JMarPT
Journal of Marine Problems and Threats
IASSSF 2(1): 63-80
ISSN 3048-037X

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Ecosystem management analysis study in tourist villages

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Received Date: October 08, 2024 Revised Date: February 01, 2025 Accepted Date: February 27, 2025

ABSTRACT

Background: Arborek Island (8.2 ha), within Raja Ampat's Dampier Strait Marine Protected Area, is a global hub for community-based marine ecotourism and rich biodiversity. Surging tourism imposes acute socio-ecological pressures on fragile habitats and threatened megafauna (*Mobula alfredi*, *Chelonia mydas*), exposing vulnerabilities inherent to small-island systems. **Methods**: This study develops an empirical spatial-ecological and polycentric governance framework, combining multi-criteria GIS overlay (1:25,000) of infrastructure and statutory forest designations with a micro-spatial threat matrix. The approach integrates Diver Carrying Capacity (DCC) modeling, propeller-wash evaluation, and governance benchmarking across Dampier Strait communities and international destinations (Apo, Sipadan, Palau, Great Barrier Reef). **Findings:** Spatial analysis reveals a spatial-institutional dichotomy: Arborek's terrestrial core (5.4 ha; 65.8%) is classified as Protected Forest (HL), while its shoreline and reef flat (2.8 ha; 34.2%) fall under Nature Reserve/Nature Tourism Sea Forest (HSAW). All 10 homestays and dive facilities cluster along the coastal margin, encroaching on the HSAW fringe. Uncontrolled vessels—propeller cavitation and anchor dragging within 50 m of shore at depths below 1.5 m, damage *Acropora* and resuspend sediments, while diver congestion during slack water disrupts manta ray cleaning and courtship. Absent decentralized wastewater treatment allows nutrient percolation through carbonate sands, triggering macroalgae blooms, and open waste burning releases toxic residues intertidally. Benchmarking shows customary tenure (*Sasi Laut*) alone is insufficient without statutory enforcement and infrastructure support. **Conclusion**: Island resilience requires hybrid, polycentric governance: offshore mooring buoys, a 4:1 diver-to-guide ratio, decentralized subsurface biofilters, and codification of *Sasi* into binding Village Regulations (*Peraturan Kampung*). Integrating ridge-to-reef policies across KLHK and KKP/BLUD is essential to achieving Target 3 of the Kunming-Montreal Biodiversity Framework. **Novelty/Originality of this article:** First empirical ridge-to-reef governance model resolving institutional overlaps between forestry decrees, marine spatial planning, and customary tenure in small-island ecotourism.

KEYWORDS: polycentric governance; ridge-to-reef; Raja Ampat; small-island ecotourism; carrying capacity.

1. Introduction

The Coral Triangle, spanning six sovereign nations across the Indo-Pacific (Indonesia, Malaysia, the Philippines, Papua New Guinea, Solomon Islands, and Timor-Leste), constitutes the global epicenter of marine biodiversity, harboring over 76% of all known scleractinian (stony) coral species, 37% of the world's coral reef fish taxa, and the most expansive mangrove and seagrass ecosystems on Earth (Allen & Erdmann, 2012; Burke et al., 2012; Spalding et al., 2021; Souter et al., 2020). Within this oceanic corridor, the Raja Ampat Archipelago in the Southwest Papua Province of Indonesia represents the global apex of marine richness, documented to support over 1,500 species of reef-associated fish,

Cite This Article:
Istiqomah, M. (2025). Ecosystem management analysis study in tourist villages. *Journal of Marine Problems and Threats, 2*(1), 63-80. https://doi.org/10.61511/jmarpt.v2i1.2025.3914

553 species of scleractinian corals (representing roughly 75% of global coral diversity), and critical migratory corridors and foraging habitats for globally threatened marine megafauna, including the reef manta ray (*Mobula alfredi*), the oceanic manta ray (*Mobula birostris*), dugongs (*Dugong dugon*), and multiple species of marine turtles (*Chelonia mydas*, *Eretmochelys imbricata*) (Mangubhai et al., 2012; BLUD UPTD Raja Ampat, 2024; Setyawan et al., 2022). Over the preceding three decades, rapid paradigm shifts in marine conservation moved policy frameworks in developing nations away from centralized, exclusionary "fortress conservation" models toward decentralized Community-Based Ecotourism (CBE) and collaborative Marine Protected Area (MPA) networks (Scheyvens, 1999; Wearing & McDonald, 2022; Hampton & Jeyacheya, 2020; Bennett et al., 2021). Ecotourism has been vigorously promoted by international development agencies, national governments, and non-governmental conservation organizations as an optimal win-win governance mechanism capable of generating sustainable, non-extractive livelihoods for coastal indigenous communities while simultaneously disincentivizing destructive artisanal fishing methodologies such as blast fishing, sodium cyanide application, shark finning, and over-harvesting of reef herbivores (Gössling et al., 2021; Mangubhai et al., 2012; Wilson et al., 2010).

Arborek Village (*Kampung Arborek*), a small Holocene sand cay spanning approximately 8.2 hectares located in the core channel of the Dampier Strait Marine Protected Area within Meos Mansar District, serves as the flagship archetype of this ecotourism transition. Historically dependent on subsistence reef gleaning, shark longlining, and artisanal net fishing, Arborek pioneered community-based marine ecotourism in the early 2000s under the facilitation of conservation non-governmental organizations and local customary leadership. This initiative culminated in the village's formal governmental ratification as an official Tourism Village (*Kampung Wisata*) in 2015 and subsequent high-profile national recognition during the 2021 Indonesian Tourism Village Award (*Anugerah Desa Wisata Indonesia*/ADWI), where Arborek was awarded honors in the "Developing" (*Berkembang*) category by the Ministry of Tourism and Creative Economy (Kementerian Pariwisata dan Ekonomi Kreatif, 2021). The global reputation of Arborek is built upon an exceptional concentration of micro-spatial marine biodiversity paired with authentic Papuan cultural traditions. The waters immediately surrounding the village—particularly the Arborek Jetty and the contiguous Manta Sandy and Manta Ridge marine corridors—host globally famous cleaning stations where resident reef manta rays aggregate to be serviced by cleaner wrasses (*Labroides dimidiatus*). Terrestrially, the community maintains ancestral cultural practices, notably the artisanal weaving of sea pandanus (*Pandanus tectorius*) into traditional hats (*Topi Manta*) and mats, providing direct cash income to women's cooperatives (Gustiarani, 2022).

Despite these socio-economic successes, the rapid escalation of tourism infrastructure, motorized vessel transits, and dive operations has introduced severe socio-ecological trade-offs. Small-island socio-ecological systems (SES) are characterized by acute biophysical and structural vulnerabilities that distinguish them fundamentally from mainland or high-island ecosystems (Poonian et al., 2010; Parris, 2016; MacNeil et al., 2019; Carl et al., 2021). First, with a total land area of just 8.2 hectares, there are no internal buffer zones or spatial safety margins to absorb infrastructure growth or waste loads. Second, small sand cays rely entirely on fragile unconfined freshwater lenses (*Ghyben-Herzberg Lenses*) floating above denser marine saltwater, where rapid freshwater abstraction for tourism homestays creates localized drawdown cones, inducing upconing and irreversible saline intrusion. Third, due to tight ridge-to-reef hydrological coupling and the absence of surface rivers, riparian buffers, or thick soil layers, any chemical, biological, or physical pollutant introduced on land transits through porous carbonate sand substrates into the coastal intertidal reef flat within hours. Fourth, because sand cays are dynamic, unconsolidated geological formations held together by surrounding fringing coral reefs and beach vegetation (*Terminalia catappa*, *Scaevola taccada*), coral degradation directly undermines natural wave attenuation, exposing the island to catastrophic coastal erosion and storm surges. In Arborek, the convergence of uncontrolled shallow-water speedboat anchoring, intensive recreational scuba diving exceeding localized carrying capacities, unmanaged coastal domestic wastewater discharge, and open-air municipal solid waste burning generates cumulative ecological degradation that threatens the very biophysical capital upon which the local tourism economy is founded (King, 2017; Hukom et al., 2018; Giglio et al., 2020).

Underlying these direct biophysical stressors is a profound structural driver: institutional, regulatory, and spatial fragmentation across multiple levels of governance. In Indonesian natural resource administration, terrestrial land-use allocation under the Ministry of Environment and Forestry (*Kementerian Lingkungan Hidup dan Kehutanan*/KLHK) operates within statutory silos that are legally and operationally disconnected from Marine Spatial Planning (*Rencana Zonasi Wilayah Pesisir dan Pulau-Pulau Kecil*/RZWP-3-K) administered by the Ministry of Marine Affairs and Fisheries (*Kementerian Kelautan dan Perikanan*/KKP) and the regional MPA management authority (*Badan Layanan Umum Daerah Unit Pelaksana Teknis Daerah*/BLUD UPTD Raja Ampat) (Agardy et al., 2011; Santos et al., 2021; Republic of Indonesia, 2023, 2024). Furthermore, traditional indigenous tenure systems (*Sasi Laut*), though constitutionally recognized and culturally respected, often lack explicit legal harmonization with statutory spatial decrees, resulting in enforcement ambiguities when external commercial dive operators and day-trip vessels enter village waters (Mangubhai et al., 2012; Sterling et al., 2020).

Previous academic studies on Arborek Island have predominantly examined isolated dimensions, such as architectural typologies and building vernaculars of community homestays (Gustiarani, 2022), general socio-economic community empowerment and livelihoods (Hadiwijoyo, 2012), or baseline ichthyological surveys and reef fish biodiversity checklists (Hukom et al., 2018). There is an acute lack of integrated, multi-disciplinary research analyzing how national statutory forestry decrees, including Protected Forest (*Hutan Lindung,* HL) and Nature Reserve and Nature Tourism Forest (*Hutan Suaka Alam dan Wisata*, HSAW), intersect with micro-scale marine tourism disturbances, diver carrying capacities, coastal hydrodynamics, and customary governance institutions (*Sasi*). The absence of a quantified ridge-to-reef carrying-capacity model leaves local leaders and MPA managers without actionable, empirical tools to balance conservation mandates with tourism development.

To resolve this critical empirical and policy gap, this study establishes an integrated ridge-to-reef spatial-ecological and governance framework to: (1) Map, quantify, and evaluate the spatial congruence between national statutory terrestrial forest designations (KLHK), baseline administrative boundaries (BIG), and actual built tourism infrastructure footprints on Arborek Island; (2) Systematically dissect the biophysical and ecological impact pathways through which marine tourism operations (boat propulsion, anchoring, diver crowding, wastewater runoff, and solid waste disposal) disrupt benthic structural integrity, water quality, and marine megafauna behavioral ecology; (3) Model quantitative Diver Carrying Capacity (DCC) and vessel density thresholds tailored specifically to Arborek's micro-spatial coral reef ecosystems; and (4) Formulate an empirical polycentric governance framework by benchmarking Arborek against adjacent tourism villages within the Dampier Strait MPA and prominent international small-island marine destinations.

2.1 Social-ecological systems (SES) and ridge-to-reef dynamics in small islands

The analytical architecture of this research is grounded in the Social-Ecological Systems (SES) framework pioneered by Ostrom (2009) and expanded by Berkes (2017), Cinner et al. (2020), and Carlisle & Gruby (2019). Under an SES paradigm, human societies and biophysical environments are viewed not as separate entities, but as tightly coupled, interacting subsystems bound by complex feedback loops, nonlinear dynamics, and structural thresholds (Ostrom, 2009; Folke et al., 2016).

In small sand cays and coral atolls with a land area under 10 square kilometers, social-ecological coupling is exceptionally tight. Small-island socio-ecological systems possess distinct structural characteristics, including severe geographic boundedness, hyperattenuated resource bases, and an absence of ecological buffer zones capable of dissipating high-intensity anthropogenic shocks (Poonian et al., 2010; Carl et al., 2021). Under the "ridge-to-reef" paradigm, the terrestrial landmass, groundwater aquifer, intertidal shoreline, and offshore fringing reefs function as a singular, indivisible biogeochemical continuum. On continental landmasses, extensive watersheds, river floodplains, estuaries, and dense soil strata provide natural mechanical filtration and prolonged water residence times, mitigating the coastal delivery of terrestrial pollutants. In direct contrast, small carbonate sand cays lack permanent surface drainage networks and thick organic soil horizons. Instead, they consist of unconsolidated biogenic carbonate sands characterized by extreme hydraulic conductivity and high permeability.

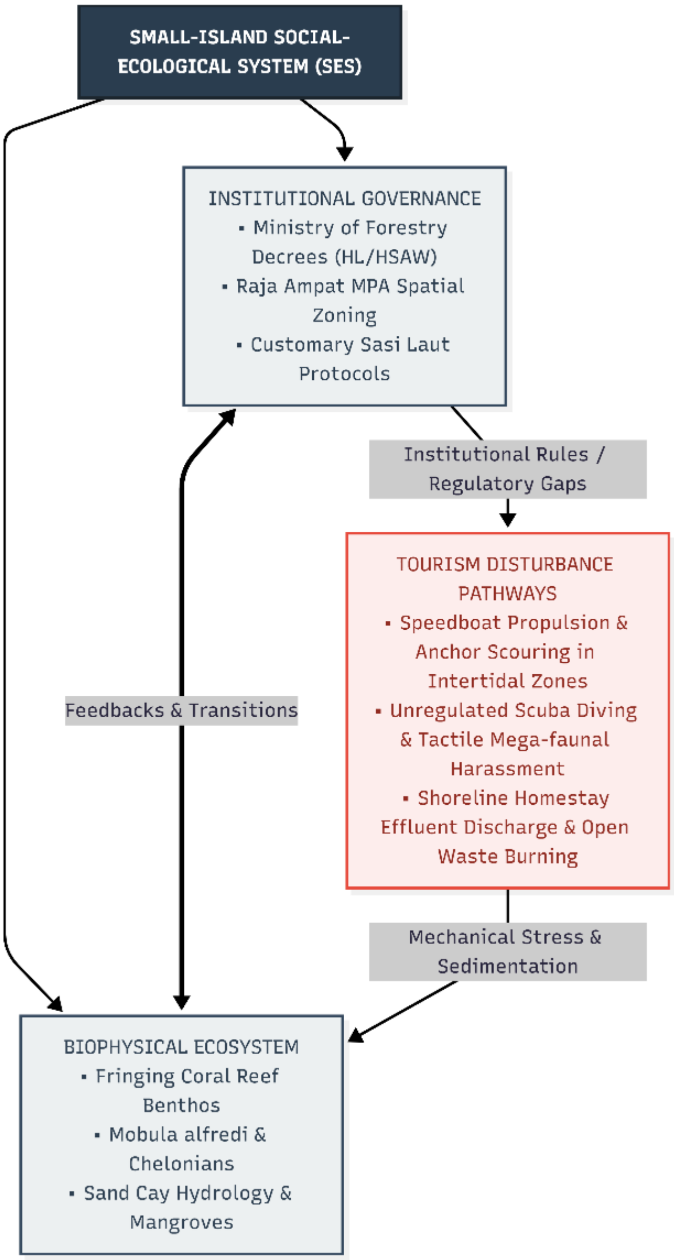

Fig. 1. Conceptual social-ecological systems (SES) framework for Arborek Island marine ecotourism

As a consequence of this hyper-permeable substrate, any anthropogenic modification occurring within the island interior produces instantaneous, direct downstream feedback upon the contiguous coral reef perimeter. Anthropogenic greywater, synthetic detergents, sewage-derived nitrates, and leachate from unmanaged solid waste do not remain sequestered within terrestrial boundaries. Rather, they transit through the shallow unconfined groundwater lens and discharge directly into the intertidal and subtidal zones via Submarine Groundwater Discharge (SGD). This tight land-sea coupling means that terrestrial tourism infrastructure expansion directly governs the biochemical and metabolic stability of the surrounding marine realm. When the recreational extraction and pollution rates surpass the biophysical regenerative thresholds of the ecosystem, the SES undergoes an ecological regime shift (Hughes et al., 2017; Bellwood et al., 2019). The system transitions from a structurally complex, calcifying, scleractinian-dominated coral reef into a degraded, macroalgae-dominated or sediment-laden rubble state characterized by depleted fisheries recruitment, collapsed tourist appeal, and impaired shoreline coastal protection.

2.2 Theoretical foundations of diver carrying capacity and benthic degradation

Recreational scuba diving has historically been promoted in conservation and tourism economics literature as a benign, non-consumptive activity that generates substantial economic revenue with minimal direct ecological impact compared to extractive artisanal fishing (Scheyvens, 1999; Hampton & Jeyacheya, 2020). However, a substantial body of empirical marine ecology and recreational management literature has firmly established that intensive diver volume exerts severe mechanical and physiological stress on benthic biogenic habitats (Hawkins et al., 1999; Poonian et al., 2010; Roche et al., 2016; Giglio et al., 2020). The mechanical impacts of recreational divers manifest across several distinct behavioral vectors (Lucrezi et al., 2019; Krieger & Chadwick, 2013); (1) Fin Strikes is Involuntary, careless, or uncoordinated fin kicks during propulsion, hovering, or rapid directional changes, which generate shearing forces capable of fragmenting fragile branching, folios, and tabular scleractinian colonies; (2) Direct Hand Touching and Grasping: Divers grabbing live coral structures to stabilize their bodies against strong tidal currents, adjust buoyancy, or steady underwater cameras during photography; (3) Knee and Body Collisions: Divers kneeling or resting directly on the reef substrate during buoyancy adjustments, equipment clearing, or group staging; (4) Equipment Dragging: Unsecured secondary regulators, submersible pressure gauges, heavy dive lights, and trailing guide lines dragging continuously across delicate benthic organisms, causing extensive abrasion to soft corals, sea fans, and sponges.

The concept of Diver Carrying Capacity (DCC) provides a theoretical framework for defining the upper limit of recreational dive activity that a specific coral reef area can accommodate over a given timeframe without incurring measurable, permanent loss of live coral cover, structural rugosity, and species diversity (Hawkins et al., 1999; Chung et al., 2018). Empirical carrying-capacity investigations across Indo-Pacific and Caribbean reef systems demonstrate that coral vulnerability to diver disturbance varies widely according to benthic composition, colony morphology, depth, and hydrodynamics. Branching morphotypes belonging to the families Acroporidae and Pocilloporidae display the lowest mechanical resistance, exhibiting catastrophic skeletal breakage thresholds when annual diver visitation exceeds moderate levels (Hawkins et al., 1999; Sumanapala & Wolf, 2020).

Conversely, massive and submassive coral colonies (such as *Porites lutea* and *faviid species*) demonstrate higher physical resistance to structural breakage from fin kicks; however, they remain highly vulnerable to sublethal physiological trauma. Repeated diver abrasion strips away the external coral mucus layer and causes mechanical epidermal lesions. These micro-abrasions disrupt the colony's natural immune defense mechanisms, creating entry vectors for virulent bacterial and fungal pathogens, which significantly increases the prevalence of coral diseases such as black band disease, white syndrome, and skeletal eroding band disease (Lamb et al., 2014; Page et al., 2019). Furthermore, dive tourism impacts are compounded by shallow-water vessel operations. Motorized speedboats operating over shallow reef flats generate hydrodynamic turbulence and severe propeller wash, which resuspends fine carbonate sediments, attenuates light penetration required for zooxanthellae photosynthesis, and directly pulverizes shallow reef crests (Erftemeijer et al., 2012; Jones, 2021).

2.3 Behavioral ecology of marine megafauna under tourism pressure

In ecotourism destinations centered on flagship species, the social-ecological carrying capacity is determined not only by benthic substrate resilience, but also by the behavioral and physiological tolerance thresholds of target marine megafauna (Setyawan et al., 2022). Arborek's marine ecotourism economy is anchored primarily by regular aggregations of the reef manta ray (*Mobula alfredi*) and foraging green sea turtles (*Chelonia mydas*). Manta rays aggregate at specific, spatially constrained patch reefs, known as cleaning stations, where they rely on specialized cleaner fishes (*Labroides dimidiatus, Thalassoma lunare*) to remove ectoparasites, clean reproductive wounds, and maintain dermal health.

Cleaning stations represent critical biophysical arenas where elasmobranchs exhibit highly ritualized, repetitive, and vulnerable behaviors (Setyawan et al., 2022). Manta rays hover at low swimming speeds, often entering a semi-quiescent metabolic state to allow cleaner wrasses access to their gill slits, oral cavities, and cephalic fins. The presence of uncontrolled recreational divers directly interferes with these essential behavioral cycles. Marine behavioral studies demonstrate that divers crowding cleaning stations, descending directly over the apex of the bommie, pursuing mantas for close-up photographs, or deploying intense artificial strobe lighting trigger acute startle-flight responses (Krieger & Chadwick, 2013; Setyawan et al., 2022).

Chronic diver-induced disturbance elevates stress hormone levels (corticosteroids) in megafauna and forces them to prematurely abandon shallow cleaning stations. Repeated displacement from cleaning stations exposes elasmobranchs to higher parasite loads, compromised immunological function, and increased expenditure of metabolic energy avoiding human disturbance. Over prolonged periods, unmanaged diver pressure can cause permanent spatial displacement, leading resident megafauna populations to abandon historically stable cleaning sites for deeper, offshore pelagic environments where tourist encounters are impossible, thereby undermining the foundational attraction of the local ecotourism economy.

2.4 Marine spatial planning and polycentric commons governance

Governing multi-use, cross-boundary marine environments requires sophisticated institutional arrangements capable of mediating resource competition between conservation, subsistence harvesting, and commercial ecotourism (Agardy et al., 2011; Day et al., 2019). Marine Spatial Planning (MSP) has emerged as the premier global policy tool for establishing spatial-temporal boundaries, allocating marine resource access rights, and separating incompatible maritime activities to minimize ecological conflict (Santos et al., 2021). However, in archipelagic nations like Indonesia, the practical implementation of MSP is complicated by overlapping statutory jurisdictions and multi-tiered legal frameworks: (1) Terrestrial Forest Law (Law No. 41 of 1999 and Law No. 6 of 2023), grants the Ministry of Environment and Forestry (KLHK) jurisdiction over state forest zones, including Protected Forest (*Hutan Lindung*/HL), strictly prohibiting commercial conversion to protect soil stability and hydrology (Republic of Indonesia, 2023); (2) Biodiversity and Ecosystem Conservation Law (Law No. 5 of 1990 and Law No. 32 of 2024), governs Nature Reserves and Nature Tourism Sea Forests (*Hutan Suaka Alam dan Wisata*/HSAW), establishing strict preservation mandates over critical habitats and endangered fauna (Republic of Indonesia, 2024); (3) Coastal Zone and Small Islands Management Law (Law No. 27 of 2007 and Law No. 1 of 2014): Grants the Ministry of Marine Affairs and Fisheries (KKP) and provincial governments authority over marine spatial zoning (RZWP-3-K) from the coastline out to 12 nautical miles; (3) Customary Law and Indigenous Marine Tenure (*Sasi Laut*), traditional community-based institutions practiced across eastern Indonesia, characterized by periodic closures of marine territories enforced through customary councils (*Lembaga Adat*) and spiritual sanctions to allow invertebrate stocks to recover (Mangubhai et al., 2012; Cohen & Steenbergen, 2015; Sterling et al., 2020).

Traditional common-pool resource theory demonstrated that neither top-down state-dominated regulation nor completely privatized free-market mechanisms can effectively manage complex, dynamic ecological systems (Ostrom, 2009, 2010). Centralized state agencies frequently suffer from severe informational deficits, lack local monitoring capacity, and fail to establish community legitimacy in remote archipelagic regions. Conversely, isolated customary governance institutions (*Sasi*) often struggle to manage modern external pressures, such as high-speed commercial dive boats, transnational liveaboard fleets, and plastic packaging waste.

To overcome these institutional vulnerabilities, modern commons theory emphasizes Polycentric Governance—a nested institutional architecture where multiple autonomous governing authorities at different spatial and legal scales (village governments, customary councils, regional MPA management units, and national ministries) interact to co-produce, monitor, and enforce rules within a unified domain (Ostrom, 2010; Carlisle & Gruby, 2019; Morrison et al., 2019). In a polycentric system, local customary norms are formally codified into statutory village regulations (*Peraturan Kampung*), while higher-level state agencies provide technical data, logistical patrol support, and legal backing, creating an adaptable, resilient institutional framework capable of resolving small-island ridge-to-reef governance dilemmas.

2. Method

2.1 Study area and environmental setting

This empirical investigation was conducted on Arborek Island (00°33′44′′ S, 130°31′18′′ E), situated in Meos Mansar District, Raja Ampat Regency, Southwest Papua Province, Indonesia. Arborek is an 8.2-hectare Holocene sand cay resting on an extensive carbonate fringing coral reef platform within the Dampier Strait. The Dampier Strait is a high-energy ocean channel connecting the western Pacific Ocean to the Seram and Halmahera Seas. It is characterized by strong semidiurnal tidal currents (frequently reaching velocities of 4 to 6 knots) that drive massive upwellings of cold, nutrient-rich water. These hydrodynamics sustain exceptional pelagic and benthic marine biodiversity, supporting dense planktonic communities that attract filter-feeding elasmobranchs (Mangubhai et al., 2012; BLUD UPTD Raja Ampat, 2024). The island experiences an equatorial marine climate with two distinct monsoon periods: the Southeast Monsoon (May to September), characterized by strong surface winds and choppy seas, and the Northwest Monsoon (November to March), characterized by calm sea states, high underwater visibility, and peak international tourist arrivals.

2.2 Geospatial multi-criteria data processing

Spatial data layers were processed using ArcGIS 10.8 (ESRI) through a systematic multi-tier protocol (Fig. 2). **Data Acquisition -** shapefiles (.shp) of administrative boundaries (village and district) were retrieved from the Indonesian Geospatial Information Agency (*Badan Informasi Geospasial*/BIG, 2020) at 1: 25,000 scale. Topographic and infrastructure layers (roads, paths, coastlines) were derived from OpenStreetMap (OSM, 2020). Forest zone boundaries were obtained from the Ministry of Environment and Forestry (KLHK, 2020) decree maps. **Topological Cleansing and Projection -** All spatial datasets were projected into the Universal Transverse Mercator (UTM) coordinate system (Zone 52S, WGS 1984 datum) to ensure metric precision. **Spatial Overlay and Intersection - m**ulti-criteria topological intersections were executed between the administrative village polygon, the built infrastructure footprint, and the statutory HL/HSAW forest polygons. This enabled the exact spatial quantification of land-use overlap with statutory conservation boundaries.

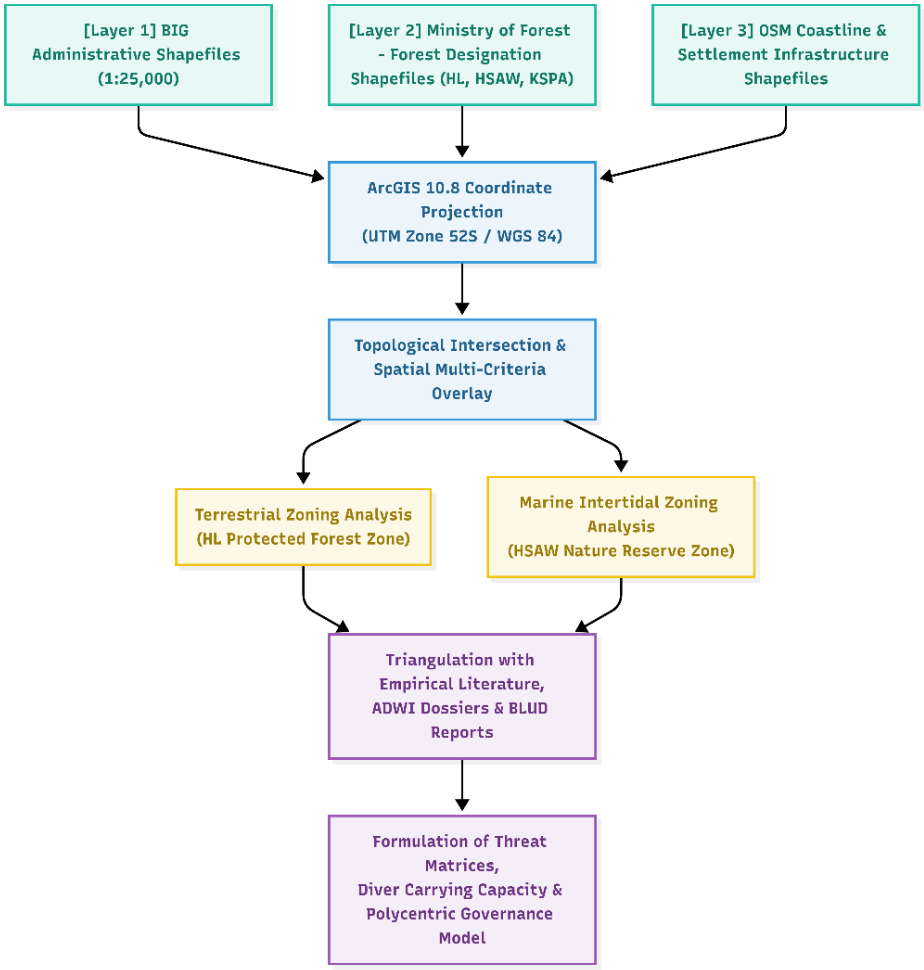

Fig. 2. Methodological and spatial overlay workflow diagram.

2.3 Qualitative triangulation and ecological synthesis

To evaluate biophysical impacts, a qualitative triangulation protocol was executed (Creswell & Creswell, 2018). Primary administrative dossiers from the Indonesian Tourist Village Award (ADWI 2021) were analyzed across 5 core dimensions: Attractions, Amenities, Digitalization, Institutions/HR, and Resilience. Ecological monitoring data from BLUD UPTD Raja Ampat (2024) and published empirical marine studies (Hukom et al., 2018; Wilson et al., 2010; King, 2017) were synthesized to determine fish biodiversity, live coral cover (LCC), and megafauna disturbance patterns. A structured threat matrix and international comparative framework were developed to benchmark Arborek's governance performance against global small-island ecotourism destinations.

3. Results

3.1 Spatial congruence analysis of terrestrial and marine designations

3.1.1 Terrestrial core (protected forest/hutan lindung-HL*)*

Encompasses approximately 5.4 hectares (65.8%) of the island's interior. Under Law No. 41 of 1999 and Law No. 6 of 2023, this zone is strictly designated to maintain hydrological stability, protect the fragile freshwater lens, and prevent coastal sand erosion. In practice, this area contains the historic village settlement, elementary school, administrative offices, church, and groundwater wells.

3.1.2 Peripheral shoreline and intertidal flats (nature reserve and sea tourism forest/hutan suaka alam dan wisata-HSAW/KSPA)

Encompasses approximately 2.8 hectares (34.2%) of the terrestrial coastal margin, along with the contiguous intertidal sand flats, seagrass beds, and fringing coral reefs. Under Law No. 5 of 1990 and Law No. 32 of 2024, this zone is designated for pristine biodiversity preservation and regulated eco-tourism. Spatial analysis reveals that all 10 active community-operated homestays, private dive centers, and timber jetty platforms are concentrated along the immediate shoreline, directly encroaching upon the statutory HSAW conservation fringe. This built footprint places intense physical, human, and chemical pressure directly on the dynamic coastal buffer strip, leading to shoreline destabilization and direct effluent discharge into the marine intertidal zone.

3.2 Comprehensive ADWI sustainability dimension assessment

Evaluating Arborek's ecotourism model across the five core dimensions of the Indonesian Tourism Village Award (ADWI) reveals significant socio-ecological trade-offs across all sectors.

Table 1. Comprehensive assessment of arborek tourism village based on ADWI dimensions and sustainability metrics

ADWI Dimension	Baseline Field & Secondary Status in Arborek	Observed Biophysical & Operational Impact Pathways	Sustainability Status & Recommended Interventions
1.Tourist Attractions (*Daya Tarik*)	240+ documented scleractinian & ichthyofaunal species; premier cleaning station for *Mobula alfredi*; nesting green sea turtles (*Chelonia mydas*); artisanal Manta Hat weaving.	Diver crowding during peak slack water; divers chasing and touching manta rays; fin shearing on shallow branching *Acropora*.	High Ecological Pressure: Requires mandatory diver carrying-capacity limits and certified local guide ratios.
2. Amenities (*Amenitas*)	10 community-owned homestays constructed from vernacular low-carbon materials (sago palm thatch, timber frames, *bobo* leaves).	Homestays discharge untreated greywater directly into coastal sands, causing localized nutrient enrichment and macroalgal blooms on the reef flat.	Moderate/High Vulnerability: Urgent need for sub-surface gravel-sand wetland biofilters.
3. Digitalization (*Digitalisasi*)	Extensive promotion via national Kemenparekraf web portals, viral social media marketing, and 4G cellular broadband connectivity.	Rapid visitor influx without pre-booking caps or quota controls, causing seasonal tourist surges that exceed island infrastructure limits.	Ungoverned Demand: Requires integration of an online carrying-capacity booking and permit ceiling system.
4. Human Resources (*SDM & Kelembagaan*)	Active Tourism Awareness Group (Pokdarwis), high female participation in artisanal handicrafts, youth boat operators and dive guides.	Dive guides lack advanced eco-briefing training, environmental enforcement credentials, and formal dive marshal certifications.	Strong Social Capital: Requires formal BLUD UPTD certification for all community dive guides.
5. Resilience & Governance	Recipient of national ADWI 2021 and ISTA	*Sasi Laut* does not formally regulate	Institutional Gap: Requires formalizing

ADWI Dimension	Baseline Field & Secondary Status in Arborek	Observed Biophysical & Operational Impact Pathways	Sustainability Status & Recommended Interventions
(*Resiliensi & Tata Kelola*)	sustainable tourism honors; active practice of ancestral *Sasi Laut* resource closures.	commercial dive operators or vessel speeds; municipal solid waste is burned in open beach pits.	*Sasi* into statutory Village Regulations (*Perkam*) and establishing mainland waste logistics

3.3 Spatial-institutional conflict analysis

A detailed evaluation of statutory legal mandates versus real-world land use highlights critical institutional conflicts.

Table 2. Spatial-institutional conflict analysis of land-sea allocations on Arborek Island.

Spatial Designation	Geographic Scope on Arborek	Statutory Mandated Functions (Laws 41/1999, 6/2023, 32/2024)	Observed Ground Utilization	Spatial Conflict Severity & Biophysical Risk
Protected Forest (*Hutan Lindung* - HL)	Central terrestrial core of the sand cay (~5.4 ha).	Watershed preservation, soil stabilization, freshwater aquifer protection. Structural commercial conversion prohibited.	Compact residential dwellings, administrative structures, public gathering spaces, shallow unconfined groundwater wells.	Low–Medium Conflict: High surface stability, but rising freshwater extraction risks saline water intrusion into the unconfined aquifer.
Nature Reserve & Sea Tourism Forest (HSAW/KSPA)	Peripheral coastal margin, intertidal sand flats, and shallow fringing reefs (~2.8 ha land + contiguous sea).	Total biodiversity preservation, educational research, strictly non-destructive low-impact tourism.	10 beachfront homestays, wooden jetties, shallow speedboat anchoring, diver and snorkeler entry channels.	Critical High Conflict: Anchor dragging, vessel hull grounding, and foot traffic pulverize live branching corals in shallow waters (<2 m).
Customary Marine Tenure (*Sasi Laut*)	Inshore coastal reef waters and lagoon areas surrounding Arborek Island.	Periodic harvest closures for commercial invertebrates (*Trochus niloticus*, sea cucumbers).	Marine dive tourism and day-boat transits operate concurrently across Sasi zones; jurisdiction overlaps with state MPA patrols.	Medium Conflict: Lack of explicit legal integration between customary village sanctions and statutory MPA enforcement protocols.

3.4 Tourism-induced biophysical impact pathways

3.4.1 Pathway 1: Mechanical anchor dragging and propeller cavitation

Due to an absence of designated offshore heavy-duty mooring buoys, commercial speedboats transport tourists directly across the intertidal sand flat into the HSAW zone. During low tide (<1.5 m depth), outboard engine propellers induce heavy cavitation and bottom scouring, resuspending fine carbonate sediments that reduce Photosynthetically

Active Radiation (PAR) and smother coral polyps (Erftemeijer et al., 2012; Jones, 2021). Dropped steel anchors and swinging anchor chains pulverize fragile branching Acropora formosa and Acropora millepora colonies, transforming complex biogenic frameworks into dead coral rubble.

3.4.2 Pathway 2: Recreational scuba overcrowding and megafauna displacement

Concentrated diving around the Arborek Jetty and adjacent cleaning stations creates severe diver crowding during tidal slack water. Unregulated divers frequently touch, crowd, and use flash photography on resident reef manta rays (Mobula alfredi) and green turtles (Chelonia mydas), interrupting essential cleaning and foraging cycles and forcing megafauna to abandon shallow cleaning stations for deeper waters (Setyawan et al., 2022; Krieger & Chadwick, 2013).

3.4.3 Pathway 3: Shoreline effluent runoff and beach waste incineration

Homestays constructed along the HSAW perimeter lack centralized wastewater systems. Greywater rich in domestic surfactants and nitrogenous compounds percolates directly through highly permeable carbonate sands into the intertidal zone, triggering localized macroalgae blooms (Dictyota, Padina) that outcompete juvenile coral recruits (Hughes et al., 2017; Lamb et al., 2014). In the absence of regular municipal waste transport to the Waisai mainland, non-organic solid waste (plastics, aluminum cans) is burned in open pits on the beach, releasing toxic ash (dioxins, heavy metals) that washes into the marine intertidal zone during high spring tides.

3.5 Discussion

3.5.1 The ridge-to-reef governance dilemma

The geospatial findings demonstrate a fundamental institutional and spatial mismatch governing Arborek Island. While the national legal framework designates the island interior as Protected Forest (HL) and its coastal periphery as Nature Reserve (HSAW), these statutory designations remain largely "paper parks" on the ground (Agardy et al., 2011; Day et al., 2019; Republic of Indonesia, 2023, 2024). Spatial designation alone cannot safeguard marine biodiversity when operational carrying capacities and terrestrial-marine linkages are ignored (Santos et al., 2021). The central challenge facing Arborek is micro-spatial saturation: an 8.2-hectare sand cay accommodating accelerating day-tripper volumes without physical zoning barriers between tourism infrastructure and fragile marine habitats.

3.5.2 Comparative analysis: Across Raja Ampat tourism villages

Evaluating Arborek alongside neighboring tourism villages in the Dampier Strait highlights diverse governance responses to ecotourism pressures.

Table 3. Comparative Governance Matrix Across Raja Ampat Tourism Villages

Tourism Village	Focal Ecotourism Assets	Statutory Zoning & Governance Mechanism	Dominant Biophysical Challenges	Transferable Best Practices
Arborek Village (Meos Mansar)	Manta cleaning stations, jetty reef biodiversity, artisanal Manta Hat weaving.	National Forestry Decrees (HL/HSAW), Customary *Sasi Laut*, ADWI Developing status.	Speedboat anchor damage, diver crowding, beach open-pit waste incineration.	Exceptional community pride, proactive youth tourism group (Pokdarwis), strong cultural identity.

Tourism Village	Focal Ecotourism Assets	Statutory Zoning & Governance Mechanism	Dominant Biophysical Challenges	Transferable Best Practices
Sawinggarai Village (Meos Mansar)	Red Bird of Paradise (*Paradisaea rubra*) display leks, coastal reef walls.	Terrestrial Conservation Forest, Village Customary Land Decrees.	Trail erosion, canopy noise disturbance from unguided wildlife photography tours.	Highly structured eco-guiding codes; strict dawn/dusk bird-watching timetables and quiet zones.
Saukabu Village (Waigeo Barat)	Mangrove blue river lagoons, coastal artisanal fisheries, orchids.	Mangrove Conservation Buffer, Raja Ampat MPA Network Zoning.	Siltation from inland runoff, localized mangrove harvesting for jetty construction.	Community-managed mangrove nursery; elevated boardwalks minimizing ground root compaction.
Yenbuba Village (Mansuar Island)	Deep reef wall drop-offs, giant clam (*Tridacna*) gardens, cape currents.	Dampier Strait MPA Marine Sanctuary, Church-Led Customary *Sasi*.	Current-induced diver drift collisions with coral tables; liveaboard anchoring.	Mandatory permanent mooring buoys; strict prohibition of motorized boat propellers near the jetty.

3.5.3 International benchmarking: Comparative small-island marine ecotourism

Benchmarking Arborek against global small-island marine destinations reveals proven governance and management strategies:

Table 4. International benchmarking: Comparative governance in global marine ecotourism destinations

Destination/Nation	Marine Ecological Setting	Governance & Statutory Structure	Operational Carrying Capacity & Management Tools	Ecological Outcomes & Key Lessons for Arborek
Apo Island, Philippines *(Cadiz & Calumpong, 2020)*	Volcanic island, community marine reserve, fringing coral reefs.	Community-Based Coastal Resource Management (CBCRM) integrated with national NIPAS legislation.	Strict No-Take Marine Sanctuary covering 10% of the reef; diver quotas (maximum 15 divers/zone/day); mandatory local guides.	Multi-decadal recovery of target predatory fish biomass; continuous local revenue generation via dive user fees.
Sipadan Island, Malaysia *(Musa, 2002; Hampton & Jeyacheya, 2020)*	Oceanic pinnacle island, world-class pelagic shark and turtle aggregations.	Centralized state-controlled total ban on island accommodations; Sabah Parks MPA permit quotas.	Total visitor permit ceiling (strictly capped at 120–176 permits/day across all operators); offshore/liveaboard lodging only.	Complete elimination of island aquifer extraction and sewage contamination; absolute protection of turtle nesting beaches.
Palau, Micronesia *(Poonian et al., 2010; Carlisle & Gruby, 2019)*	Limestone archipelagic islands, iconic manta cleaning	National Marine Sanctuary; mandatory Palau Pledge; tourist	Pre-arrival conservation briefings; mandatory 3-meter approach limits for	Exceptional compliance with marine megafauna codes of

Destination/Nation	Marine Ecological Setting	Governance & Statutory Structure	Operational Carrying Capacity & Management Tools	Ecological Outcomes & Key Lessons for Arborek
	stations and blue holes.	environmental impact fees.	mantas; total ban on reef-toxic chemical sunscreens.	conduct; sustainable conservation financing via green tourist fees.
Great Barrier Reef, Australia *(Day et al., 2019; Giglio et al., 2020)*	World's largest barrier reef system, multi-use marine park.	Multi-tiered statutory Marine Spatial Planning (MSP) enforced by federal authority (GBRMPA).	Mandatory commercial operator tourism permits; designated public/private mooring buoy grids; real-time vessel monitoring.	Effective spatial segregation between recreational and preservation zones; zero anchor damage at buoy-equipped reef sites.

3.6 Synthesis of strategic interventions for Arborek Island

Benchmarking against regional and international models yields three clear strategic imperatives: (1) Physical Mooring Infrastructure (Lessons from Yenbuba & Great Barrier Reef). Physical anchor damage can be eliminated entirely through the installation of heavy-duty, permanent offshore mooring buoys (Giglio et al., 2020; Day et al., 2019). Installing a 4-buoy mooring perimeter off Arborek's western reef would keep motorized speedboats outside the fragile intertidal coral zone; (2) Operational Ratios and Diver Carrying Capacity (Lessons from Apo Island & Palau). Diver mechanical damage and megafauna avoidance behavior decline dramatically when strict operational ratios and behavioral codes are enforced (Cadiz & Calumpong, 2020; Carlisle & Gruby, 2019). Arborek must enforce a mandatory 4:1 diver-to-guide ratio, cap total daily divers at primary sites to under 40 divers/day, and institute a strict 3-meter minimum distance rule around Mobula alfredi; (3) Accommodation Ceilings and Wastewater Biofilters (Lessons from Sipadan). Over-densification of accommodations on tiny sand cays inevitably depletes freshwater aquifers and contaminates coastal waters (Musa, 2002). Arborek should freeze homestay capacity at the current 10 units, require all homestays to install decentralized sub-surface gravel-sand wetland biofilters for greywater purification, and establish a bi-weekly solid waste export run to the Waisai mainland recycling depot.

3.7 Institutionalizing polycentric governance (Sasi Laut + MPA legislation)

To make these interventions lasting and enforceable, Arborek must adopt a polycentric governance architecture (Fig. 6) linking traditional customary authority (*Adat*) with state legislation (Ostrom, 2010; Morrison et al., 2019): (1) Enacting Village Regulations (*Peraturan Kampung/Perkam*), the Arborek Village Government (*Pemerintah Kampung*) and Customary Council (*Lembaga Adat*) must formalize ancestral *Sasi Laut* principles into statutory *Perkam*. This regulation will legally establish diver carrying capacities, speed limits within 100 meters of the reef, mandatory guide ratios, and homestay wastewater standards; (2) Community Warden Empowerment (*Masyarakat Mitra Polhut/Pokdarwis*), local village youth must receive formal training and legal deputization as community conservation wardens, authorized to conduct joint marine patrols alongside regional BLUD UPTD MPA rangers; (3) Earmarked Ecotourism Reinvestment: A dedicated percentage of local village tourism entrance fees and dive levies must be ring-fenced into a village conservation fund to support scheduled mainland waste transport, buoy maintenance, and community-led coral nursery restoration.

4. Conclusions

This study demonstrates that Arborek Island's community ecotourism model operates within a fragile social-ecological equilibrium. While statutory forestry decrees classify the island's terrestrial interior as Protected Forest (HL) and its coastline as Nature Reserve Sea Forest (HSAW), micro-spatial tourism pressures—uncontrolled speedboat anchoring, high-density scuba diving, diver-megafauna contact, and unmanaged waste disposal—threaten long-term marine ecosystem health. Overcoming these challenges requires moving beyond descriptive tourism marketing to implement a polycentric ridge-to-reef governance model combining physical mooring infrastructure, decentralized wastewater biofilters, enforceable diver carrying-capacity limits, and the codification of customary *Sasi* into legally binding Village Regulations (*Peraturan Kampung*).

The findings of this study should be interpreted within the context of two primary methodological limitations: (1) Spatial analysis relied upon national 1:25,000 to 1:250,000 GIS datasets (BIG, KLHK). While sufficient for macro- and meso-scale institutional zoning analysis, these layers lack sub-meter bathymetric resolution and localized acoustic rugosity mapping; (2) Ecological disturbance mechanisms were evaluated through qualitative triangulation and secondary synthesis of long-term BLUD UPTD monitoring data, rather than multi-season in-situ underwater photo-quadrat transects and visual census surveys.

The empirical and governance insights generated from Arborek provide direct policy lessons for coastal zone management across Indonesia and global Small Island Developing States (SIDS), particularly in operationalizing Target 3 (the 30x30 Protected Area Target) of the Kunming-Montreal Global Biodiversity Framework, ridge-to-Reef Spatial Harmonization, Statutory Diver Carrying Capacity (DCC) Standards, Future Research Directions. National environmental ministries (Ministry of Environment and Forestry and Ministry of Marine Affairs and Fisheries) must dismantle administrative silos and establish unified ridge-to-reef spatial planning frameworks that legally link terrestrial forestry boundaries with coastal marine protected area zoning on small islands under 100 km^2. Regional MPA management authorities must institutionalize mandatory DCC ceilings, dynamic permitting systems, and fixed mooring buoy networks across all registered marine tourism villages nationwide. Future investigations should establish longitudinal, in-situ benthic monitoring stations (measuring annual changes in live coral cover, calcification rates, and recruit settlement) and deploy satellite/acoustic telemetry tags to quantify the fine-scale behavioral responses of *Mobula alfredi* to varying diver densities and vessel noise profiles.

Acknowledgement
The authors extend their gratitude to the local community and customary leaders (Lembaga Adat) of Kampung Arborek, the BLUD UPTD Raja Ampat Marine Protected Area management authority, and the Indonesian Geospatial Information Agency (BIG) for facilitating spatial datasets.

Author Contribution
Conceptualization, Methodology, Spatial Data Processing, Formal Analysis, Writing – Original Draft Preparation, Review & Editing: Lead Author. All authors have read and agreed to the published version of the manuscript.

Funding
This research received no external funding.

Ethical Review Board Statement

Ethical review and approval were waived for this study due to the exclusive reliance on secondary geospatial datasets, published monitoring reports, and non-invasive qualitative synthesis.

Informed Consent Statement

Not applicable for secondary spatial analysis and literature synthesis.

Data Availability Statement

Geospatial shapefiles utilized are openly accessible from the Geospatial Information Agency (BIG) and the Ministry of Forestry.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used Grammarly and OpenAI/Google language models solely for English grammar refinement, clarity enhancement, and academic style editing. The authors manually reviewed, verified, and take full responsibility for all data, analyses, and intellectual content in the manuscript.

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