Research Paper

Assessment of Environmental Assimilative Capacity Approaches and Implementation in Indonesia

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Abstract

The concept of assimilative capacity has been used as an indicator to assess the environment's ability to absorb pollutants without damaging potentially renewable natural resources. However, comprehensive research that integrates the five renewable natural resources (fresh water, arable land, air, biodiversity, and marine ecosystems) at a macro-scale within a specific region has yet to be conducted. This study employs statistical analysis to categorize pollutant indices and ecosystem service indices and cross-tabulation to define levels of assimilative capacity. The spatial analysis visualizes the data distribution. Notably, the current calculation of environmental assimilative capacity, a pioneering effort, was conducted in Bali Province, marking a significant step forward in the field. The environmental carrying capacity of Bali Province is classified as moderate when aggregated. These findings provide essential insights for applying precautionary principles in environmental planning, aiming to improve the quality of life. They also offer valuable data for governments to shape policies for their regions. By understanding and utilizing these insights, we can work towards enhancing environmental health.

Keywords

Environmental Capacity, Potentially Renewable Natural Resources, Pollution Index, Environmental Services

1. Introduction

1.1. Background of the Study

Indonesia is projected to face significant environmental and social challenges by 2045. Its population is expected to reach 324.06 million, over 70% of which will reside in urban areas (UN-DESA, 2022; Simarmata et al., 2023). Rapid urbanization, coupled with population growth, is expected to place substantial pressure on natural resources. As human habitation expands, the demand for essential resources such as clean water, arable land, clean air, and biodiversity will increase, leading to heightened consumption levels and significant environmental stress.

The anticipated rise in consumption levels directly correlates with the growing production of waste and the exacerbation of pollution. Notably, Indonesia is already the second-largest contributor to marine plastic waste, with estimates ranging between 1.3 million and 3.2 million tons of plastic entering the oceans each year (Jambeck et al., 2015). Furthermore, Indonesia experiences severe air pollution, primarily during the dry season, driven by forest and peatland fires. In 2019, air quality index (AQI) values in certain regions exceeded 500, far surpassing the hazardous level of 300 (World Air Quality Index Project, 2019). These environmental issues highlight the critical importance of sustainable resource management to maintain the ecological balance necessary for supporting life in the country.

Recognizing the urgency of these challenges, Indonesia has taken legislative steps to address its environmental sustainability. The introduction of Law No. 32 of 2009 institutionalized the use of Environmental Carrying Capacity (ECC) and Environmental Assimilative Capacity (EAC) as essential instruments for environmental and social safeguards. These frameworks serve as tools to evaluate the environment's ability to absorb waste and pollutants without compromising ecological health. Furthermore, Government Regulation (PP) No. 22 of 2021 provides specific guidelines for waste management and pollutant standards, reinforcing efforts to mitigate environmental degradation.

Despite these initiatives, Indonesia faces substantial challenges in assessing its EAC comprehensively. Accurate methodologies and data availability remain elusive, resulting in gaps between the country's EAC assessments and the effective implementation of existing policies. This issue is particularly critical as Indonesia continues its development trajectory, and a more precise evaluation of EAC is essential to balance economic growth with environmental sustainability.

To address these gaps, the current study aims to evaluate Indonesia's environmental assimilative capacity on a macro scale, focusing on five key renewable natural resources: fresh water, arable land, air, biodiversity, and marine ecosystems. By assessing the 2023 EAC across these dimensions, this research seeks to provide actionable insights that can guide environmental planning and policy formulation in Indonesia, ensuring that development can proceed without undermining the country's ecological and environmental health.

1.2. Literature Review

Research into environmental assimilative capacity (EAC) has developed significantly in recent years as nations grapple with the need to balance development and sustainability. The EAC concept is vital to understanding how much environmental stress a region can bear before detrimental effects occur. In the case of Indonesia, where rapid urbanization, industrialization, and population growth are pressing concerns, assessing EAC becomes a crucial component of environmental management.

1.2.1 Theoretical Foundations of EAC

Environmental assimilative capacity refers to the environment's ability to absorb, break down, or disperse pollutants without damaging the ecosystem's health or functionality. Previous studies have defined EAC as a critical indicator of how much human activity an ecosystem can support sustainably (Schroll et al., 2012). This framework is particularly significant in regions like Indonesia, where natural resources are essential for both economic activities and human survival. Furthermore, by understanding EAC, planners, and policymakers can design strategies that minimize environmental degradation, thus ensuring long-term sustainability.

However, despite its importance, estimating EAC is challenging, as it requires not only extensive data but also appropriate methodological frameworks. Various studies have highlighted the difficulties in accurately measuring EAC due to the multifaceted nature of environmental systems and the interactions between different resources, such as land, water, and air (Drucker & Lafferty, 2006). Therefore, more comprehensive and region-specific methodologies are required, particularly in areas as diverse as Indonesia, to improve EAC assessments.

1.2.2 Research on Environmental Capacity in Indonesia

While research on EAC is still evolving globally, the situation in Indonesia has seen some partial studies, particularly in relation to the pollution load in river basins and air quality (Prawoto et al., 2015). These studies often focus on isolated issues, such as water pollution in specific regions or air quality in urban centers, leaving out a holistic understanding of how Indonesia's environment can assimilate various forms of stress. For instance, air pollution resulting from forest fires is well-documented, particularly in studies highlighting the sharp rise in particulate matter (PM2.5) during the dry season (World Air Quality Index Project, 2019).

Water quality has also been an area of considerable focus in EAC research in Indonesia. Indonesia's extensive river systems, which serve as vital water sources for millions of people, have been found to be increasingly polluted due to urbanization and industrial activities. Several studies have noted that large amounts of untreated wastewater are released into these rivers, pushing their assimilative capacity to the brink (Suratno & Yusuf, 2020). However, despite these findings, a comprehensive assessment of how multiple natural resources interact to form the environmental assimilative capacity is still lacking.

1.2.3 Policy Instruments and Challenges in EAC Assessment

Indonesia has developed various policy frameworks aimed at improving environmental sustainability. Law No. 32 of 2009, for instance, marks an important legislative step by emphasizing the need to consider both Environmental Carrying Capacity (ECC) and EAC as tools for safeguarding ecological health (Schroll et al., 2012). However, the effectiveness of these policies has been limited due to difficulties in data collection and application. The challenge of accessing reliable data on the state of natural resources and environmental degradation remains a significant hurdle in estimating the country's EAC accurately.

In addition, Government Regulation (PP) No. 22 of 2021 contains specific guidelines for waste management and pollutant standards. It represents a critical effort by the Indonesian government to curb the negative environmental impacts of industrial activities and urban waste production. However, the gap between the policy guidelines and their implementation persists. Studies have indicated that while the framework for EAC is in place, the actual execution of policies often falters due to a lack of adequate institutional capacity and resources (Tjandra, 2017).

1.2.4 Integrating EAC into Spatial Planning

Integrating environmental assimilative capacity into spatial planning represents another crucial development in Indonesia's environmental policy. EAC has been recognized as an essential component of regional spatial planning, particularly in determining how much human activity can be sustained without causing environmental damage (Simarmata et al., 2023). However, this integration faces several challenges, including technical limitations in accurately forecasting environmental thresholds and the capacity of local governments to implement these frameworks effectively.

Schroll et al. (2012) argue that integrating EAC into spatial planning is essential to manage the environmental impact of urbanization and industrialization, especially in regions with high population density and rapid land conversion. These insights provide a pathway to creating more resilient urban environments that balance economic growth and ecological sustainability. Despite these policy advancements, further research and refinement in methodologies are needed to close the gap between theoretical frameworks and on-the-ground applications.

The literature on environmental assimilative capacity underscores the complexity of accurately assessing how much stress Indonesia's environment can handle. While existing research highlights key aspects of water, air, and land-based resources, there remains a pressing need for a more integrated approach to understanding the interplay between multiple resources. By addressing methodological challenges, improving data collection, and ensuring the effective implementation of policies, Indonesia can make significant strides in aligning development goals with sustainable environmental management.

2. Method

Researchers selected the province of Bali as the study area for environmental assimilative capacity due to the rapid, large-scale development in the tourism sector. This growth has placed significant pressure on five potentially renewable natural resources. The increasing number of tourists, coupled with the expansion of tourism infrastructure, drives the intensive use of natural resources, which consequently diminishes the environment's assimilative capacity—its ability to absorb negative impacts like pollution and waste.

This study employs a quantitative approach, utilizing cross-tabulation, spatial analysis, and literature review methods to assess the assimilative capacity within the concept of environmental carrying capacity. Researchers use the cross-tabulation method to examine the relationship between the environmental carrying capacity concept, specifically between variables such as substances, energy, or pollutant components, and absorptive variables based on data distribution. These relationships are then statistically analyzed to determine the assimilative capacity of a given environment.

According to Creswell (2014), the quantitative approach is an effective way to identify patterns and relationships in data. Researchers analyze pollutant variables using a pollutant index approach while they assess environmental absorptive variables through an environmental service index approach. Spatial analysis is applied to map the pollutant index, convert point data into polygons, and map the environmental service index using the supply and demand approach of ecosystem services (Burkhard, 2017). Both data variables are then categorized on a scale from low to high. The overlap of these two datasets is analyzed using a series of queries to extract specific data, resulting in a mapping of the assimilative capacity of the environment across each of the five potentially renewable natural resources as part of the environmental carrying capacity assessment approach.

2.1. Data Collection

The data used in this study include:

- **Pollutant Data:** Researchers gathered the pollutant index for five potentially renewable natural resources. They used interpolated results from water quality index monitoring points for clean water resources. For land resources and biodiversity, they applied the number of hazardous and toxic waste (B3) reporting points from companies, distributing them with weighted categorization of land use. For air resources, they interpolated data from air quality index monitoring points. For marine resources, they used monitoring points with marine quality index data to identify clean waters. The Ministry of Environment and Forestry (KLHK) provided this data.
- **Absorptive Data:** Researchers applied the 2022 environmental service approach provided by the Ministry of Environment and Forestry. They used the environmental service for water provision for water resources, the environmental service for soil formation for land resources, the environmental service for habitat and biodiversity support for biodiversity, the environmental service for air quality for air resources, and notably, the comprehensive Marine Ecoregion Information for marine resources.
- **Ecoregion and Land Cover Data:** Researchers used data on Natural Landscape Characteristics (KBA) and Natural Vegetation Characteristics (KVA), along with land cover time series for 2022, provided by the Ministry of Environment and Forestry.

2.2. Data Analysis

Assessing the Assimilative Capacity of Potentially Renewable Resources

1. Identifying Pollutant Index Classes

Our researchers begin by collecting and processing the necessary data to identify pollutant index points. The process involves collecting spatial data from various monitoring points that record pollutant levels. These data points, representing specific geographic locations, are then interpolated using techniques such as Inverse Distance Weighting (IDW). This interpolation estimates pollutant values in areas between known data points, enabling the creation of a continuous surface of pollution levels. This surface is then divided into zones based on pollution intensity thresholds, transforming the scattered points into polygons that represent areas with similar pollution levels. The resulting polygons provide a clear and visual representation of the distribution of pollution, making the findings easily understandable.

2. Identifying Environmental Services Classes

Our researchers overlay ecoregion data on Natural Landscape Characteristics (KBA) and Natural Vegetation Characteristics (KVA) with Land Cover (PL) data to create environmental services through scoring and weighting methods. This approach, as highlighted by Crossman et al. (2013), provides a crucial framework for assessing the landscape's capacity to deliver ecosystem services. The identified environmental service is water regulation. Scoring assesses the condition of each environmental parameter, while weighting is applied based on the importance of each parameter, ensuring a comprehensive evaluation.

Researchers can apply the following formula:

$$\text{Environmental Service} = (W\_KBA \times KBA) + (W\_KVA \times KVA) + (W\_PL \times PL)$$

Where:

- KBA represents the score for natural landscape characteristics,
- KVA represents the score for natural vegetation characteristics,
- PL represents the score for land use,
- W_KBA is the weight for natural landscape characteristics,
- W_KVA is the weight for natural vegetation characteristics,
- W_PL is the weight for land use.

3. Development of the Assimilative Capacity Assessment Cross Tabulation Matrix

Table 1 Assimilative Capacity Assessment Cross Tabulation Matrix

Matrix		Environmental Services				
		Very Low	Low	Moderate	High	Very High
Pollution Index	Heavily Polluted	Low EAC	Low EAC	Low EAC	Moderate EAC	Moderate EAC
	Moderately Polluted	Low EAC	Low EAC	Moderate EAC	High EAC	High EAC
	Lightly Polluted	Moderate EAC	Moderate EAC	High EAC	High EAC	High EAC

Source: Author, 2024

4. Analysis and Mapping of Environmental Assimilative Capacity

The process for this analysis follows these steps: Researchers apply the overlay process from Step 1 to both pollutant index data and environmental services index data. By comparing the results from two different periods, they can identify the assimilative capacity of each potentially renewable natural resource using a series of queries to extract specific data.

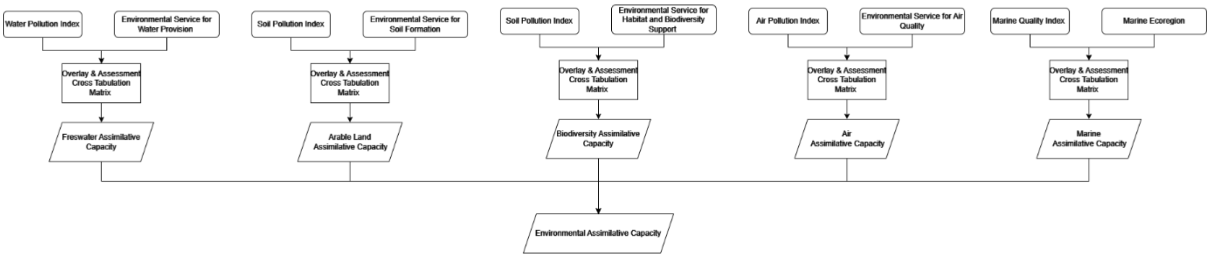

Figure 1 Assessment Methodology. Source: Author, 2024

3. Findings and Discussion

3.1. Assessment of Assimilative Capacity

Freshwater Assimilative Capacity

Widely, 83% of the pollutant index identifies pollutants in the moderately polluted category. The distribution of water pollutant indices reveals that 2% of the low or heavily polluted index affects the Denpasar area and its surroundings, while 15% of the lightly polluted index impacts the highlands of Buleleng, Bedugul, and Bangli. This data underscores the fact that high pollution levels in Bali Province can make water unsuitable for consumption without thorough treatment, significantly exacerbating the clean water crisis in many areas.

Additionally, the environmental services index for water supply shows that 50.63% of the region falls into the very low and low categories, while 49% falls into the moderate category. This finding underscores the inadequacy of Bali’s natural absorption capacity. A lower environmental services index for water supply suggests that the availability of usable water decreases, highlighting the urgent need for action.

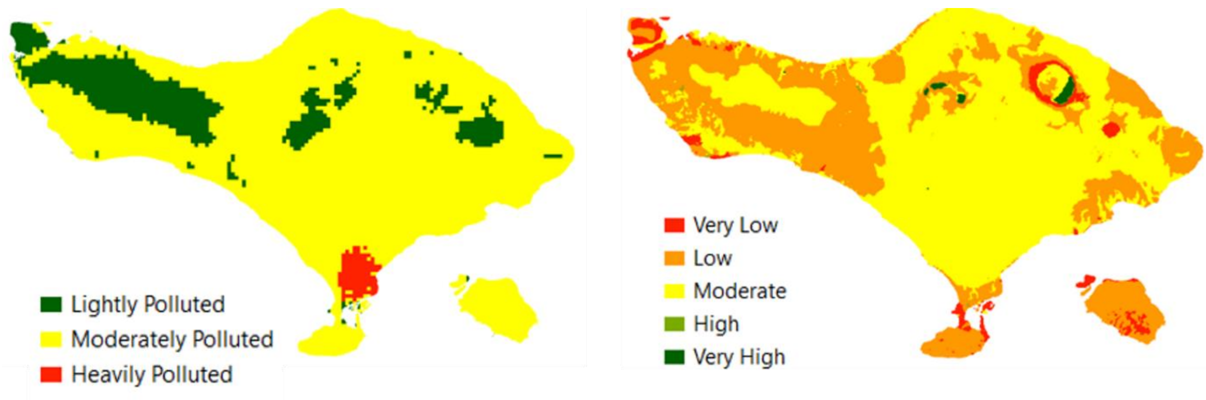

Figure 2 (Left) Water Pollution Index and (Right) Ecosystem Services - Water Providers. Source: KLHK, 2022

These two factors indicate that pollution and lack of usable water dominate much of the region. Consequently, Bali Province’s clean water assimilative capacity ranks as moderate. When an ecosystem or water body has a low assimilative capacity, it struggles to absorb or break down pollutants, which can lead to pollutant accumulation in the water, potentially causing more severe contamination. This highlights the vulnerability of the environment to the effects of pollution.

Arable Land

The distribution of pollution indices for agricultural land shows that 4% of the land in this region is categorized as highly polluted, presenting significant challenges for agricultural productivity. This category generally affects areas with intensive farming practices or poor waste management. Meanwhile, 55% of the agricultural land falls into the moderately polluted category, indicating that while these lands still hold agricultural potential, pollution remains a major barrier to achieving high yields.

In terms of environmental services related to soil formation regeneration, agricultural land in Bali Province shows a less concerning trend. Approximately 16% of agricultural land in this region provides very low levels of ecosystem services, such as nutrient cycling and soil health. This shows that soil degradation and pollution likely reduce the capacity of these areas to sustain agricultural production. The moderate level of ecosystem services, covering 52% of the land, suggests that some areas are better managed but still face risks related to sustainable farming.

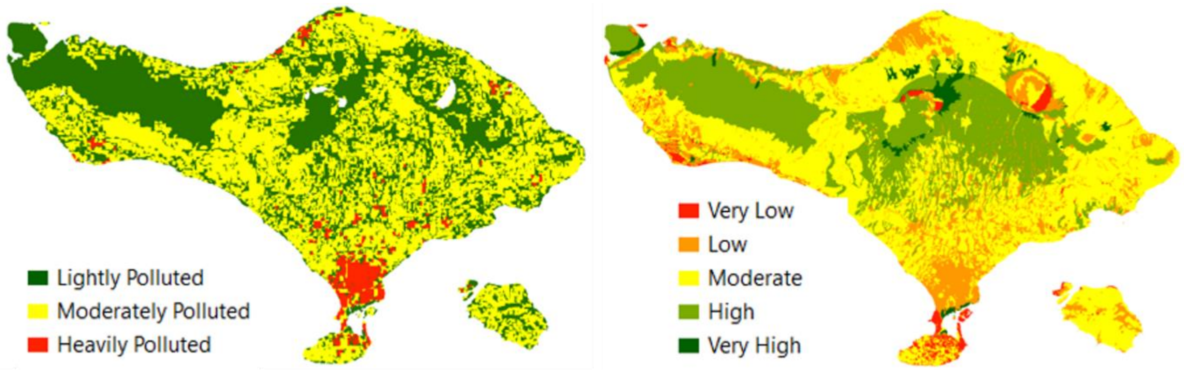

Figure 3 (Left) Soil Pollution Index and (Right) Ecosystem Services - Soil Formation for Land Resources. Source: KLHK, 2022

The combined impact of pollution and declining ecosystem services leads to a landscape with diminished assimilative capacity. With a significant portion of farmland both polluted and offering low ecosystem services, maintaining sustainable food production presents an increasing challenge. Addressing soil health and sources of pollution could help restore agricultural productivity in Bali Province.

Biodiversity

Regarding biodiversity, 41% of the biodiversity areas in Bali Province are categorized as highly polluted, threatening habitats and ecosystems vital to various species. This pollution directly affects the resilience of biodiversity in the region, making it more difficult for flora and fauna to thrive. Moderately polluted areas, which cover 55%, still support life but face increasing challenges due to habitat degradation and contamination.

In terms of ecosystem services supporting habitats and biodiversity, Bali's biodiversity shows a mixed picture. About 29% of biodiversity areas offer very low support for habitats and biodiversity. This means the biodiversity in these areas only partially benefits the ecosystem, whether due to pollution, habitat loss, or other environmental pressures. Conversely, 60% of the area shows very high scores, indicating that some biodiversity hotspots are still functioning well in supporting critical ecological processes.

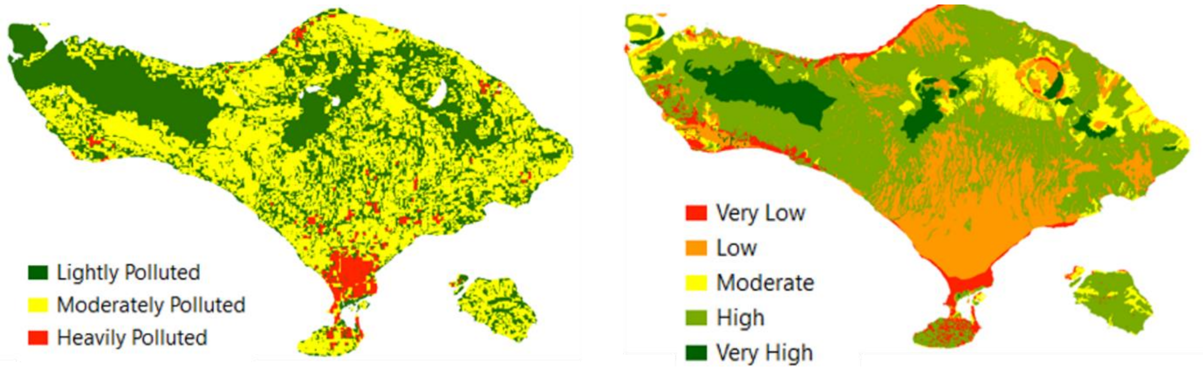

Figure 4 (Left) Soil Pollution Index and (Right) Ecosystem Services - Habitat And Biodiversity Support. Source: KLHK, 2022

Pollution pressures and varying levels of ecosystem services create a fragile balance for Bali's biodiversity. Without strong conservation efforts and pollution management, this balance, which supports Bali's rich biodiversity, may become increasingly disrupted, potentially leading to species population declines and ecosystem health deterioration.

Air

Broadly, almost all the air pollution index identifies pollutants within the mildly polluted category. The distribution of air pollution indices indicates that 1% of the highly polluted index affects urban areas with heavy traffic, such as Denpasar and Kuta, while 20% of the mildly polluted air index occurs in highland areas like Buleleng and Bedugul. This data shows that although most of Bali experiences low to moderate air pollution, areas with intensive human activity are more vulnerable to poor air quality.

Furthermore, the environmental service index for clean air provision shows that 4.25% of Bali is categorized as very low, while 42.87% falls into the moderate category. This shows that while much of the region still maintains moderate air quality, pollution significantly impacts some areas, and the ecosystem's ability to filter or break down air pollutants continues to decline. These areas may require additional measures to prevent further degradation of air quality.

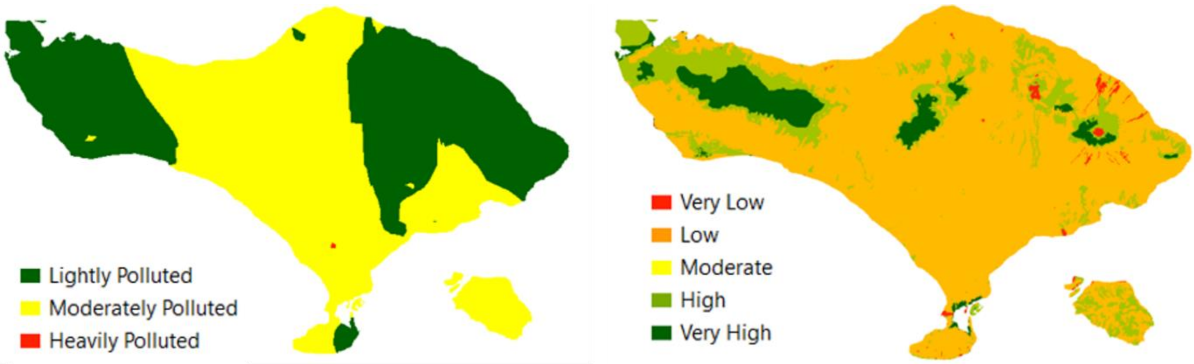

Figure 5 (Left) Air Quality Index and (Right) Ecosystem Services - Air Quality. Source: KLHK, 2022

These two factors indicate that air pollution and ecosystems' limited capacity to maintain clean air are major concerns in many regions. With much of the ecosystem's air capacity only at moderate levels, Bali faces challenges in balancing human activity and environmental health. Failure to address pollution sources could lead to an accumulation of air pollutants, ultimately increasing health risks for the population and threatening environmental sustainability.

Ocean

In Bali Province, there are currently only 15 monitoring points dedicated to tracking seawater quality, concentrated solely around the waters of Tanjung Benoa Beach. Recent data reveals that 10 out of these 15 points are classified as heavily polluted. Additionally, Tanjung Benoa Beach itself is considered moderately polluted, with several water quality parameters exceeding the maximum allowable limits for marine tourism, according to environmental standards. This highlights not only the localized environmental stress but also the need for expanded monitoring and stronger marine protection strategies, particularly in areas heavily utilized for tourism.

The concept of a marine ecoregion goes beyond geographic boundaries, encompassing distinct ecological areas characterized by unique marine biodiversity and environmental conditions. Understanding these ecoregions is critical for effective conservation strategies and the sustainable management of marine resources. By integrating both biotic (living organisms, such as fish, coral, and other marine species) and abiotic (non-living components like water quality, temperature, and nutrient levels) factors, conservation efforts can be better targeted to protect the complex interactions that support marine life. This holistic approach is essential for maintaining the ecological integrity and resilience of marine ecosystems in the face of environmental challenges and human activities.

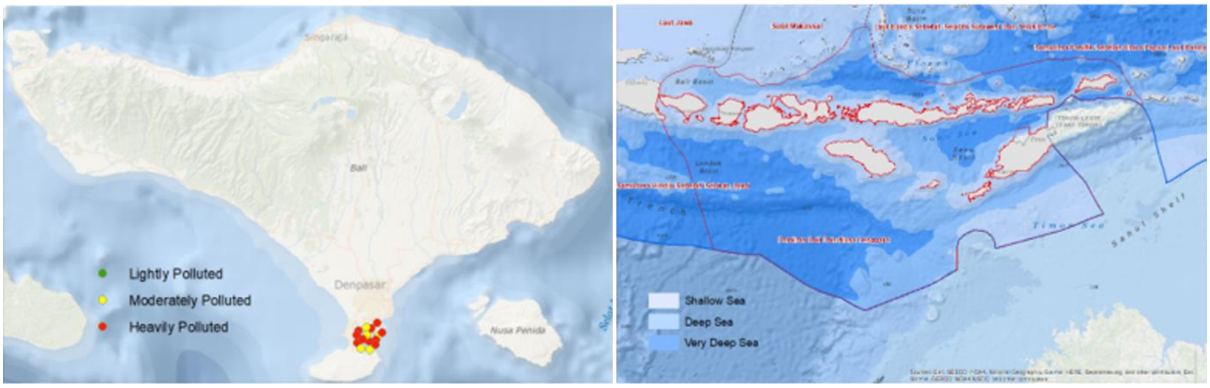

Figure 6 Monitoring Points with Seawater Quality Index and (Right) Marine Ecoregion Information. Source: KLHK, 2022

3.2. Mapping the EAC Value

Freshwater

A spatial distribution of the freshwater assimilative capacity across Bali Province is categorized into three levels: High EAC (green), Moderate EAC (yellow), and Low EAC (orange/red). From the map, it is evident that areas with high assimilative capacity (green) are scarce, representing only about 6% of the region. These areas are confined to a few localized patches, while the majority of Bali is dominated by regions with moderate to low capacity to absorb and process pollutants. The map illustrates a critical situation where most of the island's freshwater systems are no longer able to effectively handle pollution, threatening both water quality and overall ecosystem health.

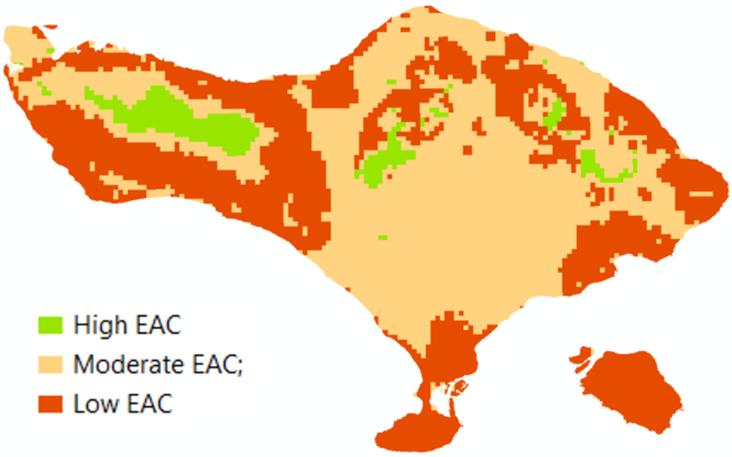

Figure 7 Freshwater Assimilative Capacity. Source: Data Processing Results, 2024

Arable Land

Notably, 48% of arable land in the province is classified as having a high assimilative capacity, indicating a significant ability of these regions to absorb pollutants and support agricultural activities. This high capacity is crucial for maintaining food self-sufficiency in Bali, enabling the land to withstand and mitigate the impacts of agricultural runoff and other pollutants. The presence of high EAC areas suggests that there are substantial opportunities for sustainable farming practices and conservation efforts in these regions.

However, the map also highlights areas with low EAC, primarily located in the southern part of the island, particularly near urbanized zones and coastal areas. These low EAC regions indicate a higher susceptibility to pollution and a decreased ability to support agricultural activities. The concentration of low EAC areas near urban centers underscores the gravity of the situation, signifying the challenges faced due to urban expansion, which often leads to habitat degradation and increased pollution. The proximity of these regions to vital freshwater resources exacerbates the risk of water quality degradation, threatening not only agricultural productivity but also the overall health of ecosystems in Bali. Addressing the imbalance between high and low EAC areas will be essential for ensuring long-term environmental sustainability and agricultural resilience.

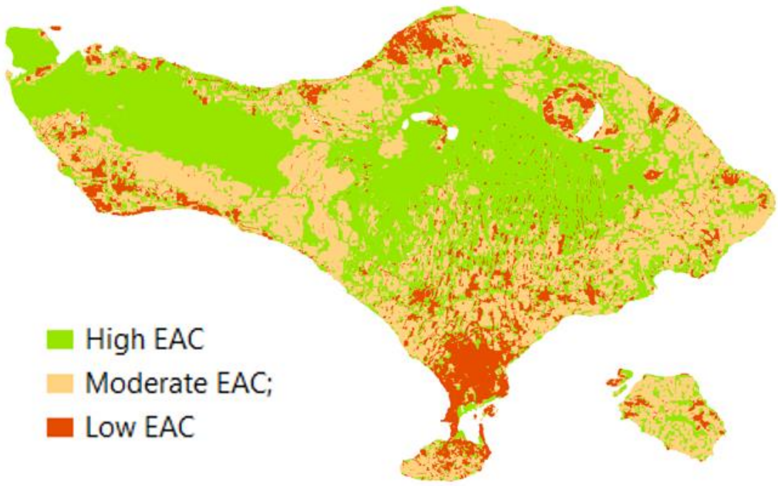

Figure 8 Arable Land Assimilative Capacity. Source: Data Processing Results, 2024

Biodiversity

The map depicts the Biodiversity Assimilative Capacity (EAC) of Bali Province, highlighting different levels of ecological sensitivity and vulnerability across the region. About 65% of the province is categorized as having a high EAC, meaning that these areas are capable of absorbing pollutants while maintaining genetic and habitat diversity. This ensures that various species continue to thrive and interact within these ecosystems. The areas marked in red indicate regions with low EAC, primarily sprawling in the southern part of Bali. This region encompasses the urban and highly developed areas around Denpasar and the southern peninsula, including popular tourist destinations like Kuta, Nusa Dua, and Jimbaran, where biodiversity is more vulnerable due to development pressures and lower capacity to mitigate environmental impact.

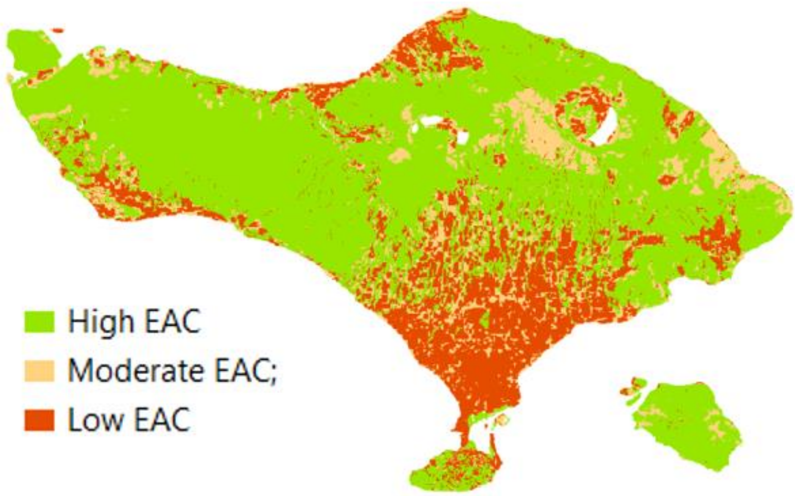

Figure 9 Biodiversity Assimilative Capacity. Source: Data Processing Results, 2024

Air

The image displays the air assimilative capacity (EAC) across Bali Province, revealing that 53% of the area is categorized as having high air quality capacity, represented in yellow and green tones. This significant percentage indicates that the province has a strong ability to absorb air pollutants, thereby maintaining good air quality and minimizing health risks related to air pollution for both residents and visitors. However, regions with low EAC are primarily concentrated in the southern part of the island, particularly in urbanized areas such as Denpasar and Kuta. These densely populated locations face challenges related to traffic congestion, industrial activities, and tourism, leading to increased levels of air pollution and posing potential health risks. Addressing these challenges through effective environmental management strategies will be essential to sustain air quality across Bali.

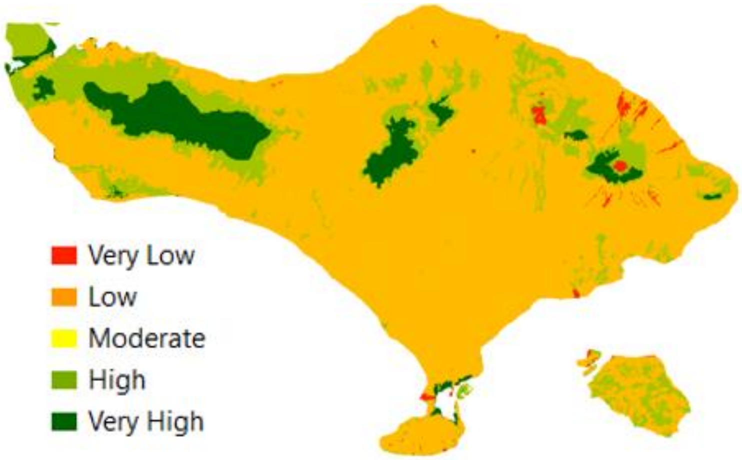

Figure 10 Air Assimilative Capacity. Source: Data Processing Results, 2024

Ocean

The southern coastal waters of Bali Province exhibit a lower Environmental Assimilative Capacity (EAC) compared to other regions, indicating a diminished ability to absorb and neutralize pollutants. This reduced capacity is attributed to the detection of pollutants at consistent depths along the coastline, signifying a pervasive distribution of contaminants in these marine areas. Notably, the southern coastlines, encompassing areas such as Kuta, Seminyak, and Canggu, face significant pollution challenges, particularly from plastic waste and urban runoff (Siddharta, 2019). In contrast, the northern and eastern coasts, which are less developed and more rural, tend to have higher EAC levels, benefiting from relatively pristine conditions and robust natural filtration systems.

Mangrove ecosystems, vital for coastal health, are present in both heavily and sparsely populated areas of Bali. However, their health varies; mangroves near urbanized regions like Denpasar are often degraded due to pollution and land-use changes, while those in less developed areas remain relatively healthy (Sugiana, 2022). The condition of mangroves directly influences the EAC of coastal waters, as healthy mangroves enhance water quality through nutrient cycling and sediment trapping, thereby bolstering the environment's capacity to assimilate pollutants.

Environmental Assimilative Capacity

The table highlights the environmental status of key potentially renewable natural resources, revealing that freshwater is the most vulnerable, with moderate pollution, low ecosystem services, and a low capacity to absorb pollutants. Arable land, while also moderately polluted, has a moderate capacity to support ecosystem services and process pollutants. Biodiversity, air, and ocean resources are in better condition, showing high environmental assimilative capacity and ecosystem services, though moderate pollution levels could pose future risks. Overall, the data suggests that freshwater systems need the most urgent attention, while ongoing monitoring of pollution in other areas is crucial for long-term sustainability.

Table 2 Results of The Category Class of Each Level of Assimilative Capacity of Each Potentially Renewable Natural Resource.

Potentially Renewable Natural Resources	Fresh Water	Arable Land	Biodiversity	Air	Marine
Pollutant Index	Moderately Polluted	Moderately Polluted	Moderately Polluted	Lightly Polluted	Moderately Polluted
Ecosystem Services Index	Low	Moderate	High	Moderate	High

Potentially Renewable Natural Resources	Fresh Water	Arable Land	Biodiversity	Air	Marine
Environmental Assimilative Capacity	Low	Moderate	High	High	High

Source: Data Processing Results, 2024

The radar chart provides a visual comparison between the Pollution Index (represented in black) and the Ecosystem Services Index (represented in green) across five key resources: Fresh Water, Air, Arable Land, Biodiversity, and Marine environments. Each resource is assigned a weight by the Analytic Hierarchy Process (AHP), with Fresh Water weighted at 0.44, Arable Land at 0.26, Biodiversity at 0.12, Air at 0.00076, and Marine at 0.09. The chart reveals that the pollutant index for Fresh Water and Air is significantly higher than their respective ecosystem services indices, suggesting that these resources are more polluted in relation to the ecosystem benefits they provide. For Arable Land, the indices are nearly identical, indicating a balance between the pollution levels and the resource's capacity to deliver ecosystem services. In contrast, Biodiversity and Marine environments exhibit a higher ecosystem services index compared to their pollutant index, suggesting that despite some pollution, these resources continue to provide considerable ecological value.

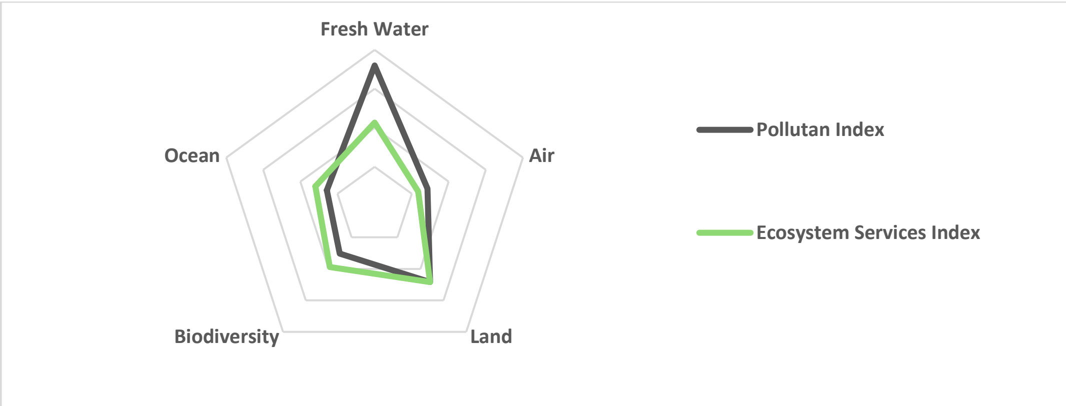

Figure 11 The radar chart provides a visual comparison between the Pollutant Index (represented in black) and the Ecosystem Services Index (represented in green) across five key resources. Source: Data Processing Results, 2024

In terms of the relationship between the pollutant index and ecosystem services index, freshwater and air show a higher pollutant index than their respective ecosystem services index. This means that these resources are more polluted than they are able to provide ecological benefits, highlighting their vulnerability and the need for intervention. For arable land, the pollutant index is equal to the ecosystem services index, indicating a balance between pollution levels and the land's ability to support agriculture and ecological functions, though both are under moderate stress. In contrast, biodiversity and ocean resources show a lower pollutant index compared to their ecosystem services index, meaning that despite some pollution, these systems continue to provide significant ecological benefits, reflecting their resilience and higher capacity to maintain ecosystem health.

3.3. Research Limitations

The primary limitation of this research lies in the fact that environmental assimilative capacity calculations were not based on direct pollutant samples but instead relied on aggregated and interpolated data. Additionally, the monitoring points are limited and concentrated mainly in industrial areas, which has led to elevated pollutant index values in both industrial and residential zones. Furthermore, when assessing air and water resources, important factors such as water currents, wind direction, and their interactions with air and freshwater were not considered. In terms of biodiversity, the study needs a specific approach to address its role in natural resource management. Since pollutant absorption varies across species, the differing capacities of species to absorb pollutants should have been considered. This omission could impact the accuracy of the assimilative capacity assessment at the ecosystem level.

4. Conclusion

4.1. Broader Project Impact

This research highlights the potential for reducing pollution, enhancing ecosystems, and fostering climate resilience through sustainable practices. By promoting green infrastructure and integrating environmental assimilative capacity assessments, Indonesia can better manage urbanization and protect ecosystems. Additionally, education and behavior change initiatives can empower communities to adopt eco-friendly practices, reducing waste and pollution. These efforts build social capital, equipping communities to adapt to climate change while fostering a healthier environment and enhancing resilience against environmental stresses.

4.2. Next Development

Data capital and the development of calculations enhance integrated water management systems, waste management, and water recycling systems for adaptive management. Field data play a crucial role in adaptive management by informing the implementation of green infrastructure and optimizing integrated water management, waste management, and water recycling systems to improve ecosystem services. Data capital is essential in optimizing resource allocation in waste management practices by leveraging advanced analytics and real-time data. This integration not only strengthens decision-making processes but also assures more efficient operations, instilling confidence in the system.

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