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Environmental Carrying Capacity Based on Ecosystem Services for Settlement Development Plans in The Sota State Border Area, Merauke

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ABSTRACT

Sustainable settlement design necessitates the incorporation of environmental carrying capacity determined by ecosystem services. In border areas like the Sota Border Area (KPN) in Papua, ecological pressures intensify as a result of population expansion and economic endeavours. This study assesses the environmental carrying capacity and resilience of settlements through an ecosystem services framework, comparing conditions in 2019 and 2024 to evaluate the impact of development plans. The analysis focuses on five key ecosystem services: food provision, clean water supply, water flow regulation and flood control, disaster protection, and air quality maintenance. Data collection involved field surveys, remote sensing, and GIS-based spatial overlay analysis to map land use changes and ecosystem service values. Results in 2019 showed residential development concentrated in zones with high ecosystem service values, such as food provision (771.7 ha in SUB BWP 2) and clean water supply (742.98 ha in SUB BWP 3). Development in low-lying areas prioritized flood regulation (460.1 ha in SUB BWP 1) and disaster protection (560.7 ha in SUB BWP 1). By 2024, developed land in the very high clean water supply zone of SUB BWP 1 increased sharply from 0.10 ha to 28.86 ha. This research highlights the critical need to incorporate ecosystem service data into settlement planning to sustain environmental capacity and enhance border region sustainability.

INTRODUCTION

Ecosystem services play a vital role in sustainable development by enhancing human well-being and ensuring ecological balance that supports long-term life systems. These services include essential resources, climate regulation, flood control, and biodiversity conservation. They are generally classified into four categories—provisioning, regulating, cultural, and supporting services—reflecting how ecosystems contribute to human and environmental resilience (Rahning Utomowati et al., 2024; Sangadji et al., 2019).

The ecosystem services framework offers a foundation for understanding how ecosystems provide essential direct and indirect benefits to human well-being. According to the Millennium Ecosystem Assessment (2005), (Blampied et al., 2022; Olschewski & Klein, 2011; Puri et al., 2017), these services are classified into four categories: provisioning, regulating, supporting, and cultural services. This classification allows for a holistic assessment of ecosystem contributions and helps clarify human–environment interactions.

The Sota State Border Area (KPN) in Papua is strategically located for national sovereignty and security, bordering Papua New Guinea, Australia, and Palau. As regulated by Presidential Regulation No. 32 of 2015, its development must align with sustainability principles and ecosystem protection. Amid plans for new residential settlements driven by population and economic growth, the region faces serious spatial planning challenges that demand rigorous environmental carrying capacity assessments (Pahuluan et al., 2017).

Such assessments ensure that ecological functions are not compromised before land conversion or infrastructure development begins. Environmental carrying capacity denotes an ecosystem's enduring capability to furnish resources and services without inducing long-term deterioration (Febriarta et al., 2022; R. A. V. W. Saputra et al., 2023). Integrating this evaluation into spatial planning is key to balancing development goals with environmental resilience in the Sota border region.

Research on ecosystem service assessment in settlement planning has grown considerably. However, its integration with spatial planning remains limited, especially in ecologically fragile regions like the Sota State Border Area. Most existing studies emphasize natural resource carrying capacity—such as water or soil suitability—while overlooking the complex socio-ecological dynamics unique to border zones. Meanwhile, geospatial approaches using GIS and remote sensing to evaluate ecosystem services within spatial planning frameworks are still evolving (Widiatmaka et al., 2016).

To fill existing research gaps, this study develops a comprehensive ecosystem service assessment model that integrates ecological and environmental aspects. It also critically evaluates the implementation of the 2019 residential development plan by analyzing and comparing land use patterns observed in 2024. This dual approach provides a holistic perspective on how well settlement planning aligns with environmental carrying capacity, illuminating its impacts on landscape dynamics and sustainability in the Sota region.

In Indonesia, ecosystem carrying capacity and resilience assessments are increasingly framed through ecosystem service approaches integrating environmental, social, and economic perspectives. Standard methods include both qualitative and quantitative analyses, such as ecosystem service mapping and supply-demand matrices to evaluate whether ecosystems can meet community needs (Arkham et al., 2023; Riqqi et al., 2019; Sari et al., 2021; Yuliana et al., 2020). Tools like GIS enhance spatial accuracy (Burkhard, 2018), while service-based models help assess sustainability through the balance of supply and demand (Balzan & Debono, 2018)

Despite global progress, research in Indonesia often remains narrowly focused on isolated factors such as water availability or land suitability (Widiatmaka et al., 2016). These approaches overlook the complex socio-ecological interactions, particularly relevant in ecologically sensitive border areas like Sota, where integrated spatial planning remains underdeveloped. Additionally, most studies concentrate on specific ecosystems or services—such as mangroves—without considering broader ecological interdependencies (Arkham et al., 2023; Mulawarman et al., 2020), and often neglect key social aspects like community engagement in natural resource management (Rachmansyah et al., 2023; S. Saputra, 2019).

The ecosystem services approach has become increasingly relevant in Indonesia. It provides an integrated framework combining ecological, social, and economic dimensions in spatial assessments (Wilkerson et al., 2018). Its application in spatial planning improves natural resource governance and supports decisions that maintain ecosystem integrity (Komarawidjaja, 2017; Santoso et al., 2020). This is especially crucial in ecologically sensitive areas like the Sota Border Region, where balancing development and environmental sustainability is a strategic priority.

Evidence shows that incorporating ecosystem services into planning processes enhances the evaluation of development impacts on both ecosystems and communities (Feng Bin et al., 2025). The framework aids planners in identifying conservation zones, promoting environmentally responsible land use, and formulating adaptation strategies to climate risks (Utomowati et al., 2024).

This study evaluates ecosystems' carrying and supporting capacity for settlement development based on an ecosystem services approach in the Sota State Border Area. In addition to assessing current ecosystem capacity, this research will evaluate the effectiveness of the 2019 residential development plan by comparing it with the actual land use conditions in 2024, to determine whether environmental carrying capacity considerations have been adequately implemented. Using a field survey combined with GIS-based overlay analysis, this study maps the dynamics of ecosystem service supply and demand to support scientifically grounded, sustainable spatial planning. The findings are expected to offer practical recommendations for policymakers and planners to manage natural resources more effectively in border areas, especially amid increasing environmental pressures from climate change and population growth.

RESEARCH METHODS

Geographical Conditions of the Study Area

This study was conducted in the Sota District of the Merauke Regency in the Papua Province of Indonesia. Papua Province is in southern Indonesia, the largest of the provinces' regencies/cities. The 2,500-hectare study area includes only one administrative area: Kampung Sota (Figure 1).

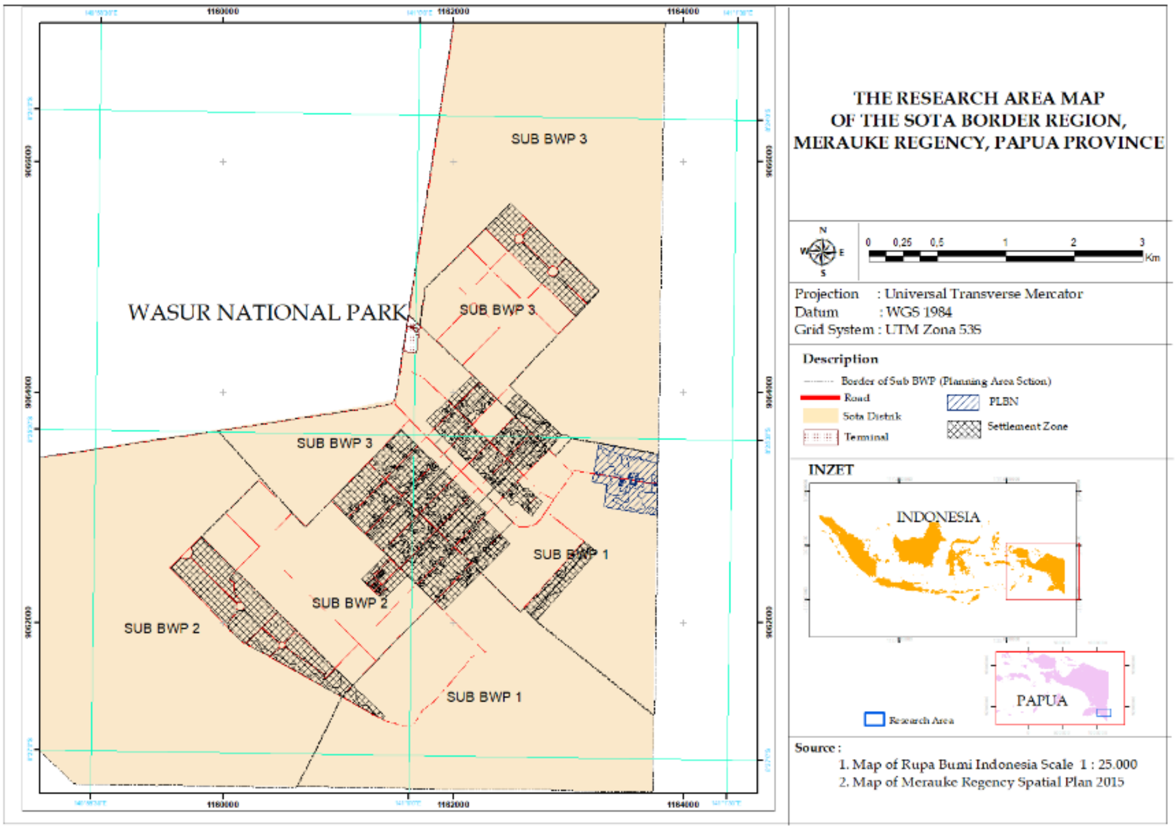

Figure 1. Map of the Research Area of the Sota Border Region, Merauke Regency, Papua Province (Source: Data Processing, 2025)

The Sota District research area is characterized by flat to gently sloping terrain, with slope gradients ranging from 0–2% in the east to 5–8% in the west. Geologically, the southern coastline consists of alluvial deposits, while the northern part is dominated by quartz sand and pumice formations. The soils include organosols, alluvial, and gray hydromorphic types commonly found in swamp and brackish areas, underlain by Quaternary sandstone and conglomerate (QS) structures. The region is also traversed by several rivers, including the Maro River, which serve as vital freshwater sources for irrigation and inter-village water transport. Using recent satellite imagery, mapping environmental carrying capacity based on ecosystem services began with land cover interpretation. This process involved identifying and delineating dominant land cover types in the Sota State Border Area (KPN). Field verification (ground checks) was carried out in key locations to validate the accuracy of spatial data.

Research Type and Materials

This is an applied, quantitative study with a spatial approach that uses advanced analysis with a geographic information system (GIS). This system integrates primary and secondary data. Primary data consists of direct observations using drones to produce aerial photographs of the conditions to be assessed, such as land cover types and landforms. These observations will be validated against ecoregion maps. Additionally, primary data includes expert justifications for determining the weighting of ecosystem services. The secondary data used in this study consists of the 2013 Papua Island Ecoregion Map at a scale of 1:500,000 and the 2014 Papua Island Land Cover Map at a scale of 1:250,000, both of which were sourced from the Ministry of Environment and Forestry (KLHK). The article also uses land cover data from Sentinel-2 satellite imagery from https://livingatlas.arcgis.com/landcoverexplorer in 2029 and 2024. The classification technique used is supervised classification based on the Random Forest algorithm. The purpose of creating the 2024 land use map is to evaluate the impact of development implementation.

Research Techniques and Analysis

The expected outcome of this research is a carrying capacity map based on ecosystem services. This map will later inform settlement planning in the research area. First, the land cover of the research area was interpreted. In the initial process, land cover interpretation is done by observing aerial photos taken in the field using drones and comparing them with land cover maps from the Ministry of Environment and Forestry. This activity was carried out in 2019, before the Sota KPN development was implemented. Validation was done through field visits to several locations. Next, the land cover map will be used as a proxy to create an ecosystem service map.

The next step is creating an ecoregion map based on the landform map. The landform map is obtained by analyzing the topography and landform units in the study area. A field check ensures the created map is consistent with existing conditions.

The assessment of each map, irrespective of its categorization as a land cover or ecoregion map, is conducted to ascertain its relevance to the ecosystem services under consideration. Experts (expert judgment) from academia, local officials, and public figures assess and weigh these proxies. This activity was carried out by several experts who participated in the public consultation for the Strategic Environmental Assessment (SEA) of the Detailed Spatial Plan (DSP) for the Sota KPN in 2019. The assessment and prioritisation of ecosystem services by specialists in land cover and ecoregions was performed using the Analytical Hierarchy Process (AHP) (Rawat et al., 2022). Following the evaluation of each variable, the resulting data were then overlaid, and the overlay results were classified into five classes ranging from Very High to Very Low. The final step entailed visualizing the spatial ecosystem service index (ESI) and subsequent analysis.

The subsequent step entailed integrating the carrying capacity map with the 2024 land cover map, thereby facilitating the identification of transpired alterations. The Millennium Ecosystem Assessment (2005) classification system divides ecosystem services into four categories: provisioning services, regulating services, supporting services, and cultural services. Table 1 presents the Classification of Ecosystem Services.

Table 1. Classification of Ecosystem Services

Classification of Ecosystem Services		Operational Definition
A. Provisioning Functions		
1	Food (P1)	Marine food, woodland resources (flora and fauna), agricultural and plantation food items, cattle commodities
2	Clean water (P2)	Terrestrial water supply (including storage capacity) and water supply from surface sources
3	Fiber (P3)	Forest products, marine commodities, and agricultural & plantation materials
4	Fuel (P4)	Supply of firewood and fossil fuels
5	Genetic resources (P5)	Supply of Genetic Resources encompassing flora and wildlife
B. Regulating Function		
1	Climate regulation (R1)	Regulation of temperature, humidity, and precipitation, alongside greenhouse gas and carbon management.
2	Water flow & flood management (R2)	Hydrological cycle and natural infrastructure for water retention, flood management, and water conservation.
3	Disaster prevention and protection (R3)	Natural infrastructure for the prevention and protection against wildfires, erosion, abrasion, landslides, storms, and tsunamis.
4	Water purification (R4)	Ability of aquatic systems to dilute, degrade, and assimilate pollutants
5	Waste treatment and decomposition (R5)	Sites' ability to neutralise, digest, and absorb waste and litter
6	Air quality maintenance (R6)	Ability to manage atmospheric chemical systems
7	Regulation of natural pollination (R7)	Distribution of habitats for natural pollinator species
8	Pest & disease control (R8)	Distribution of habitats for pest and disease-inducing species and their management agents
C. Cultural Function		
1	Residence & living space (sense of place) (C1)	A residence for thriving, a "hometown" cornerstone imbued with emotional significance.
2	Recreation & ecotourism (C2)	Geographical attributes, natural distinctiveness, or particular traits that serve as tourist attractions
3	Aesthetics (C3)	Natural beauty with commercial appeal

D. Supporting Function		
1	Soil formation & fertility maintenance	Fertility of soil
2	Nutrient cycling	Soil fertility and agricultural productivity levels
3	Primary production	Oxygen production, habitat supply for species
4	Biodiversity	Biodiversity

(Source: Muta'ali, 2019)

RESULTS AND DISCUSSION

Five types of ecosystem services relevant to human settlements were selected for analysis, even though the classification of ecosystem services outlined by the Millennium Ecosystem Assessment (2005) encompasses a significantly broader range of services. The five ecosystem services selected for analysis are as follows: food provision, clean water provision, water flow regulation and flood control, disaster protection, and air quality regulation and maintenance. This ecosystem service analysis uses data from 2019, before the implementation of the settlement development plan, to provide an early picture of development in the study area.

Settlement Planning based on Food Provision Ecosystem Services

A comprehensive analysis of the food provision ecosystem services data reveals a consensus regarding the direction of settlement development in the study area. Development has been predominantly concentrated in the Very High and High classes, indicating a strategic approach to urban planning and development. This phenomenon is manifestly evident from the distribution of built-up areas across the three Sub-Planning Areas (SUB BWP). In SUB BWP 1, most settlements are classified as High (468.9 ha) and Very High (174.3 ha) categories, with a mere 1.3 ha classified as Moderate, and no development observed in the Low or Very Low categories. A similar pattern is observed in SUB BWP 2 and SUB BWP 3, with no residential development in the Low category. SUB BWP 2 recorded an area of 771.7 ha in the Very High class and 213.7 ha in the Medium class, while SUB BWP 3 recorded 761.2 ha in the Very High class and 167.5 ha in the Medium class (Table 2 & Figure 2).

Table 2. Area classification of Food Provision Ecosystem Services in Sota 2019

	Very High (Ha)	High (Ha)	Medium (Ha)	Low (Ha)	Very Low (Ha)
SUB BWP 1	174.3	468.9	1.3	0	0
SUB BWP 2	771.7	0	213.7	0	0
SUB BWP 3	761.2	0.0	167.5	0.0	0.0

(Source: Research Result, 2025)

Settlement Planning based on Clean Water Ecosystem Services

Spatial data on clean water ecosystem services (JE P2) indicators demonstrate that settlement development planning in the Sota District, Merauke, has been executed with consideration of the region's ecological capacity to support clean water needs. In the three Sub-Planning Areas (SUB BWP 1, SUB BWP 2, and SUB BWP 3), built-up areas are concentrated in the Very High and High classes, with a significant proportion.

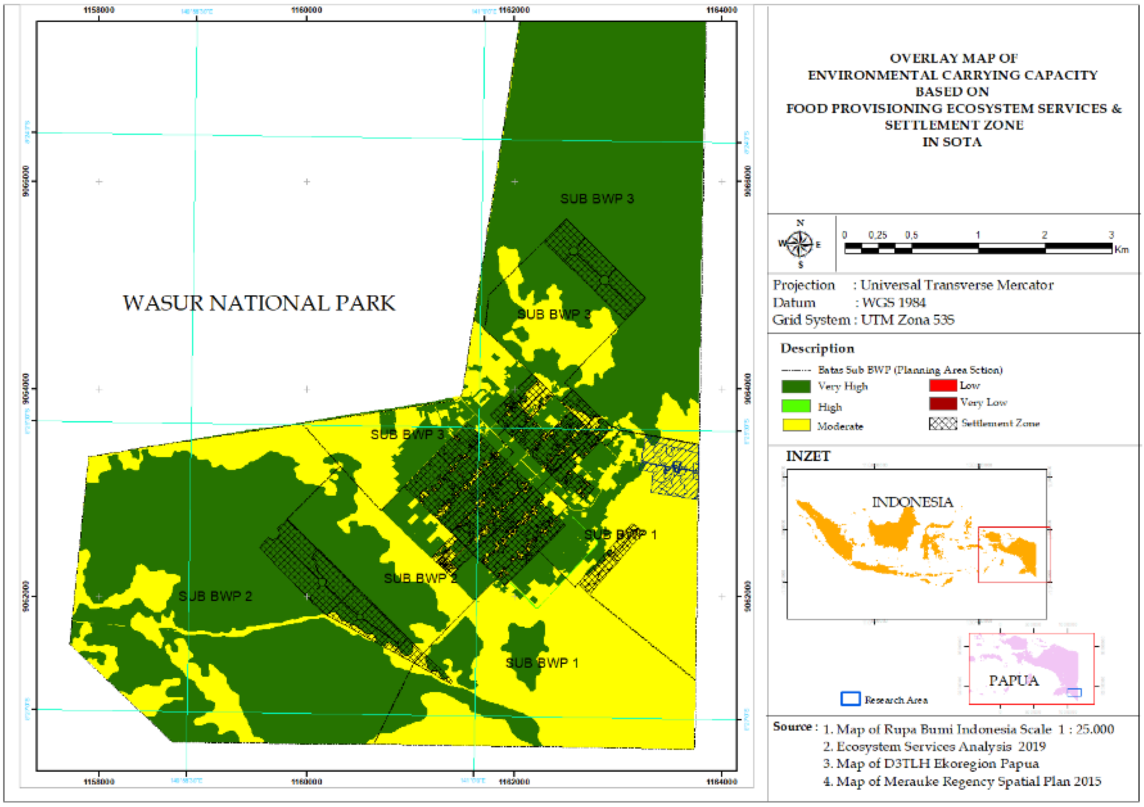

Figure 2. Overlay Map of Environmental Carrying Capacity Based on Food Provisioning Ecosystem Services & Settlement Zone 2019 (Source: Data Processing, 2025)

SUB BWP 1 recorded 159.70 ha of settlements in the Very High class, 467.77 ha in the High class, and only 16.97 ha in the Medium class. A similar pattern is exhibited by SUB BWP 2, with a predominance of development in the Very High category (749.80 ha), the High category (210.93 ha), and 24.65 ha in the Medium category. SUB BWP 3 also exhibits consistency in this development pattern, with 742.98 ha in the Very High category, 175.09 ha in the High category, and only 10.59 ha in the Medium category. A review of residential development across all sub-regions reveals an absence of any development in the Low and Very Low categories (Table 3 & Figure 3).

Table 3. Area Classification of Clean Water Ecosystem Services in Sota 2019

	Very High (Ha)	High (Ha)	Medium (Ha)	Low (Ha)	Very Low (Ha)
SUB BWP 1	159.70	467.77	16.97	0.0	0.0
SUB BWP 2	749.80	210.93	24.65	0.0	0.0
SUB BWP 3	742.98	175.09	10.59	0.0	0.0

(Sources: Research Result, 2025)

Settlement Planning based on Ecosystem Services for Water Flow Regulation & Flood Control

Data concerning ecosystem services in the water flow regulation and flood control category (JE R2) offer significant insights into the suitability of settlement planning for local ecosystem conditions. A thorough analysis of data from three Sub-Planning Areas (SUB BWP) reveals that most built-up areas are situated in zones exhibiting low to very low water regulation capacity. However, there are also contributions to higher classes.

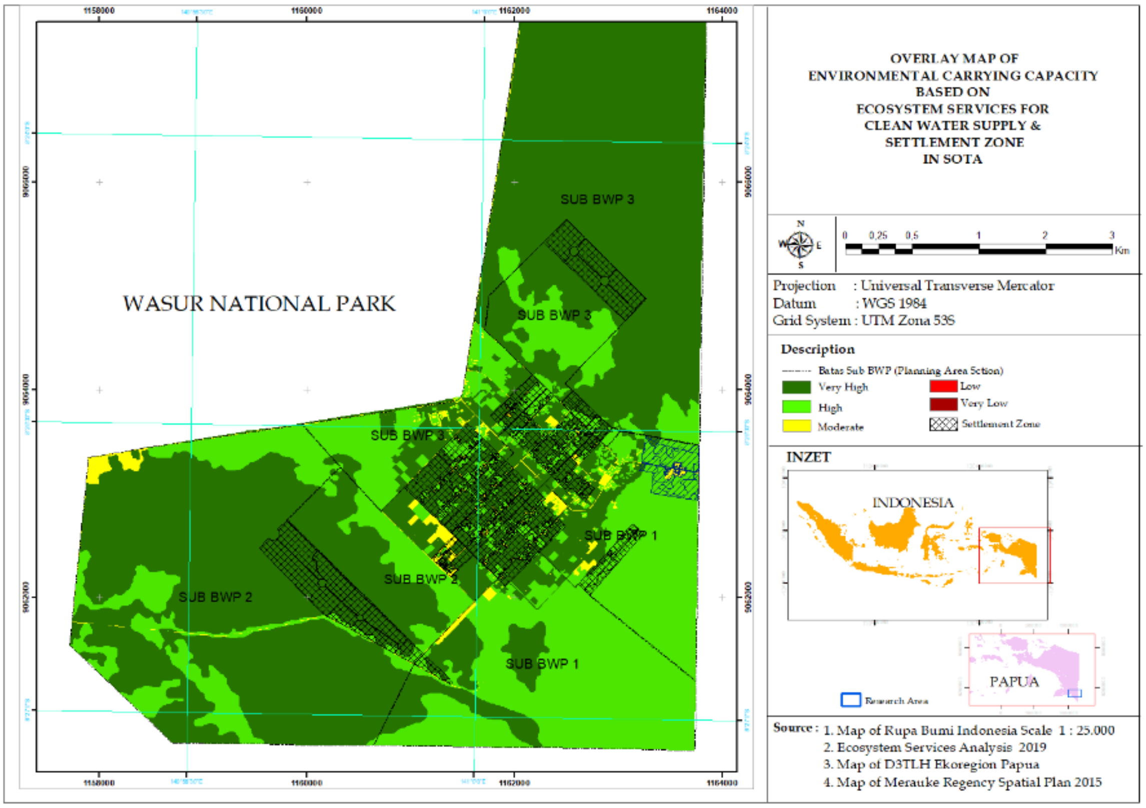

Figure 3. Overlay Map of Environmental Carrying Capacity Based on Ecosystem Services for Clean Water Supply & Settlement Zone 2019 (Source: Data Processing, 2025)

In SUB BWP 1, the largest residential area is in the Low class (460.1 ha), with limited contributions from the High class (72.27 ha) and Very Low and Moderate classes (10.21 ha each). This finding suggests that most urban areas are located within zones exhibiting a high probability of natural water flow disturbances, including flooding and waterlogging. Conversely, SUB BWP 2 exhibits a more balanced distribution between the Moderate (97.45 ha) and Low (198.94 ha) classes. However, it persists in demonstrating a prevalence in regions characterized by moderate to high risk of water flow disruption. (Table 4 & Figure 4).

Table 4. Area Classification of Ecosystem Services for Water Flow Regulation & Flood Control in Sota 2019

	Very High (Ha)	High (Ha)	Medium (Ha)	Low (Ha)	Very Low (Ha)
SUB BWP 1	0	72.27	10.21	460.1	10.21
SUB BWP 2	0	10.21	97.45	198.94	15.26
SUB BWP 3	0	666.21	94.71	166.1	1.7

(Source: Research Result, 2025)

Settlement Planning based on Ecosystem Services for Disaster Prevention and Protection

A spatial analysis of JE R3 ecosystem services, which reflect disaster prevention and protection functions, reveals that the majority of settlement development in the study area—particularly in the Sota District, Merauke—is concentrated in areas with low (Low) and very low (Very Low) protection capacity. This phenomenon is evident in the distribution of built-up areas across the three Sub-Planning Areas (SUB BWP).

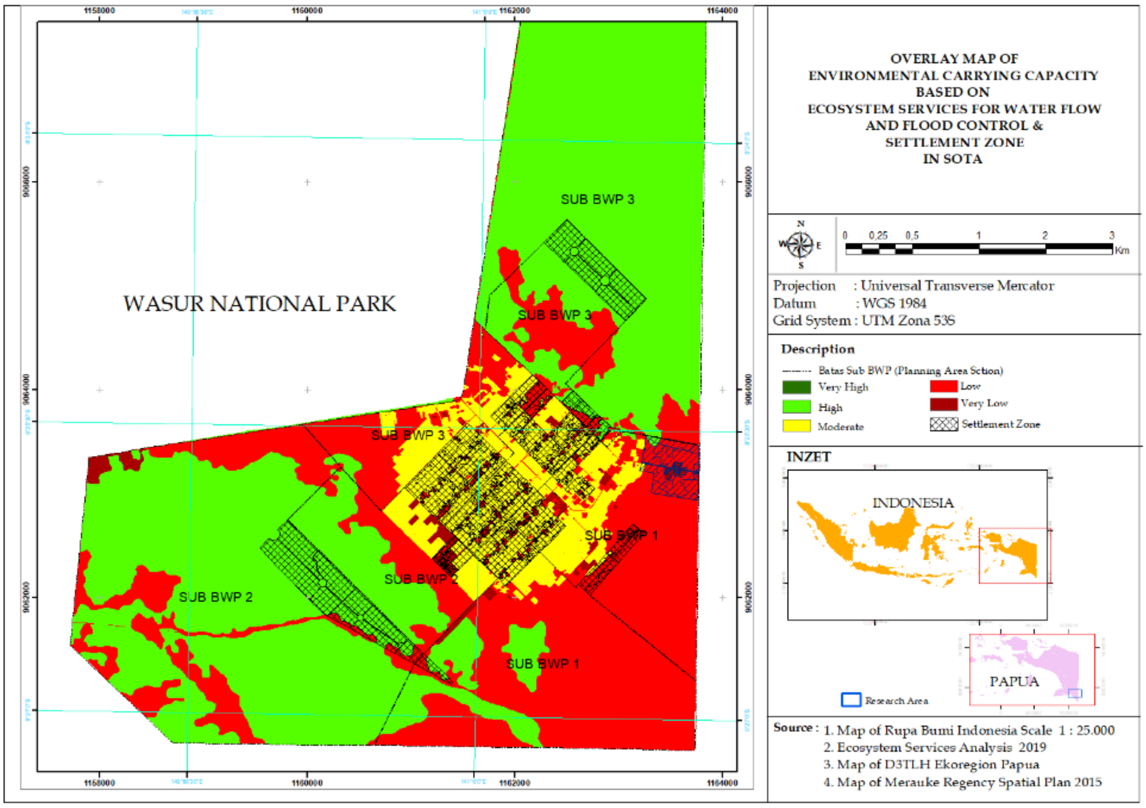

Figure 4. Overlay Map of Environmental Carrying Capacity based on Ecosystem Services for Water Flow Regulation & Flood Control 2019 (Source: Data Processing, 2025)

In SUB BWP 1, 560,698 ha of the total built-up area is in the Low zone, accompanied by 10,210 ha in the Very Low zone, and only 73,536 ha in the Moderate class. SUB BWP 2 demonstrates even higher values in the Low class (673,727 ha) and Moderate class (296,388 ha), with 15,263 ha in the Very Low class. Similarly, SUB BWP 3 is characterized by a preponderance of development in the Moderate (666,212 ha) and Low (260,792 ha) classes, with a negligible presence in the Very Low class (1,652 ha). (Table 5 & Figure 5).

Table 5. Area Classification of Ecosystem Services for Disaster Prevention and Protection in Sota 2019

	Very High (Ha)	High (Ha)	Medium (Ha)	Low (Ha)	Very Low (Ha)
SUB BWP 1	0.00	0.00	73.53	560.69	10.21
SUB BWP 2	0.00	0.00	296.38	673.72	15.26
SUB BWP 3	0.00	0.00	666.21	260.79	1.65

(Source: Research Result, 2025)

Settlement Planning and Air Quality Maintenance Ecosystem Services

According to JE R6, there is a significant correlation between the location of residential development and the ecosystem's capacity to support air quality maintenance functions in the Sota District of Merauke. The three sub-planning areas (SUB BWP) exhibit different trends, but development tends to occur in zones with moderate to low capacity to support healthy air quality.

In SUB BWP 1, the most significant built-up area is in the low class (441.74 hectares), followed by very low (114.7 hectares) and a small portion in the very high class (88 hectares). Meanwhile, SUB BWP 2 and SUB BWP 3 show more positive trends, with residential development dominating the high class at 695.10 and 684.15 hectares, respectively. However, both subregions recorded significant development in the low and very low classes, totaling over 290 hectares per region. (Table 6 & Figure 6).

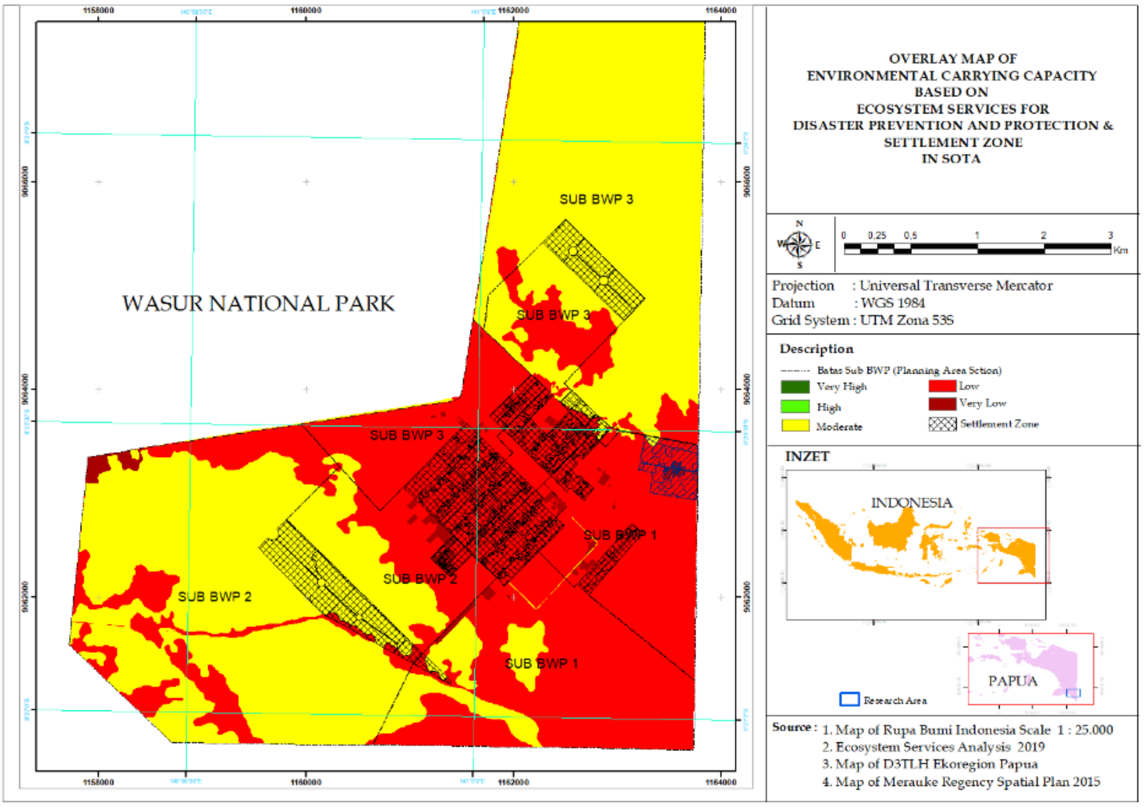

Figure 5. Overlay Map of Environmental Carrying Capacity based on Ecosystem Services for Disaster Prevention and Protection 2019 (Source: Data Processing, 2025)

The stagnation observed in the Moderate and High categories across all geographical regions indicates that areas with moderate to high air filtration capabilities have not been utilized balanced. Moreover, developing the Low and Very Low zones in the context of air quality can exacerbate local atmospheric conditions, particularly if the augmentation of green open spaces or shade-providing vegetation does not accompany it.

Table 6. Area Classification of Ecosystem Services in Sota 2019

	Very High (Ha)	High (Ha)	Medium (Ha)	Low (Ha)	Very Low (Ha)
SUB BWP 1	0	88.01	0.000	441.74	114.69
SUB BWP 2	0	695.09	0.000	183.03	107.24
SUB BWP 3	0	684.15	0.000	150.16	94.33

(Source: Research Result, 2025)

While there are positive indications of the development direction in SUB BWP 2 and 3, the significant proportion of low-capacity areas indicates that residential development planning has not fully considered the dimension of ecosystem services related to air quality maintenance. Consequently, it is imperative to incorporate ecological approaches into spatial planning and regional development policies, particularly by fortifying green zoning and ecological corridors that play a role in nature.

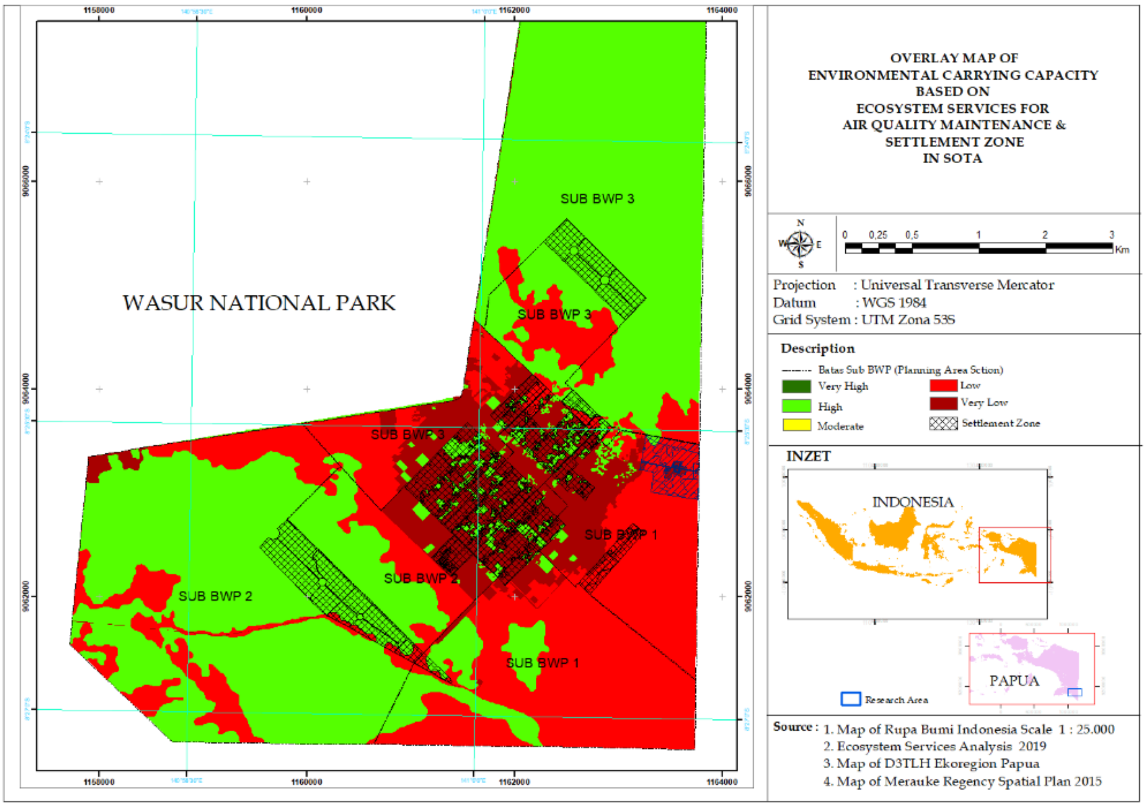

Figure 6. Overlay Map of Environmental Carrying Capacity based on Ecosystem Services for Air Quality Maintenance & Settlement in Sota 2019 (Source: Data Processing, 2025)

Evaluation of Environmental Carrying Capacity Based on Ecosystem Services for Settlements in 2019–2024

This subsection discusses the evaluation of settlement development plans based on the environmental carrying capacity of ecosystem services in the study area. The evaluation compared ecosystem services on developed land in 2019 with the condition in 2024**.**

Figure 7 (a) illustrates the spatial and temporal dynamics of built-up areas categorized by land use intensity (Very High, High, Moderate) within three sub-watersheds (SUB BWP 1, 2, and 3) over five years. Built-up expansion is presented in hectares (ha), highlighting shifts that may impact the food provision function of ecosystem services.

Notably, SUB BWP 3, which had no built-up area in 2019, shows a dramatic increase by 2024, especially under the Very High intensity class (32.81 ha), suggesting rapid urban encroachment. In contrast, SUB BWP 1 experienced a moderate reduction in total built-up area, with a decline particularly in Moderate intensity zones, potentially reflecting policy or planning interventions. SUB BWP 2 slightly increases in high-intensity development but remains relatively stable overall.

These spatial patterns signal a growing threat to food provisioning services, particularly in regions undergoing unregulated or high-intensity land conversion. The findings emphasize the need for integrated land-use planning that safeguards ecological functions while accommodating development pressures.

Figure 7(b) visualizes the spatial distribution and temporal change of built-up land across three sub-watersheds between 2019 and 2024, disaggregated by land use intensity. It shows how urban expansion could impact the ecosystem services' clean water supply function.

In particular, SUB BWP 1 shows a dramatic increase in built-up area under the Very High intensity class from 0.10 ha (2019) to 28.86 ha (2024), signaling accelerated urbanization. Meanwhile, SUB BWP 3 maintains a consistently high value in this category, while SUB BWP 2 shows a modest decline. These shifts emphasize the importance of strategic watershed management to mitigate risks to clean water provisioning.

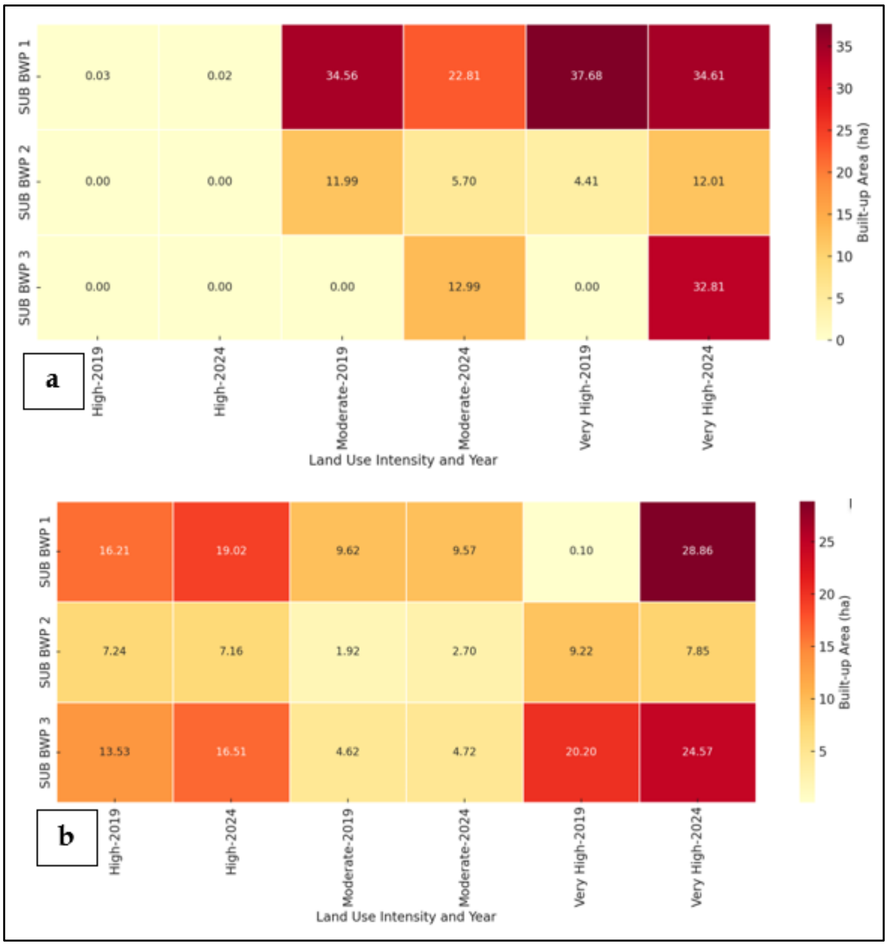

Figure 7. (a). Heatmap of Built-up Area on Food Provision Ecosystem Services across Three Sub-BWPs in 2019 and 2024; (b). Heatmap of Built-up Area on Clean Water Supply Ecosystem Services (Source: Research Result, 2025)

Figure 8 (a) illustrates the spatial and temporal shifts in built-up land across three Sub-Planning Regions (SUB BWP) between 2019 and 2024, categorized by land use intensity levels from Very High to Very Low.

The data reveal a concentration of built-up expansion in Moderate and low-intensity areas, particularly in SUB BWP 3, where moderate-intensity development grew from 26.13 ha to 32.59 ha. In contrast, SUB BWP 2 experienced a sharp reduction in all land use intensity classes, likely indicating land reclamation efforts, restoration programs, or effective spatial control policies.

These land use transitions have significant implications for ecosystem services related to water regulation and flood control. Increased built-up areas, especially in lower-intensity zones, can reduce groundwater recharge, elevate surface runoff, and impair natural flood buffering capacity—posing heightened risks of localized flooding in downstream areas, especially during the rainy season in Sota District, Merauke.

This highlights the urgent need for spatial planning frameworks integrating hydrological ecosystem services into development decisions, ensuring flood resilience and ecological sustainability (Fan et al., 2021).

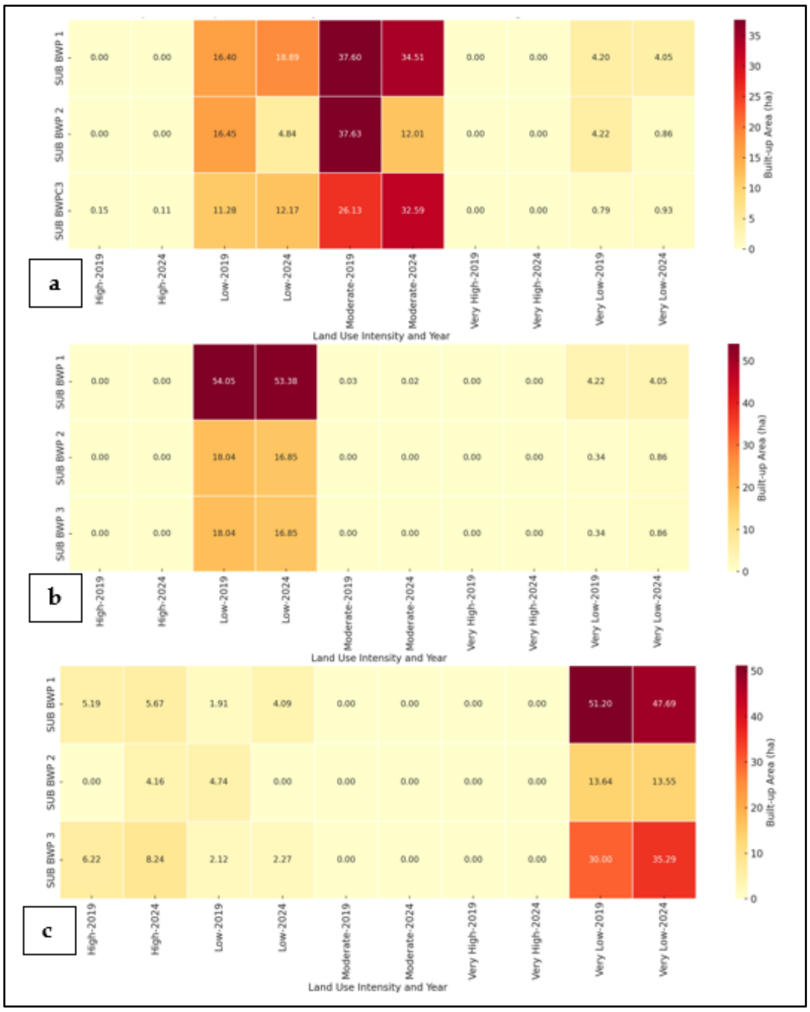

Figure 8. (a). Heatmap of Built-up Area on Ecosystem Services: Water Flow Regulation & Flood Control in Sota District, Merauke; (b). Heatmap of Built-up Area on Ecosystem Services for Disaster Prevention and Protection in Sota District, Merauke; (c). Heatmap of Built-up Area on Air Quality Maintenance Ecosystem Services in Sota District, Merauke. (Source: Research Result, 2025)

Figure 8(b) presents the built-up areas' spatial and temporal dynamics across three Sub-Regional Planning (SUB BWP) from 2019 to 2024, categorized by land use intensity from Very High to Very Low.

The most notable concentration of built-up land occurs within the low-intensity category, especially in SUB BWP 1, which shows the highest values in both years. SUB BWP 2 and SUB BWP 3 exhibit parallel patterns, with a slight decrease in low-intensity development and a marginal increase in very low-intensity areas.

No development was recorded in the high- or high-intensity zones, indicating effective land conservation or regulatory zoning. However, the expansion of built-up land—even in lower-intensity areas—can still undermine ecosystems' functionality in mitigating disaster risks such as floods, erosion, and extreme temperatures.

This analysis underscores the importance of integrating Disaster Risk Reduction (DRR) strategies into spatial planning and land use policy to ensure sustainable and resilient landscapes, particularly in vulnerable regions like Sota District, Merauke.

Figure 8 (c) displays the distribution of built-up land within three Sub Bagian Wilayah Perencanaan (SUB BWPs) from 2019 to 2024, categorized by land use intensity. The focus is on how these changes may impact ecosystem services related to air quality maintenance.

The largest concentrations of built-up land occur in the Very Low intensity class, particularly in SUB BWP 1 and SUB BWP 3. These areas recorded the highest values in 2019 (51.20 ha and 30.00 ha, respectively), with moderate increases by 2024. A noticeable expansion also occurs in the high-intensity class in SUB BWP 3 and newly emerges in SUB BWP 2.

While no substantial development appears in the Moderate or Very High categories, the expansion in low-intensity areas still poses a risk to natural air filtration functions, especially if accompanied by increased emissions from urban infrastructure. This trend may reduce the ecosystem's capacity to mitigate airborne pollutants and maintain breathable air.

Thus, spatial planning in the Sota District should integrate strategies for conserving vegetated zones and limiting development in areas critical for air purification, such as urban green belts and ecological zoning (Vieira et al., 2018).

CONCLUSION

This study successfully evaluated the value of ecosystem services in supporting settlement planning in the Sota Border Area (KPN). The evaluation was based on five main categories: food and clean water provision, water flow and flood regulation, disaster protection, and air quality maintenance. Spatial analysis shows that, in 2019, most settlement development occurred in zones with very high and high ecosystem service values. This was particularly true for the food provision function (SUB BWP 2: 771.7 hectares) and clean water provision (SUB BWP 3: 742.98 hectares). However, development in flood regulation and disaster protection dominated low-to-very-low zones, such as SUB BWP 1, reaching 560.7 hectares in the low class for disaster protection. Comparing 2019 and 2024 data reveals an increase in developed land in the very high clean water category, rising from 0.10 to 28.86 hectares in SUB BWP 1. Conversely, regarding air quality maintenance, SUB BWP 1 exhibited development dominance in the low air quality zone, reaching 441.74 hectares in 2019. These results suggest that development has not fully aligned with ecosystem capacity, particularly in regulatory and protective functions. Therefore, integrating ecosystem service assessments into settlement planning is crucial to ensuring sustainable and adaptive development that aligns with local ecological conditions.

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