system. Each criterion was transformed into standardized scores using a reverse disparity scoring system, in which lower scores (0.50) indicate more favorable conditions and higher scores (1.50) reflect greater environmental pressure. Weighted aggregation of sub-criteria produced composite indices for each evaluation component (Table 2), and the overall watershed carrying capacity status was determined based on the final composite weighted score across all criteria and sub-criteria, as classified in Table 3. The overall research workflow, including data collection, integration, analysis, and interpretation processes, is illustrated in Figure 2.

Result and Discussion

Assessment of Carrying Capacity Values and Status in the Sentarum Lake Sub-Watershed

Based on the assessment of carrying capacity values and status, the composite carrying capacity index for the Danau Sentarum Sub-Watershed was 78.00, placing the area in the "good" category (Table 4). While this result indicated that the landscape was still capable of supporting existing pressures, its proximity to the lower limit of the "good" category indicated a gradual shift away from "very good" conditions (<70) and toward the threshold of the "moderate" category (>90). This pattern serves as an early warning signal, indicating that emerging pressures, if left unmanaged, could progressively erode the overall carrying capacity of the watershed.

Analysis of the five evaluation criteria indicated that the ecological pillars remained the primary stabilizing force within the system. Land conditions and water regimes scored 32.50 and 16.50, respectively, accounting for approximately 62.8% of the total carrying capacity (Table 4). This dominance reflects the continued integrity of key biophysical attributes, including a low proportion of degraded land, moderate vegetation cover, and relatively effective land management practices. This finding is consistent with previous studies in tropical wetland-dominated watersheds, which demonstrate that landscape stability is primarily maintained through soil protection and vegetation-mediated hydrological regulation (Ivory et al., 2019; Tarigan et al., 2018). However, the proportion of natural vegetation in the Danau Sentarum Sub-Watershed has dropped below 50%, indicating that ecological stability increasingly relies on favorable management conditions rather than structural ecosystem redundancy, which may increase sensitivity to future land use changes (Rijal et al., 2025).

Table 4. Carrying Capacity Assessment and Status

Criteria / Sub-Criteria	Analysis Result	Score	Weight	Value	Percentage
Land Condition (Weight = 40, Max Value = 60)				(32.5)	41.67
a. Critical Land (%)	5.60 %	0.75	20	15.00	
b. Vegetation Cover (%)	43.50 %	1.00	10	10.00	
c. Land Use Value	0.02	0.75	10	7.50	
Water System Condition (Weight = 10, Max Value = 30)				(16.50)	21.15
a. Flow Regime Coefficient	4.84	0.50	5	2.50	
b. Annual Runoff Coefficient	0.51	1.50	5	7.50	
c. Sediment Load (ton/ha/year)	2,074	0.50	4	2,00	
d. Flood Frequency (time/year)	1.20	1.25	2	2.50	
e. Water Use Index (m^3/capita/year)	28,950.8	0.50	4	2,00	
Socio-Economic Condition (Weight = 20, Max Value = 30)				(17.75)	22.76
a. Population Pressure (ha/number of farmer families)	11.80	0.50	10	5.00	
b. Community Welfare Level (%)	63.90	1.50	7	10.50	
c. Regulatory Presence and Enforcement	Available	0.75	3	2.25	
Water Infrastructure Investment (Weight = 10, Max Value = 15)				(5.00)	6.41
a. Urban Classification	No city	0.50	5	2.50	
b. Water Infrastructure Value (Rp)	412,984,580	0.50	5	2.50	
Spatial Utilization (Weight = 10, Max Value = 15)				(6.25)	8.01
a. Protected Area (%)	45.10	0.75	5	3.75	
b. Cultivated Area (%)	90.90	0.50	5	2.50	
Total Score				78.00	
Carrying Capacity Status				Good	

Socioeconomic criteria represent the most significant constraints on the long-term carrying capacity of watersheds. With a score of 17.75, accounting for approximately 22.76% of the total index, this component fell into the moderate category, highlighting the structural imbalance between the ecological integrity and human well-being. Despite relatively favorable biophysical conditions, the high poverty rate (63.9%) indicated that ecosystem services have not been effectively translated into sustainable livelihoods. This result is in line with previous studies showing that socioeconomic vulnerability is a key driver of ecosystem degradation, as it promotes short-term, subsistence-oriented resource use in ecologically sensitive areas (Dixon et al., 2003; Lamsal et al., 2015). In the context of the Danau Sentarum Sub-Watershed, this mismatch underscores that maintaining ecological stability alone is insufficient without parallel improvements in local economic resilience.

Conversely, the relatively low scores for water infrastructure investment (5.00) and spatial utilization (6.25) yield two key interpretations. First, the limited contribution of water infrastructure investment indicates that hydrological regulation within the watershed is predominantly governed by natural mechanisms, such as lakes, wetlands, and vegetation cover, rather than engineered structures. This suggests that large-scale human interventions, including levees, dams, and other hydraulic infrastructure, are currently minimal or unnecessary. Such systems are commonly associated with higher ecological flexibility and lower dependence on rigid structural controls, particularly in wetland-dominated landscapes. Nevertheless, reliance on natural regulatory mechanisms may increase vulnerability to future climate extremes, including intensified rainfall events or prolonged dry periods (Estrela-Segrelles et al., 2024). Simultaneously, spatial utilization scores indicate that land use patterns remain relatively stable, with cultivation activities largely concentrated on flat terrain. However, the declining effectiveness of protected areas, reflected in the decreasing proportion of intact natural vegetation, has the potential to weaken their function as ecological buffers (Cheng et al., 2023; Li et al., 2024). This condition underscores the need to prioritize the protection and restoration of natural vegetation within conservation policies to sustain the carrying capacity and long-term resilience of the water catchment area, especially Lake Sentarum (Tarigan et al., 2018; L. Wang et al., 2025; Yi et al., 2023).

Overall, the carrying capacity profile of the Danau Sentarum Sub-Watershed reflected a fragile equilibrium, where strong ecological performance partially masked emerging hydrological and socioeconomic vulnerabilities. Although the landscape currently maintains functional stability, increasing runoff coefficients and flood frequency indicate early signs of hydrological stress, consistent with the phenomenon of pseudo-hydrological stability observed in other tropical watersheds (Sadhwani et al., 2023). If socioeconomic pressures and land-use dynamics are not addressed through adaptive ecosystem-based planning, this apparent stability could gradually shift towards structural degradation (Y. Wang et al., 2022; Wu et al., 2025). These findings reinforce and extend previous studies emphasizing the importance of integrating carrying capacity indicators into regional planning as a preventive tool to guide land-use decisions, strengthen ecosystem resilience, and reduce long-term environmental risks (Mahmud et al., 2021; Setyowati, 2021; Sriyana, 2018).

Multidimensional Carrying Capacity Paradox of the Sentarum Lake Sub-Watershed

A more detailed examination at the sub-criteria level revealed distinct patterns of resilience and emerging critical thresholds within the carrying capacity system. The multidimensional carrying capacity profile of the Sentarum Lake Sub-Watershed, as visualized by the radar chart (Figure 3), displays heterogeneous web patterns that reflect the contrasting performance among individual sub-criteria. In this visualization, values extending outward toward 1.50 indicate subcriteria experiencing higher pressure or deteriorating conditions, whereas values closer to the center (0.50) represent lower pressure and more favorable conditions.

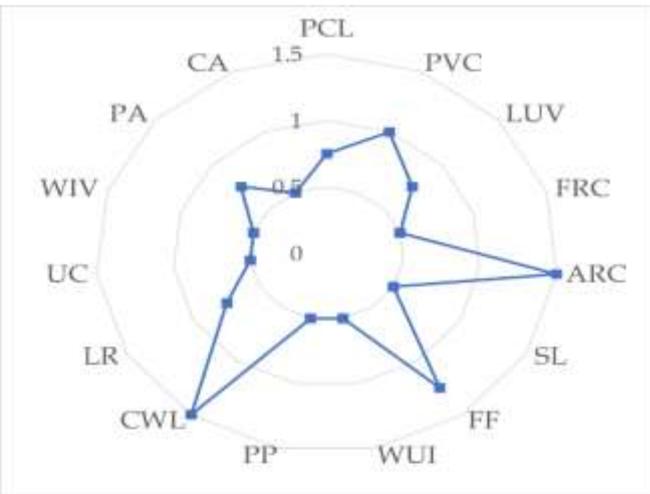

Figure 3. Multidimensional carrying capacity profile of the Sentarum Lake Sub-Watershed. Note: PCL: percentage of critical land; PVC: percentage of vegetation cover; LUV: land use value; FRC: flow regime coefficient; ARC: annual runoff coefficient; SL: sediment load; FF: flood frequency; WUI: water use index; PP: population pressure; CWL: community welfare level; LR: local regulation; UC: urban classification; WIV: water infrastructure value; PA: protected area; CA: cultivated area

Among the 15 subcriteria evaluated, the distribution of scores ranged from optimal to critical. The lowest (best) score of 0.50 was recorded for the flow regime coefficient, sediment load, water use index, population pressure, urban classification, water infrastructure investment and cultivated areas (Table 4). Intermediate scores of 0.75 were observed for the proportion of critical land, land management performance, regulatory presence and enforcement, and protected areas. Vegetation cover reached a moderate score of 1.00, whereas higher pressure was indicated by scores of 1.25 for flood frequency. The most critical condition was identified in the community welfare and annual runoff coefficient indicator, which reached a maximum score of 1.50. The resulting asymmetric radar pattern (Figure 3) demonstrates that, despite generally favorable conditions across many sub-criteria, pronounced deviations occur within the socio-economic and annual hydrological dimensions, providing visual evidence that the current carrying capacity is already under strain in this region.

The primary resilience of the Sentarum Lake Sub-Watershed is supported by strong hydrological buffering functions and relatively stable demographic conditions, as reflected by the predominance of subcriteria scoring 0.50. A low-flow regime coefficient indicates that the lake–wetland system continues to buffer seasonal discharge fluctuations effectively, whereas low sediment loads suggest that erosion processes remain largely controlled, thereby preventing premature sedimentation. These biophysical strengths are further reinforced by high per-capita water availability, as indicated by the favorable water-use index, and low population pressure, which collectively limit the anthropogenic stress on the landscape. The absence of urban centers, minimal investment in hydraulic infrastructure, signaling continued reliance on natural hydrological processes (Canteiro et al., 2024), and compliance with land use allocation in cultivated areas further confirm the integrity of this system. Together, these conditions constitute the ecological foundation sustaining the current "good" carrying capacity status and reflect a landscape that retains a degree of self-recovery capacity, a characteristic typical of relatively intact wetland-dominated watersheds (Lane et al., 2023).

However, early signs of disturbance emerge within land- and governance-related sub-criteria, as reflected by scores of 0.75 for critical land proportion, land management performance, regulatory enforcement, and protected areas. These values indicate that, although policy instruments formally exist, supported by local watershed forums and customary lake fisheries regulations, their effectiveness at the operational level remains limited. The presence of critical land and the declining effectiveness of protected areas suggest that increasingly dynamic land-use demands are gradually eroding landscape protection thresholds (Li et al., 2024). This condition reflects a transition from an ideal conservation state toward a more contested landscape, consistent with findings from previous studies indicating that increasing land-use pressure progressively weakens ecosystem protection thresholds

(Felipe-Lucia et al., 2020; Hillebrand et al., 2020). Without strengthened enforcement and consistent land-use governance, the ecological integrity of protected areas is likely to deteriorate further (Brenes et al., 2018; Eklund et al., 2017).

Anthropogenic pressure was more evident in the vegetation cover sub-criterion, which recorded a moderate score of 1.00. Natural forest cover has declined below 50% at the landscape scale, approaching the minimum threshold required to maintain effective hydrological protection. This reduction signals increasing competition for land, particularly for non-forest uses. If spatial planning is not carefully managed, further loss of natural vegetation will not only diminish biodiversity habitat but also reduce the forest's capacity to dissipate rainfall energy and regulate runoff. These processes are widely recognized as precursors to accelerated surface runoff, soil erosion, and hydrological instability in tropical watersheds (Artika et al., 2022; Tarigan et al., 2018).

The decline in forest vegetation is closely linked to reduced infiltration capacity, as evidenced by the instability of annual hydrological indicators. The occurrence of flooding more than once per year, reflected by an average flood frequency score of 1.25, revealed an early indication of the transition from infiltration-dominated to surface flow-dominated hydrological processes in the watershed. This shift was further corroborated by the annual runoff coefficient, which reached a maximum score of 1.50, indicating that approximately 50% of the annual rainfall was converted directly into surface runoff rather than infiltrating into the subsurface. These indicators suggest a progressive decline in the capacity of the Sentarum Lake landscape to regulate water storage and attenuation, signaling the gradual loss of its function as a hydrological "sponge". This pattern is consistent with previous studies in tropical wetland catchments, which show that vegetation loss and land-use change contribute to increased surface runoff and reduced infiltration capacity (Garza-Díaz et al., 2022; Yang et al., 2022).

Another most critical vulnerability within the carrying capacity profile lies in the socio-economic dimension, where community welfare reached the maximum score of 1.50. The high poverty rate (63.9% of households) indicates a systemic failure to translate ecological wealth into sustainable local livelihoods. This condition creates a socio-ecological paradox: while biophysical conditions remain relatively favorable, local communities continue to experience severe economic vulnerability. Furthermore, this finding supports previous studies indicating that structural poverty is a key driver of intensified resource extraction, as communities prioritize short-term survival over long-term sustainability (Barbier, 2010; Wackernagel et al., 2021). Accordingly, this sub-criterion represents the weakest link in the carrying capacity system of the Sentarum Lake Sub-Watershed.

Collectively, the distribution of the subcriteria scores confirmed strong functional interdependencies within the carrying capacity system. Severe socioeconomic stress (1.50) is likely to progressively undermine vegetation integrity (1.00), which, in turn, weakens land infiltration capacity and elevates annual flood risk (1.25). Although primary hydrological buffering and demographic conditions currently remain favorable (0.50), their long-term resilience is threatened by the fragility of the socio-economic foundation. This contradiction highlights that low population pressure alone does not guarantee equitable benefit distribution. Extensively cultivated areas combined with reduced forest cover suggest the dominance of large-scale land control, which limits local access to resources. Consequently, the "good" carrying capacity status (index = 78.00) represents a fragile equilibrium in which remaining biophysical strengths are increasingly challenged by persistent poverty and unequal resource access. Therefore, strengthening landscape governance cannot rely solely on technical or ecological interventions but must holistically integrate ecosystem protection with socio-economic restructuring to ensure long-term carrying capacity sustainability, which is consistent with broader evidence that aligning conservation and development objectives is essential for durable socio-ecological resilience (Fenta et al., 2023; Tang et al., 2022; Wolka et al., 2023).

Implications for Landscape Conservation Governance

The combination of low population pressure, high poverty levels, and declining forest cover within protected areas and across the broader landscape highlights the urgent need to realign conservation strategies with livelihood security. These conditions indicate that landscape governance in the Sentarum Lake Sub-Watershed must move beyond restrictive conservation toward a productive conservation model. Forest-like land management through agroforestry-based systems has emerged as a strategic intervention, enabling food production and income generation while maintaining vegetation structure and soil infiltration functions (Fahad et al., 2022; VijayKumar et al., 2024). By integrating local food crops under economically valuable tree canopies, agroforestry offers a pathway to strengthen household resilience without further forest conversion, thereby simultaneously addressing food security, poverty alleviation and hydrological sustainability (Duffy et al., 2021).

The limited effectiveness of existing local regulations, coupled with declining forest cover outside formally protected areas, underscores the importance of strengthening community-based governance (Jenke, 2024). Landscape governance should prioritize the formal recognition of customary rules and community agreements through village-level regulations that establish locally managed protected zones within non-forest land areas. Such an approach would empower communities to map, monitor, and catchment areas that currently fall outside the formal conservation frameworks. Community-based conservation not only closes governance gaps in degraded buffer areas but also enhances participatory monitoring, ensuring that conservation measures remain adaptive to dynamic land use pressures at the local scale (Funder et al., 2013).

Despite relatively favorable scores for protected areas and vegetation cover, elevated annual runoff coefficients and flood frequency reveal structural weaknesses in the current spatial planning. These indicators confirm that existing land-use allocations have failed to compensate for the loss of infiltration capacity caused by the degradation of forests. Consequently, landscape governance must reorient spatial planning priorities toward flat terrain and wetland ecosystems that function as critical water-retention zones, even if they are often perceived as suitable for expansion. A moratorium on the further conversion of the remaining natural forests is essential to restore the landscape's hydrological "sponge" function (Filoso et al., 2017; Peña-Arancibia et al., 2019). At the same time, the strong natural hydrological buffering capacity of the Sentarum Lake system, combined with minimal infrastructure intervention, creates a strong rationale for implementing Payment for Ecosystem Services (PES) schemes. By providing direct economic incentives to local communities to maintain ecosystem services, PES can transform conservation from a perceived constraint into a viable economic asset, thereby aligning poverty reduction with long-term landscape resilience (Bell et al., 2018; Le et al., 2024).

Conclusion

This study demonstrates that the Sentarum Lake Sub-Watershed is currently characterized by a "good" carrying capacity status, yet this condition reflects a fragile equilibrium in which strong ecological performance masks emerging hydrological and socio-economic vulnerabilities. The identification of pseudo-hydrological stability reveals that favorable indicators, such as stable flow regimes and high water availability, may obscure underlying functional degradation, as indicated by a high annual runoff coefficient, increasing flood frequency, and declining vegetation cover. In addition, the coexistence of low population pressure and high poverty levels highlights a significant socio-ecological imbalance, suggesting that ecosystem services have not been effectively translated into local economic resilience. Therefore, strengthening landscape governance requires the integration of ecosystem-based spatial planning, protection and restoration of natural vegetation, and the development of inclusive, nature-based livelihood strategies to ensure long-term socio-ecological resilience.

Acknowledgments
The authors would like to express their sincere gratitude to their academic supervisors, the Government of Kapuas Hulu Regency, the Department of Housing, Settlement Areas, Land Affairs, and Environment, the Betung Kerihun and Sentarum Lake National Park Authority, and the Kapuas Watershed Management Agency for their valuable support, guidance, and institutional assistance during this study. The authors also thank their colleagues, reviewers, and all key informants for their constructive feedback and insights. We hope that this study will contribute to the advancement of sustainable watershed management in Indonesia.

Author Contributions
Conceptualization, I.K., R.S., L.B.P., and A.Z.; formal analysis, I.K., and D.K.; investigation, I.K., and D.K.; supervision, R.S., L.B.P., and A.Z.; writing—original draft preparation, I.K.; writing—review and editing, I.K., R.S., L.B.P., and A.Z. All authors have contributed to the completion of this manuscript. They have read and agreed to the published version of the manuscript.

Funding
This research received no external funding.

Conflicts of Interest
The authors declare no conflict of interest.

References

Agustini, S. R., & Swasto, D. F. (2023). Identification of Local Wisdom in Community Culture in Danau Sentarum National Park. *Built Environment Studies*, *4*(2), 14–24. https://doi.org/10.22146/best.v4i2.6681

Alifatri, L. O., Hariyadi, S., & Adi Susanto, H. (2017). Analisis Daya Dukung Lahan untuk Pengembangan Budi Daya Kerapu di Perairan Tambak Kecamatan Cilebar, Kabupaten Karawang. *Jurnal Ilmu Pertanian Indonesia*, *22*(1), 52–66. https://doi.org/10.18343/jipi.22.1.52

Andryannur, H., Akbar, A. A., & Sulastri, A. (2022). Pengaruh Perubahan Tutupan Lahan Terhadap Jasa Ekosistem Pangan Di Taman Nasional Danau Sentarum. *Jurnal Ilmu Lingkungan*, *20*(3), 615–627. https://doi.org/10.14710/jil.20.3.615-627

Anshari, G., Kershaw, A. P., van der Kaars, S., & Jacobsen, G. (2004). Environmental change and peatland forest dynamics in the Lake Sentarum area, West Kalimantan, Indonesia. *Journal of*

Quaternary Science, *19*(7), 637–655. https://doi.org/10.1002/jqs.879

Artika, E., Yuwono, S. B., Banuwa, I. S., Setiawan, A., Bakri, S., & Wahono, E. P. (2022). The effect of land cover forest on fluctuations in availability of water in the Batutegi Dam, Lampung, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1027*, 012006. https://doi.org/10.1088/1755-1315/1027/1/012006

Astari, W., Yustiana, Y., & Prihadi, N. (2023). Business Models and Strategies for Managing Indigenous-based Natural Tourism in and around Danau Sentarum National Park (Ecotourism Meliau Hamlet). *Jurnal Ilmu Kehutanan*, *17*(2), 163–172. https://doi.org/10.22146/jik.v17i2.6497

Barbier, E. B. (2010). Poverty, development, and environment. *Environment and Development Economics*, *15*(6), 635–660. https://doi.org/10.1017/S1355770X1000032X

Bell, A. R., Benton, T. G., Droppelmann, K., Mapemba, L., Pierson, O., & Ward, P. S. (2018). Transformative change through Payments for Ecosystem Services (PES): A conceptual framework and application to conservation agriculture in Malawi. *Global Sustainability*, *1*, e4. https://doi.org/10.1017/sus.2018.4

Brenes, C. L. M., Jones, K. W., Schlesinger, P., Robalino, J., & Vierling, L. (2018). The impact of protected area governance and management capacity on ecosystem function in Central America. *PLoS ONE*, *13*(10). https://doi.org/10.1371/journal.pone.0205964

Cahyono, H. W. H., Utomowati, R., & Noviani, R. (2022). Daya Dukung Lahan dan Daya Dukung Permukiman dengan Pendekatan Kemampuan Lahan di Kecamatan Sragen dan Kecamatan Sambungmacan Kabupaten Sragen. *Teknik PWK (Perencanaan Wilayah Kota)*, *11*(3), 215–223. https://doi.org/10.14710/tpwk.2022.30470

Cai, W., Shu, C., & Lin, L. (2024). Integrating Ecosystem Service Values into Urban Planning for Sustainable Development. *Land*, *13*(12), 1985. https://doi.org/10.3390/land13121985

Canteiro, M., Cotler, H., Mazari-Hiriart, M., Babinet, N., & Maass, M. (2024). Natural dynamics and watershed approach incorporation in urban water management: A scoping review. *Plos One*, *19*(8), e0309239. https://doi.org/10.1371/journal.pone.0309239

Cheng, Y., Wu, H., & Yang, B. (2023). Conserving habitat and ecosystem in protected areas amid increasing intensive human modification: A case study of China's Pan-Pearl River Delta. *Ecological Indicators*, *154*, 110799. https://doi.org/10.1016/j.ecolind.2023.110799

Dakos, V., & Kéfi, S. (2022). Ecological resilience: What to measure and how. *Environmental Research Letters*, *17*, 043003. https://doi.org/10.1088/1748-9326/ac5767

del Monte-Luna, P., Brook, B. W., Zetina-Rejón, M. J., & Cruz-Escalona, V. H. (2004). The carrying capacity of ecosystems. *Global Ecology and Biogeography*, *13*, 485–495. https://doi.org/10.1111/j.1466-822X.2004.00131.x

Dixon, A. B., & Wood, A. P. (2003). Wetland cultivation and hydrological management in eastern Africa: Matching community and hydrological needs through sustainable wetland use. *Natural Resources Forum*, *27*(2), 117–129. https://doi.org/10.1111/1477-8947.00047

Djalil, F., Lihawa, F., & Koem, S. (2023). Kajian Daya Dukung Lahan Permukiman Kota Gorontalo. *GEOGRAPHY : Jurnal Kajian, Penelitian Dan Pengembangan Pendidikan*, *11*(2), 322. https://doi.org/10.31764/geography.v11i2.16271

Duffy, C., Toth, G. G., Hagan, R. P. O., McKeown, P. C., Rahman, S. A., Widyaningsih, Y., Sunderland, T. C. H., & Spillane, C. (2021). Agroforestry contributions to smallholder farmer food security in Indonesia. *Agroforestry Systems*, *95*(6), 1109–1124. https://doi.org/10.1007/s10457-021-00632-8

Eklund, J., & Cabeza, M. (2017). Quality of governance and effectiveness of protected areas: crucial concepts for conservation planning. *Annals of the New York Academy of Sciences*, *1399*(1), 27–41. https://doi.org/10.1111/nyas.13284

Estrela-Segrelles, C., Pérez-Martín, M. Á., & Wang, Q. J. (2024). Adapting Water Resources Management to Climate Change in Water-Stressed River Basins—Júcar River Basin Case. *Water*, *16*, 1004. https://doi.org/10.3390/w16071004

Fahad, S., Chavan, S. B., Chichaghare, A. R., Uthappa, A. R., Kumar, M., Kakade, V., Pradhan, A., Jinger, D., Rawale, G., Yadav, D. K., Kumar, V., Farooq, T. H., Ali, B., Sawant, A. V., Saud, S., Chen, S., & Poczai, P. (2022). Agroforestry Systems for Soil Health Improvement and Maintenance. *Sustainability*, *14*, 14877. https://doi.org/10.3390/su142214877

Felipe-Lucia, M. R., Soliveres, S., Penone, C., Fischer, M., Ammer, C., Boch, S., Boeddinghaus, R. S., Bonkowski, M., Buscot, F., Fiore-Donno, A. M., Frank, K., Goldmann, K., Gossner, M. M., Hölzel, N., Jochum, M., Kandeler, E., Klaus, V. H., Kleinebecker, T., Leimer, S., … Allan, E. (2020). Land-use intensity alters networks between biodiversity, ecosystem functions, and services. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(45), 28140–28149. https://doi.org/10.1073/pnas.2016210117

Fenta, A. A., Tsunekawa, A., Haregeweyn, N., Tsubo, M., Yasuda, H., Kawai, T., Berihun, M. L., Ebabu, K., Sultan, D., & Mekuriaw, S. (2023). An integrated framework for improving watershed management planning. *Environmental Research*, *236*, 116872. https://doi.org/10.1016/j.envres.2023.116872

Filoso, S., Bezerra, M. O., Weiss, K. C. B., & Palmer, M. A. (2017). Impacts of forest restoration on water yield: A systematic review. *PLOS ONE*, *12*(8), e0183210. https://doi.org/10.1371/journal.pone.0183210

Funder, M., Danielsen, F., Ngaga, Y., Nielsen, M. R., & Poulsen, M. K. (2013). Reshaping conservation: The social dynamics of participatory monitoring in Tanzania's community-managed forests. *Conservation and Society*, *11*(3), 218–232. https://doi.org/10.4103/0972-4923.121011

Garza-Díaz, L. E., & Sandoval-Solis, S. (2022). Identifying Thresholds, Regime Shifts, and Early Warning Signals Using Long-Term Streamflow Data in the Transboundary Rio Grande–Rio Bravo Basin. *Water*, *14*, 2555. https://doi.org/10.3390/w14162555

Giesen, W., & Anshari, G. Z. (2016a). Danau Sentarum National Park (Indonesia). In C. Finlayson, G. Milton, R. Prentice, & N. Davidson (Eds.), *The Wetland Book* (pp. 1–10). Springer. https://doi.org/10.1007/978-94-007-6173-5

Giesen, W., & Anshari, G. Z. (2016b). Danau Sentarum National Park (Indonesia). *The Wetland Book*, *41*, 1–10. https://doi.org/10.1007/978-94-007-6173-5_44-2

Hasudungan, A. (2010). Forestry Crisis in Danau Sentarum National Park ,. *Economics and Finance in Indonesia*, *57*(3), 307–314. Retrieved from https://ideas.repec.org/a/lpe/efijnl/200914.html

Hidayat, H., Aisyah, S., Kurniawan, R., Ridwansyah, I., Samir, O., & Sri Haryani, G. (2021). Flood Pulse and Aquatic Habitat Dynamics of The Sentarum Floodplain Lakes Area. *Indonesian Journal of Limnology*, *1*(1), 27–37. https://doi.org/10.51264/inajl.v1i1.2

Hillebrand, H., Donohue, I., Harpole, W. S., Hodapp, D., Kucera, M., Lewandowska, A. M., Merder, J., Montoya, J. M., & Freund, J. A. (2020). Thresholds for ecological responses to global change do not emerge from empirical data. *Nature Ecology and Evolution*, *4*(11), 1502–1509. https://doi.org/10.1038/s41559-020-1256-9

Ivory, S. J., McGlue, M. M., Spera, S., Silva, A., & Bergier, I. (2019). Vegetation, rainfall, and pulsing hydrology in the Pantanal, the world's largest tropical wetland. *Environmental Research Letters*, *14*, 124017. https://doi.org/10.1088/1748-9326/ab4ffe

Jenke, M. (2024). Community-based forest management moderates the impact of deforestation pressure in Thailand. *Land Use Policy*, *147*, 107351. https://doi.org/10.1016/j.landusepol.2024.107351

Kallio, H., Pietilä, A. M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, *72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Kementerian Lingkungan Hidup. (2014). *Pedoman Penentuan Daya Dukung dan Daya Tampung Lingkungan Hidup*. Kementerian Lingkungan Hidup.

Lamsal, P., Pant, K. P., Kumar, L., & Atreya, K. (2015). Sustainable livelihoods through conservation of wetland resources: A case of economic benefits from Ghodaghodi Lake, western Nepal. *Ecology and Society*, *20*(1), 10. https://doi.org/10.5751/ES-07172-200110

Lane, C. R., Creed, I. F., Golden, H. E., Leibowitz, S. G., Mushet, D. M., Rains, M. C., Wu, Q., D'Amico, E., Alexander, L. C., Ali, G. A., Basu, N. B., Bennett, M. G., Christensen, J. R., Cohen, M. J., Covino, T. P., DeVries, B., Hill, R. A., Jencso, K., Lang, M. W., … Vanderhoof, M. K. (2023). Vulnerable Waters are Essential to Watershed Resilience. *Ecosystems*, *26*(1), 1–28. https://doi.org/10.1007/s10021-021-00737-2

Le, T. A. T., Vodden, K., Wu, J., Bullock, R., & Sabau, G. (2024). Payments for ecosystem services programs: A global review of contributions towards sustainability. *Heliyon*, *10*, e22361. https://doi.org/10.1016/j.heliyon.2023.e22361

Li, G., Fang, C., Watson, J. E. M., Sun, S., Qi, W., Wang, Z., & Liu, J. (2024). Mixed effectiveness of global protected areas in resisting habitat loss. *Nature Communications*, *15*, 8389. https://doi.org/10.1038/s41467-024-52693-9

Mahmud, Wijaya, D., Wahyudi, & Kusumandari, A. (2021). Evaluasi Daya Dukung dan Skenario Konservasi DAS Wosi diKabupaten Manokwari, Papua Barat. *Jurnal Ilmu Kehutanan*, *15*(2), 231–246. https://doi.org/10.22146/jik.v15i

Nurlukman, C. P., Noer, M., Arham, B., Stevany, D., Aisyah, S., & Kusratmoko, E. (2025). Analisis Daya Dukung Lahan Berdasarkan Kebutuhan dan Ketersedian Lahan Pertanian dan Perkebunan di Kab. Purwakarta Tahun 2020. *Paspalum: Jurnal Ilmiah Pertanian*, *13*(1), 227–237. https://doi.org/10.35138/paspalum.v13i1.966

Onrizal, Kusmana, C., Saharjo, B. H., Handayani, I. P., & Kato, T. (2005). Review: Social and Environmental Issues of Danau Sentarum National Park, West Kalimantan. *Biodiversitas*, *6*(3), 220–223.

Peña-Arancibia, J. L., Bruijnzeel, L. A., Mulligan, M., &

van Dijk, A. I. J. M. (2019). Forests as 'sponges' and 'pumps': Assessing the impact of deforestation on dry-season flows across the tropics. *Journal of Hydrology*, *574*, 946–963. https://doi.org/10.1016/j.jhydrol.2019.04.064

Rijal, S., Samsuri, Masruroh, H., Nursaputra, M., A, C., & Ardi, N. Z. P. (2025). Ecological Sensitivity of the Mata Allo Sub-Watershed, South Sulawesi: A Spatial Analysis Using Principal Component Analysis. *Sustainability*, *17*, 447. https://doi.org/10.3390/su17020447

Rojikhah, A., Leksono, A. S., & Rachmansyah, A. (2024). Spatial Planning for Agricultural Development Based on Carrying Capacity of Ecosystem Services in The Melolo Transmigration Area, East Sumba. *Jurnal Presipitasi: Media Komunikasi Dan Pengembangan Teknik Lingkungan*, *21*(1), 223–236. https://doi.org/10.14710/presipitasi.v21i1.223-236

Roslinda, E. (2019). Economic valuation of the danau sentarum national park, West Kalimantan, Indonesia. *Biodiversitas*, *20*(7), 1983–1989. https://doi.org/10.13057/biodiv/d200726

Sadhwani, K., & Eldho, T. I. (2023). Assessing the Vulnerability of Water Balance to Climate Change at River Basin Scale in Humid Tropics: Implications for a Sustainable Water Future. *Sustainability*, *15*, 9135. https://doi.org/10.3390/su15119135

Setyowati, D. L. (2021). Assessment of Watershed Carrying Capacity and Land Use Change on Flood Vulnerability Areas in Semarang City. *Forum Geografi*, *35*(2), 141–152. https://doi.org/10.23917/forgeo.v35i2.15542

Shiferaw, N., Habte, L., & Waleed, M. (2025). Land use dynamics and their impact on hydrology and water quality of a river catchment: a comprehensive analysis and future scenario. *Environmental Science and Pollution Research*, *32*(7), 4124–4136. https://doi.org/10.1007/s11356-025-35946-y

Shoozan, A., & Mohamad, M. (2024). Application of Interview Protocol Refinement Framework in Systematically Developing and Refining a Semi-structured Interview Protocol. *SHS Web of Conferences*, *182*, 04006. https://doi.org/10.1051/shsconf/202418204006

Sriyana, I. (2018). Evaluation of watershed carrying capacity for watershed management (a case study on Bodri watershed, Central Java, Indonesia). *MATEC Web of Conferences*, *195*, 05003. https://doi.org/10.1051/matecconf/201819505003

Tang, X., & Adesina, J. A. (2022). Integrated Watershed Management Framework and Groundwater Resources in Africa—A Review of West Africa Sub-Region. *Water*, *14*(3), 288. https://doi.org/10.3390/w14030288

Tarigan, S., Wiegand, K., Sunarti, & Slamet, B. (2018). Minimum forest cover required for sustainable water flow regulation of a watershed: A case study in Jambi Province, Indonesia. *Hydrology and Earth System Sciences*, *22*(1), 581–594. https://doi.org/10.5194/hess-22-581-2018

Utami, W. D., Abuyahman, R. F., & Sahrul, S. (2025). Potensi Wisata Pulau Sepandan di Taman Nasional Danau Sentarum Kabupaten Kapuas Hulu Kalimantan Barat. *Jurnal Global Ilmiah*, *2*(11), 907–916. https://doi.org/10.55324/jgi.v2i11.266

VijayKumar, R., Tiwari, P., Daniel, S., Kumar, K. R., Mishra, I., KS, A., & Shah, D. (2024). Agroforestry Systems: A Pathway to Resilient and Productive Landscapes. *International Journal of Environment and Climate Change*, *14*(12), 177–193. https://doi.org/10.9734/ijecc/2024/v14i124617

Wackernagel, M., Hanscom, L., Jayasinghe, P., Lin, D., Murthy, A., Neill, E., & Raven, P. (2021). The importance of resource security for poverty eradication. *Nature Sustainability*, *4*(8), 731–738. https://doi.org/10.1038/s41893-021-00708-4

Wang, L., Song, X., Liu, Y., Li, L., Zhao, X., Meng, P., Fu, C., Wei, W., Wang, X., & Li, H. (2025). Effects of Long-Term Vegetation Restoration on Green Water Utilization Heterogeneity in the Loess Plateau Based on Field Experiments and Modeling. *Plants*, *14*, 644. https://doi.org/10.3390/plants14050644

Wang, Y., He, Y., Li, J., & Jiang, Y. (2022). Evolution Simulation and Risk Analysis of Land Use Functions and Structures in Ecologically Fragile Watersheds. *Remote Sensing*, *14*, 5521. https://doi.org/10.3390/rs14215521

Wenpeng, D., Huimin, Y., Yanzhao, Y., & Fang, L. (2018). Evaluation Methods and Research Trends for Ecological Carrying Capacity. *Journal of Resources and Ecology*, *9*(2), 115–124. https://doi.org/10.5814/j.issn.1674-764x.2018.02.001

Wolka, K., Biazin, B., Getachew, F., Girma, F., & Desta, G. (2023). Towards sustainable watershed-based landscape restoration in degraded drylands: Perceived benefits and innovative pathways learnt from project-based interventions in Ethiopia. *Journal of Environmental Management*, *335*, 117499. https://doi.org/10.1016/j.jenvman.2023.117499

Wu, J., Li, W., Du, H., Wan, Y., Yang, S., & Xiao, Y. (2025). Nonlinear responses of coupled socioecological systems to land use and climate changes in the Yangtze river basin. *Scientific Reports*, *15*, 6940. https://doi.org/10.1038/s41598-025-92084-8

Yang, X., Wang, Z. H., & Wang, C. (2022). Critical transitions in the hydrological system: Early-warning signals and network analysis. *Hydrology and Earth System Sciences*, *26*(7), 1845–1856. https://doi.org/10.5194/hess-26-1845-2022

Yasmi, Y., Colfer, C. J. P., Yuliani, L., Indiatmoko, Y., & Heri, V. (2007). Conflict management approaches under unclear boundaries of the commons: Experiences from Danau Sentarum National Park, Indonesia. *International Forestry Review*, *9*(2), 597–609. https://doi.org/10.1505/ifor.9.2.597

Yi, H., Wang, Y., Lou, Y., & Han, X. (2023). Effects of Vegetation Restoration on the Hydrological Regimes of the Chinese Loess Plateau: A Comparative Analysis of Forested and Less-Forested Catchments. *Forests*, *14*, 1199. https://doi.org/10.3390/f14061199

Yuniarti, E., Soekmadi, R., Arifin, H. S., & Noorachmat, B. P. (2018). Analisis Potensi Ekowisata Heart of Borneo Di Taman Nasional Betung Kerihun Dan Danau Sentarum Kabupaten Kapuas Hulu. *Jurnal Pengelolaan Sumberdaya Alam Dan Lingkungan*, *8*(1), 44–54. https://doi.org/10.29244/jpsl.8.1.44-54