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Balancing Nets and Lives: A Socio-Ecological Analysis of Sustainable Fisheries on the Indian Coast of the Gulf of Mannar

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Abstract: The Gulf of Mannar, a UNESCO World Biosphere Reserve, faces severe overfishing and habitat degradation threats. In this study, we investigate the pivotal role of ecosystem services in sustaining local livelihoods and overall well-being. By conducting a comprehensive survey of 480 respondents across two districts, we gathered extensive data on demographics, livelihoods, fishing practices, reliance on ecosystem services, and community management participation. The analysis reveals a critical dependence on the Gulf's resources (income, food security, traditions) with gender disparities (men fish, women in pre-/post-harvest). Still, fishing is only allowed in the 10 km buffer zone (not the core zone). The findings emphasize the promise of community-based strategies, such as Marine Protected Areas and reviving co-management committees, for achieving sustainable fisheries management. However, we also identify gaps, including the need for more nuanced well-being indicators and improved models for community management participation. To address these challenges, we advocate for sustainable fishing practices, tackling social inequities, especially gender disparities in resource access and decision-making, and investing in fishing communities' healthcare, education, and social safety nets. Promoting alternative livelihoods can alleviate pressure on fish stocks, and empowering local communities through capacity building and community-based management initiatives is crucial for ensuring the long-term sustainability of the Gulf of Mannar ecosystem and the well-being of its dependent communities. This multifaceted approach holds significant promise for balancing ecological health with human prosperity.

Keywords: Gulf of Mannar; sustainable fisheries management; ecosystem services; community-based strategies; gender disparities

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1. Introduction

Sustainable fisheries practices are crucial for maintaining healthy marine ecosystems, ensuring long-term economic viability for fishing communities, and contributing to global food security [1]. Unsustainable practices, however, can lead to overfishing, habitat destruction, and declining fish stocks, jeopardizing food security and livelihoods [2]. Sustainable fisheries management offers a solution by balancing resource utilization with ecosystem health [3]. The Gulf of Mannar, an inlet of the Indian Ocean, is between southeastern India and western Sri Lanka. This gulf is bordered to the northeast by Rameswaram Island, Adam's (Rama's) Bridge—a chain of shoals—and Mannar Island. The Indian port city of Tuticorin is located along the Gulf's coastline. Notably, the Gulf of Mannar is famous for

its pearl banks and the presence of the sacred chank, a species of gastropod mollusks. The Gulf of Mannar, a UNESCO World Biosphere Reserve harbors rich coral reefs, seagrass meadows, and mangroves, providing critical habitat for fish populations and supporting coastal communities [4]. However, it faces challenges like overfishing and habitat degradation. Understanding the social dimensions of sustainable fisheries is vital for effective management. Ecosystem health and fishing communities' well-being are closely related [5]. By examining these social dimensions, including gender dynamics and community-based management strategies, we can develop policies that balance ecological sustainability with socio-economic development [6].

1.1. Problem Statement

Ramanathapuram and Thoothukudi districts, located on the southeastern coast of Tamil Nadu, rely on the Gulf's marine resources for their livelihoods [7]. The region's coast is a hotspot for marine biodiversity. Fishing communities in Ramanathapuram and Thoothukudi face multiple challenges. Overfishing [8], habitat degradation [9], and climate change [10] threaten fish stocks, the mainstay of their livelihoods. Limited resources and socioeconomic factors, such as inadequate access to capital, education, and health services, as well as market limitations and policy constraints [11] further exacerbate these issues. Gender disparities, where women often have less access to resources and decision-making power, add another layer of complexity [12]. Understanding the social dimensions of sustainable fisheries is crucial. Ecosystem services [13] like fish stocks and coastal protection are vital for these communities. However, the link between these services and well-being aspects like income and social cohesion remains underexplored. This research aims to quantify these interactions using econometric models [7] to inform policy and sustainable management practices. Sustainable fisheries management requires a comprehensive approach. While fish stocks are critical, the social dimension is equally important. Fishing communities are linked to the ecosystem, and their well-being and knowledge are essential for effective resource management [14]. Studying the social dimensions involves examining economic, social, and health well-being, understanding gender dynamics, and analyzing community-based management strategies [15]. This holistic approach ensures both ecological and social sustainability are prioritized.

1.2. Research Objectives

This research aims to bridge the knowledge gap by investigating two primary questions: how do ecosystem services, impacted by ecosystem health, influence the livelihoods of local communities in the Gulf of Mannar? and what are the interactions between ecosystem services and human well-being in these regions, considering factors such as economic security, health, and social cohesion? This study will quantify the dependence of these communities on various services, such as fish stocks and coastal protection, for their livelihoods and basic needs [16]. Furthermore, we explored the intricate relationships between these services and different aspects of well-being, including economic security, health, and social cohesion [13]. By employing a quantitative approach, this research will shed light on the socio-ecological dynamics of the Gulf of Mannar fisheries. The research delves deeper by examining gender roles within these communities, specifically how gender influences access to resources and decision-making processes. Additionally, the effectiveness of community-based management strategies will be assessed, a crucial factor for the long-term sustainability of the ecosystem and local livelihoods [17]. This comprehensive understanding of the social and ecological dynamics will provide a foundation for informed policy and sustainable management practices in the Gulf of Mannar.

This paper presents a detailed analysis of the Gulf of Mannar, examining the intricate relationships between its ecosystems, socio-economic conditions, and the influence of coastal ecosystem services (CES) on human well-being.

This study begins by outlining the ecological and socio-economic characteristics of the region, emphasizing its biodiversity and the dependence of local communities on marine

ecosystems for sustenance and livelihoods. Section 2 includes a thorough description of data collection, survey design, sampling strategies, and the application of statistical techniques, such as regression models, to evaluate the link between ecosystem health, community well-being, and food security. The findings and discussion underscore the socio-economic reliance on CES, the challenges posed by unsustainable practices, and the vulnerabilities faced by coastal communities. This paper emphasizes the importance of sustainable management to mitigate these challenges. This comprehensive approach provides a nuanced understanding of the ecological and socio-economic interactions within the Gulf of Mannar region.

2. Material and Methods

2.1. Description of the Study Area

The Gulf of Mannar (Figure 1), situated between the southeastern tip of India and the west coast of Sri Lanka, is a shallow bay forming part of the Laccadive Sea in the Indian Ocean, covering an area of about 10,500 square kilometers [18]. This unique marine ecosystem, designated as a UNESCO World Biosphere Reserve, includes island, mangrove, seagrass, and coral reef ecosystems. It supports a rich biodiversity, hosting over 4000 species of flora and fauna [19]. The Gulf of Mannar Marine National Park spans 560 square kilometers. In the region comprising 21 small islands along the Tamil Nadu coast, ranging from Rameswaram Island to Tuticorin, anthropic impacts have significantly altered the natural environment. The overexploitation of natural resources, including fishing grounds and marine resources, has strained local ecosystems [20]. The loss of forest coverage due to urban expansion has been profound, with extensive clearing for residential and industrial purposes. Urban expansion itself has encroached upon natural habitats, displacing native flora and fauna. Pollution from industrial activities, urban runoff, and maritime traffic has further degraded water quality and marine biodiversity in the surrounding waters. These cumulative impacts underscore the urgent need for sustainable development practices and effective conservation measures to safeguard the ecological integrity of this fragile island ecosystem. These islands, surrounded by highly productive fringing and patchy coral reefs, serve as critical habitats for a variety of marine species, including sea cows that feed on the seagrass beds [19]. While the political borders between India and Sri Lanka are well defined by the International Maritime Boundary Line (IMBL) that cuts across the Gulf of Mannar, the fishing communities from both sides often face challenges in adhering strictly to these boundaries. Despite the legal constraints, there are instances where Indian fishers from the Ramanathapuram and Thoothukudi districts cross into Sri Lankan waters, either intentionally or unintentionally, in pursuit of better fishing grounds. Similarly, Sri Lankan fishers have been reported to cross into Indian waters. This occurs because the Gulf of Mannar is a shared ecosystem with rich marine resources, and the traditional knowledge and practices of these fishing communities often predate the demarcation of political borders. However, this reciprocal movement frequently leads to conflicts and arrests, making transboundary fishing a contentious issue between the two nations. This research, however, focuses solely on the fishing communities on the Indian side of the Gulf of Mannar, particularly in the districts of Ramanathapuram and Thoothukudi.

The socio-economic aspects of the Gulf of Mannar region are heavily influenced by these ecosystems. Ramanathapuram and Thoothukudi districts, located on the southeastern coast of Tamil Nadu, rely on the Gulf's marine resources for their livelihoods [21].

Ramanathapuram's small-scale fisheries play a vital role in local livelihoods but face numerous challenges, including declining fish stocks and limited access to modern technology like sonar, advanced vessels, and storage facilities, which hinders their efficiency in terms of catch volume, safety, and time management [11]. The fishing community in Ramanathapuram is substantial, with around 47,000 active fishers engaged in small-scale fishing operations. In 2019, the district's fish landings were recorded at approximately 85,000 tons annually, primarily consisting of species such as sardines, mackerel, and prawns.

However, due to technological and infrastructural gaps, the productivity of small-scale fisheries is significantly lower compared with larger, industrial fisheries.

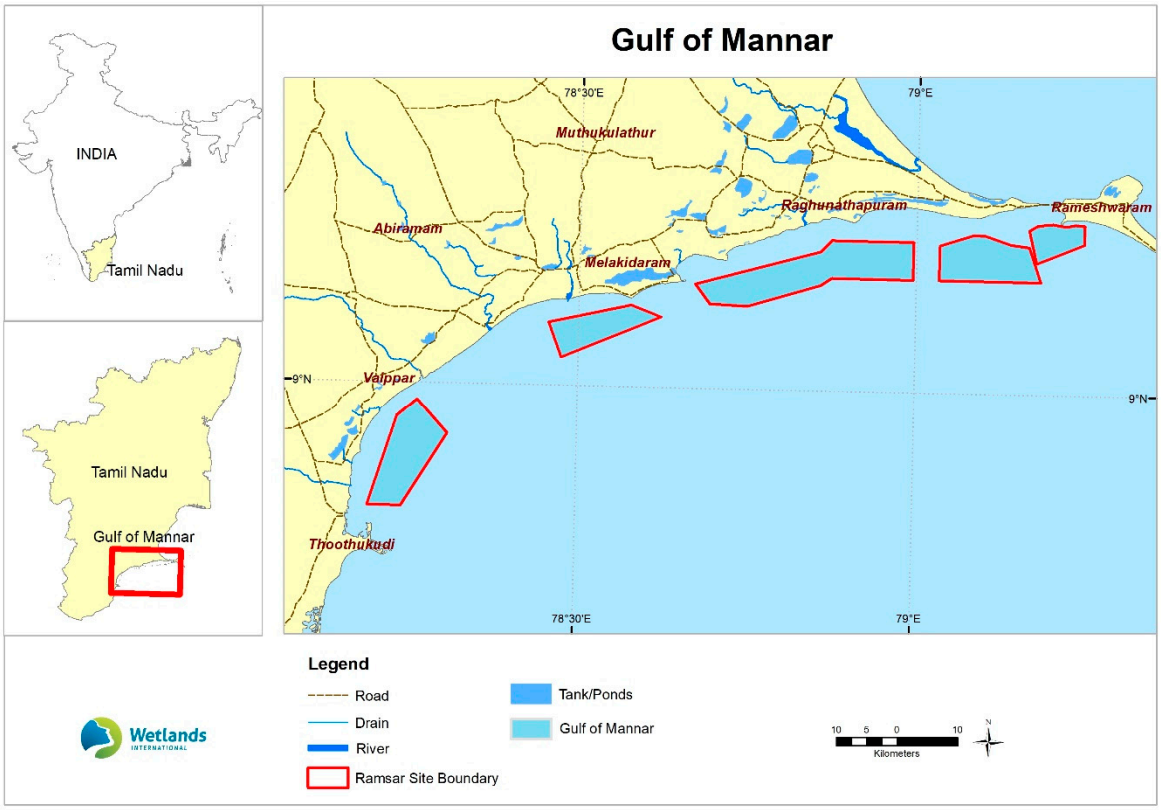

Figure 1. Detailed Map of the Gulf of Mannar Islands (Tamil Nadu, India). Source: Ramsar Sites Information Service.

The types of fisheries practiced in the region include both artisanal and mechanized methods. Artisanal fishers primarily use traditional boats like catamarans and small trawlers, which limit their capacity to venture into deeper waters. In contrast, mechanized fisheries, though fewer in number, dominate in terms of catch volume due to their larger vessels and better equipment. The main fishing categories include pelagic species (e.g., sardines and mackerel), demersal species (e.g., snappers and groupers), and shellfish (e.g., prawns and crabs). Artisanal fisheries are crucial for local consumption and the livelihood of coastal communities, while mechanized fisheries cater more to the broader national and export markets.

Despite their significance, these small-scale fishers struggle against competition from larger fisheries and market limitations related to quality control and access to lucrative markets, especially for export-grade fish. The mechanized sector, with its larger boats and modern gear, catches a disproportionately larger share of the marine resources, exacerbating the struggles faced by small-scale fishers in the region [4]. This dynamic continues to challenge the sustainability of both fisheries and local livelihoods.

In contrast, Thoothukudi, an industrial hub and major port city, hosts a more mechanized fishing sector compared with Ramanathapuram, but this sector faces significant pressures from pollution and overfishing. The fishing community in Thoothukudi is sizable, with over 25,000 active fishers working primarily in mechanized fisheries [4]. The district's total annual fish landings were recorded at around 115,000 tons in 2020, with a significant portion of the catch coming from mechanized trawlers and deep-sea vessels. Major fish species include ribbonfish, cuttlefish, and squid, alongside a variety of demersal and pelagic species.

Thoothukudi's fishing practices are more diversified, with mechanized fisheries accounting for approximately 70% of the total catch. These fisheries primarily use trawl nets, purse seines, and gillnets, with a focus on both local consumption and export markets. The mechanized sector benefits from better access to technology, including sonar and refrigeration systems, which allows them to fish further offshore and store their catch for longer periods. Artisanal and small-scale fishers, though fewer in number compared with Ramanathapuram, still play a critical role in the local fishing economy, primarily targeting coastal species like sardines and mackerel.

However, the industrialization of the port city has introduced challenges, such as increased marine pollution from industrial discharges and port activities, leading to the degradation of coastal waters. Overfishing is another significant issue, with mechanized trawlers depleting fish stocks faster than they can regenerate, which in turn impacts the livelihoods of small-scale fishers who depend on inshore fisheries. This overexploitation has led to a decline in key species like prawns and cuttlefish, which have seen a drop in catch volumes over the past decade [22].

The intricate connection between the health of marine ecosystems and the socio-economic conditions of these coastal communities underscores the importance of sustainable fisheries management. Fishing communities in Ramanathapuram and Thoothukudi rely on ecosystem services for food security, economic stability, and cultural practices [23]. Understanding the interactions between ecosystem services and human well-being in these districts is essential for developing strategies that support both ecological conservation and community livelihoods [9].

2.2. Demographic and Socio-Economic Profile

Fishing is the primary economic activity, with Ramanathapuram characterized by small-scale fisheries and trawlers (Figure 2) and Thoothukudi featuring a more industrialized sector, supported by a major port [24]. While both districts benefit from aquaculture, concerns about sustainability and social equity arise [21]. Traditional gender roles persist, with men mainly engaged in fishing and women in post-harvest activities, yet women's contributions are often undervalued [25]. Social structures, including caste dynamics, influence access to resources and economic opportunities, though Thoothukudi's urbanization presents slightly different dynamics [26]. Understanding these socio-economic complexities is crucial for sustainable management strategies [27]. Access to education and healthcare services varies across the districts, with coastal communities often facing challenges. In Ramanathapuram, lower literacy rates and limited educational facilities hinder socio-economic development, particularly among fishing families [28]. Thoothukudi fares better in terms of educational infrastructure, but disparities remain, especially in rural and coastal areas [29].

The Gulf of Mannar, renowned for its rich marine biodiversity, has faced significant ecological degradation due to human activities by local fishing communities, particularly in the past. Historically, practices like coral removal for lime production caused extensive damage to coral reefs. Current regulations for fisheries management in Tamil Nadu include restrictions on fishing zones, seasonal bans, and the use of specific types of nets to preserve marine biodiversity. The government enforces a 45-day annual fishing ban, particularly for trawlers, to allow fish stocks to replenish, but this often leads to economic strain and conflicts within fishing communities. In addition, restrictions on destructive fishing practices, such as bottom trawling, aim to mitigate environmental damage but face resistance from some fishermen due to livelihood concerns. Regulations often intersect with caste and social hierarchies, where access to resources and decision-making power can exacerbate tensions and inequities within communities. The coastal villages in the Ramanathapuram and Thoothukudi districts rely predominantly on fishing, as agricultural activities remain unproductive. The economic conditions are dire, with many living below the poverty line and lacking adequate water supply, medical care, and reliable power [30]. These challenges contribute to low productivity, improper marketing systems, and a lack

of additional vocations, resulting in a low standard of living and chronic debt among fishermen [31]. Fishing remains the primary economic activity, with 47 fishing villages—38 in Ramanathapuram and 9 in Thoothukudi—depending solely on it for livelihood [32]. The Gulf of Mannar's fishing sector utilizes a mix of traditional and modern vessels [33], and the lack of alternative income sources further exacerbates economic vulnerability in these coastal communities [34]. However, traditional crafts like catamarans, masula boats, vatti, and vallam persist alongside nearly 500 mechanized boats, highlighting the need for regulations to address the potential damage certain gears used on these vessels can cause to coral reefs [27]. However, destructive fishing methods, such as illegal pair trawling, increase seawater turbidity and damage breeding grounds, further depleting marine resources [18].

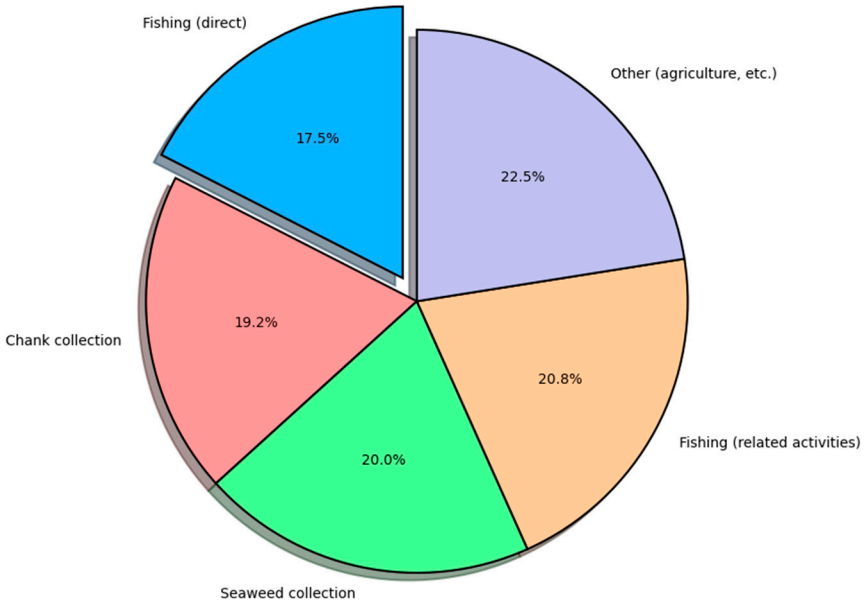

Figure 2. Different livelihood activities pursued by fishing communities in Ramanathapuram and Thoothukudi. Source: Primary survey data.

The value chain of fisheries and aquaculture in the Gulf of Mannar primarily involves fishers and middlemen, with most production being commercialized locally through intermediaries. Middlemen play a crucial role in the sale of fish, often purchasing catches directly from the fishers at lower prices and selling them at a profit in larger markets, limiting the fishers' direct access to major consumer markets [24]. While some fishers and their families engage in fish processing, such as drying and salting, which adds value to their products, this remains limited and primarily focused on local consumption [35]. Seaweed collection, another significant activity, involves both men and women, but processed seaweed is typically sold to external markets or industries by middlemen rather than directly by the fishers [36]. The seaweeds are crucial for agar and algin industries and are also used for human consumption and as fertilizer [37]. Despite their economic importance, the over-exploitation of seaweeds affects coral reef ecosystems due to increased siltation. Agriculture is limited but includes coconut and other food crops. Areas like Thoothukudi, Keelakkarai, and Mandapam practice coconut and Palmyra plantation, while floriculture is noted in some northern regions. In the Gulf of Mannar, conflicts between fishers using different fishing gears—such as trawlers and traditional boats—are common, especially over shared fishing grounds, leading to internal strife [38]. To address these issues, marine spatial planning (MSP) has been recognized as a critical tool, though it remains in the early stages of development for this region. Efforts are being made by both governmental agencies and non-governmental organizations to establish zoning regulations, such as the designation of no-fishing zones around coral reefs and restricted areas for certain gear types

to reduce competition and environmental impact [39]. However, the implementation of comprehensive MSP faces challenges due to enforcement issues and competing economic interests [40].

2.3. Survey and Data Collection

To investigate the social dimensions of fisheries and the role of ecosystem services in the Gulf of Mannar, a quantitative survey approach was employed. A stratified random sampling technique ensured representativeness across various fishing communities in Ramanathapuram and Thoothukudi districts. The population was stratified based on village size and type of fishing activity (traditional vs. modern). The fishing community in the Gulf of Mannar region is substantial, comprising tens of thousands of individuals across the 47 fishing villages, with a mix of small-scale and industrial fishers [32]. The sample of 480 respondents was designed to be representative of both the geographic distribution and diversity of fishing gear used in the region, ensuring coverage across the strata [11]. While many respondents were active fishers, the selected households could include individuals not directly involved in fishing, such as family members engaged in related activities like fish processing or seaweed collection, to capture a broader socioeconomic perspective [39]. The primary data collection tool was a structured questionnaire, which was translated into the local language for better comprehension and pre-tested with a small sample to ensure clarity, validity, and reliability. Key sections of the questionnaire addressed demographics (age, gender, education level, household size), livelihood and well-being (income sources, food security, health status), fishing activities (participation levels of men and women), and ecosystem services (dependence on fish stocks, coastal protection, other services). The data collection process took place over April and May 2024, covering approximately 60 villages. During this period, either data were combined based on the homogeneity of conditions observed across the villages, or a representative sample from each village was not feasible. In some cases, this was due to practical limitations, such as the difficulty of maintaining an even number of interviews across similarly sized villages. As a result, while certain villages had a larger number of interviews, others of comparable size had fewer, potentially impacting the representativeness of the sample. Nevertheless, the observed uniformity of socio-ecological conditions across the surveyed villages helped justify combining the data where necessary to ensure robust analysis.

Trained field researchers administered the surveys to consenting participants, ensuring anonymity and confidentiality throughout the process. Ethical considerations were paramount; informed consent was obtained from all participants before data collection, detailing the study's purpose, the voluntary nature of participation, and assurances of confidentiality. To identify and assess coastal ecosystem services (CES) in the Gulf of Mannar, we reviewed the scientific literature and reports on the region's ecosystems. We adapted a CES assessment framework to the specific context and refined service definitions for clarity. Based on this review, we compiled a list of potential CES (fish capture, water purification, etc.) and assigned importance scores based on the gathered information. Finally, we analyzed the data to understand the relative importance and distribution of CES within the Gulf of Mannar.

2.4. Statistical Techniques

In this research, Python version 3.12.4 was employed for data analysis and the creation of major visualizations, involving steps such as data preparation, descriptive analysis, and econometric modeling. During the data cleaning and organization phase, we checked for missing values and outliers to ensure data integrity, followed by the creation of a codebook detailing each variable, its type, and its scale of measurement. We identified dependent variables including well-being indicators (e.g., household income, health status, educational attainment, and access to services), gender dynamics (e.g., participation rates in fishing activities and income disparity), and community-based management outcomes (e.g., participation in decision-making and perceived benefits). Independent variables

comprised demographic factors (e.g., age, education, household size), economic factors (e.g., income, occupation), social factors (e.g., community engagement, gender roles), and environmental factors (e.g., access to resources, ecological health indicators).

For descriptive analysis, we calculated summary statistics such as the mean, median, standard deviation, and range for continuous variables, and analyzed frequency distributions for categorical variables. Additionally, cross-tabulations were conducted to examine relationships between categorical variables, such as gender and participation in community management, providing insights into the socio-ecological dynamics within the study area. This comprehensive approach allowed us to effectively assess the interactions between ecosystem services and human well-being in the Gulf of Mannar.

2.4.1. Multiple Regression Analysis

In the analysis, multiple regression was employed to assess the impact of various factors on well-being within the coastal communities studied. The regression model was structured as follows:

$$\begin{aligned} Y(Well-being) &= \beta_0 + \beta_1(Ecosystem\ Health) + \beta_2(Fish\ Capture\ Rating) \\ &+\beta_3(Water\ Quality\ Rating) + \beta_4(Interaction : Fish\ Capture \\ &* Sustainable\ Practices) + \beta_5(Other\ Socio-economic\ factors) + e \end{aligned}$$

Here, *well-being (Y)* represents the dependent variable, while the independent variables include *ecosystem health, fish capture rating*, and *water quality rating*. Additionally, an interaction term (β_4) was included to examine how the combined influence of fish capture and sustainable practices affects well-being. Other socio-economic factors such as income, education, and community participation were also considered.

This model allows for the simultaneous evaluation of multiple factors and their relative importance in determining well-being [41]. The inclusion of interaction terms can help explore complex relationships, such as whether sustainable practices in fisheries enhance the benefits of fish capture on well-being [42].

In adapting the model, certain assumptions were taken into account, including the linearity of relationships, independence of errors, and homoscedasticity. Data transformations were applied where necessary to meet these assumptions, ensuring that the estimates were reliable and unbiased [43].

2.4.2. Logistic Regression

Logistic regression was used to analyze the interaction between ecosystem services and food security, a specific aspect of well-being in the Gulf of Mannar. The logistic regression model is expressed as follows:

$$\begin{aligned} Logit\ (P_{FoodSecure}) &= \beta_0 + \beta_1\ (Fish\ Capture\ Rating) + \ \beta_2\ (Water\ Quality\ Rating) \\ &+\beta_3\ (Interaction :\ Fish\ Capture\ *\ Income\ from\ Tourism) + \beta_4\ (Household\ Size) \\ &+\beta_5\ (Education\ Level) + e \end{aligned}$$

In this model, $P_{FoodSecure}$ represents the probability of a household being food secure, modeled as the dependent variable. The independent variables include *fish capture rating, water quality rating*, and *household size*, along with the interaction term *fish capture* $\times$ *income from tourism* to explore the combined effects of fisheries and tourism income on food security. *Education level* is also included as an additional socio-economic factor.

Logistic regression is well-suited for this analysis because it models the probability of an event occurring (in this case, food security), with the dependent variable being binary (food secure vs. not food secure). The inclusion of interaction terms allows for the examination of how multiple variables, like fish capture and tourism income, together influence food security outcomes [44].

To ensure the robustness of the model, adaptations included checking for multicollinearity and performing goodness-of-fit tests. The Hosmer–Lemeshow test was used to verify the model's fit, and outliers were managed through data transformations or robust standard errors [45].

3. Results and Discussion

The Gulf of Mannar's coastal communities exhibit a profound reliance on the health of their surrounding ecosystem. Fishing dominates their economic landscape, directly employing around 65% of the workforce and encompassing a wider network of related activities (20%). Seaweed collection (2%) and even seemingly separate activities like agriculture (18.8%) and firewood collection further illustrate the intricate link between human well-being and the environment (Figure 3). Traditional fishing communities in the Gulf of Mannar rely on mangrove forests for wood used in fishing gear and firewood, contributing to local livelihoods. Approximately 100,000 people in this region depend on these resources, with the mangrove cover declining by 23% in Tamil Nadu over the last decade due to the overexploitation of firewood and fishing materials. This illustrates the conflict between economic needs and conservation efforts, highlighting the need for the sustainable management of mangrove ecosystems.

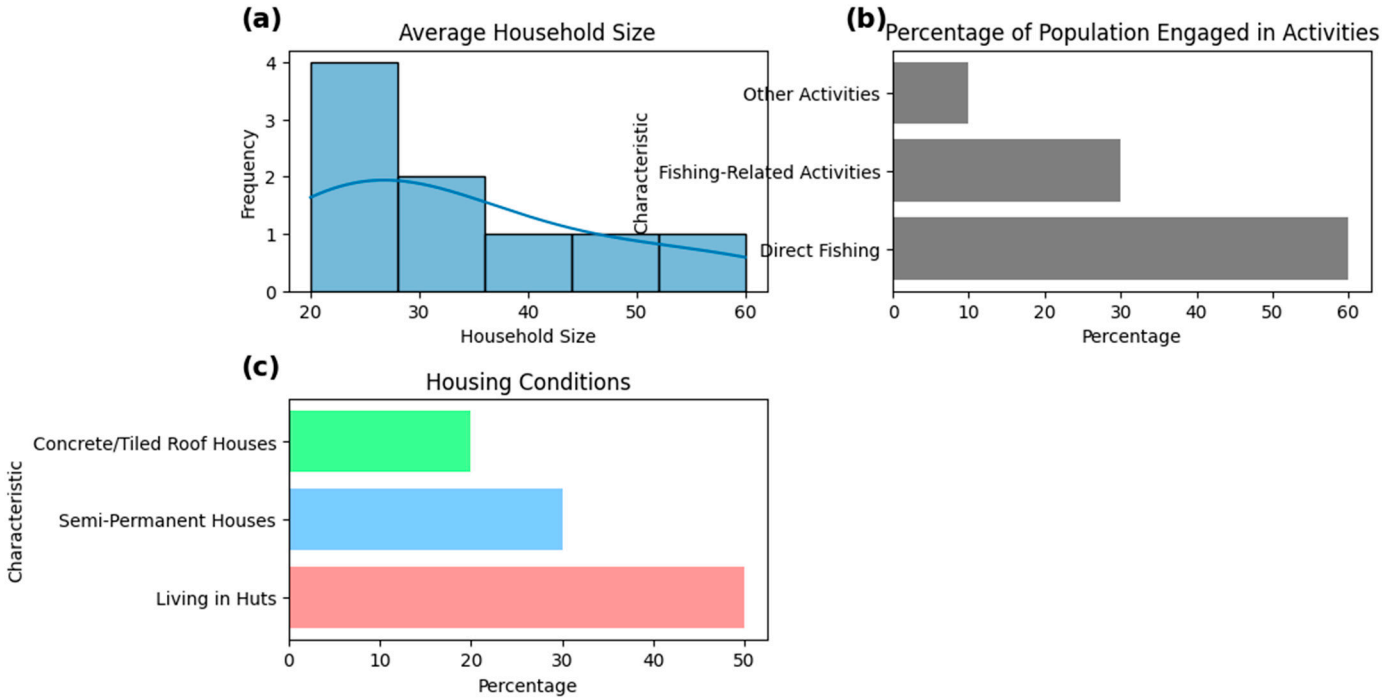

Figure 3. Subplots of socio-economic characteristics. (**a**) Household size distribution with bars for frequency and a blue line showing the smoothed KDE. (**b**) Percentage of population engaged in fishing-related activities. (**c**) Housing conditions by population percentage in huts, semi-permanent, and concrete houses. Source: Primary survey data.

This dependence reflects patterns observed in other coastal regions, such as the Sundarbans in India and the Mekong Delta in Vietnam, where local economies similarly hinge on ecosystem services [39]. However, this dependence presents a double-edged sword. While the ecosystem provides vital resources through fishing, seaweed, and potentially chank collection, unsustainable practices risk depleting these resources, echoing findings from studies in the Coral Triangle, where overexploitation has led to significant declines in fish stocks [46]. The Gulf of Mannar region has a management plan in place, including the establishment of the Gulf of Mannar Marine National Park, which imposes fishing restrictions in designated areas to protect biodiversity. Fishing bans during the spawning season and restrictions on certain destructive fishing methods, such as bottom trawling,

are enforced to preserve marine ecosystems. Despite these efforts, compliance remains a challenge, with over 80% of fishers reporting dependence on illegal or unregulated fishing for livelihood sustenance.

In the Gulf of Mannar, precarious housing conditions among fisherfolk are closely tied to their dependence on marine resources, with many families living in vulnerable structures due to limited income from fishing. Sustainable resource management measures, such as closed fishing seasons and capture limits on key species, have reduced monthly catches by up to 30%, leading to a significant decline in household income and deepening economic hardship. This demonstrates that while "sustainable" management may protect ecosystems, the lack of alternative livelihoods exacerbates social issues, underscoring the need to integrate human dimensions into conservation planning. This situation mirrors similar challenges faced by coastal communities in Bangladesh, where inadequate housing exacerbates vulnerabilities to environmental hazards [47]. This highlights the critical need for sustainable resource management. Balancing ecological health with economic well-being is essential for long-term prosperity, a concept supported by comparative research on coastal resilience and sustainability [48].

This study's focus on gender dynamics reveals that while men dominate fishing at sea, women play a crucial yet undervalued role in pre- and post-harvest activities. This gender disparity weakens household dynamics and community resilience, aligning with findings from research in the Philippines, where women's limited access to resources and decision-making affects sustainable fishing practices [49]. Integrating women's perspectives is crucial for developing equitable policies and promoting long-term environmental well-being.

The multiple regression analysis on household well-being in the Gulf of Mannar found household size and assets to be significant predictors. The lack of economic alternatives, age restrictions on entering fisheries, and weak social security systems significantly affect well-being in the Gulf of Mannar region, where larger households are associated with lower well-being scores (p-value = 0.026), while higher asset ownership improves well-being (p-value = 0.000). These findings are consistent with research in similar coastal settings, highlighting the importance of material security in determining well-being [50]. However, factors like education and fishery dependency showed no significant impact, mirroring the model limitations noted by [51], suggesting that further investigation is needed to address these gaps. Combining all interviewees into one group may obscure significant differences between communities in the Gulf of Mannar, as living conditions and fleet types differ notably between Ramanathapuram (traditional fisheries) and Thoothukudi (industrial fisheries). A comparison between these districts could reveal stronger contrasts, as the current model explains only 20.4% of the variation in well-being scores (R-squared = 0.204), indicating missing variables. Despite this, the model remains statistically significant (F-statistic p-value = 7.82×10^{-9}), suggesting that further investigation into community-specific factors is essential.

Valuations of the Gulf of Mannar's ecosystem services (Table 1) highlight its multi-faceted importance, with high scores for fish capture, aquaculture, and water resources, reflecting the region's dependency on these services. This mirrors findings from other coastal ecosystems, where economic and non-monetary values of ecosystem services are crucial for understanding local dependencies [52,53]. Future research combining qualitative methods with economic models could provide deeper insights into these interdependencies, as suggested by recent studies in the Andaman and Nicobar Islands [54].

Table 1. Valuation of Ecosystem Services by Average Rating.

Index	Ecosystem Service	Average Rating	Comment on Data Interpretation
0	Fish capture	3.045833	Critical for both traditional and industrial fisheries.
1	Fish aquaculture	3.079167	Needs emphasis on results, key for industrial fisheries.
2	Salt	2.991667	Provides moderate value to both fisheries, with industrial higher use.
3	Seaweed, seagrass, honey, fibre, timber, materials	3.070833	Relevant to traditional livelihoods; should be discussed separately.
4	Water non-drinking 1 (Industrial use)	3.029167	Likely related to industrial uses (e.g., cooling, processing).
5	Aquaculture	3.14375	Most importantly; the emphasis in both data sets, is stronger for industrial.
6	Water non-drinking 2 (Ecological services)	3.091667	Relates to ecological value, and a stronger impact on traditional fisheries.
7	Cooling agent for power plants	2.983333	Important for industrial use but less so for traditional.
8	Carbon sequestration	2.9625	Important but has even weight in both fisheries.
9	Control erosion	2.985417	Significant for both groups, particularly those dependent on mangroves.
10	Flood control	3.085417	Important for coastal protection, especially for traditional fishers.
11	Maintenance of the nursery population	3.014583	Relevant for both fisheries and more critical for traditional.
12	Groundwater recharge	2.895833	Moderate importance, particularly for ecological services.
13	Storm protection	2.9625	High relevance for communities in traditional fisheries.
14	Activities (immersive interactions)	3.079167	Direct engagement like tourism; has more value in industrial areas.
15	Activities (passive interactions)	2.90625	Indirect value is important for cultural/ecological services.
16	Education and training	3.04375	Benefits both sectors, particularly in sustainable practices.
17	Culture and heritage	2.975	More valued by traditional communities due to cultural ties.
18	Aesthetic value	2.960417	Important for tourism; slightly stronger for industrial fisheries.
19	Sacred values	3.002083	Significant cultural and spiritual value, mainly for traditional groups.
20	Existence value	3.04375	Equally important for both fleets, reflecting broader ecological value.
21	Bequest value	3.04375	Reflects intergenerational importance, is equally relevant for both types.

Source: Author's compilation.

The logistic regression analysis on food security in the Gulf of Mannar region, using predictors such as Fish Capture Rating and Water Quality Rating, yielded a low pseudo-R-squared value of 0.008, indicating limited explanatory power (Figure 4). This low variability suggests that factors beyond fisheries and water quality, such as the uneven distribution of aquaculture and differences between traditional and industrial fishing communities, may play a significant role. Given that aquaculture is more concentrated in industrial regions like Thoothukudi, further differentiation between these communities may help better explain food security outcomes [55]. This finding is consistent with research by [56], which found similar issues in predicting food security using limited socio-economic and environmental variables. Potential reasons for these findings include the complexity of socioeconomic and environmental interactions, data limitations, and measurement issues.

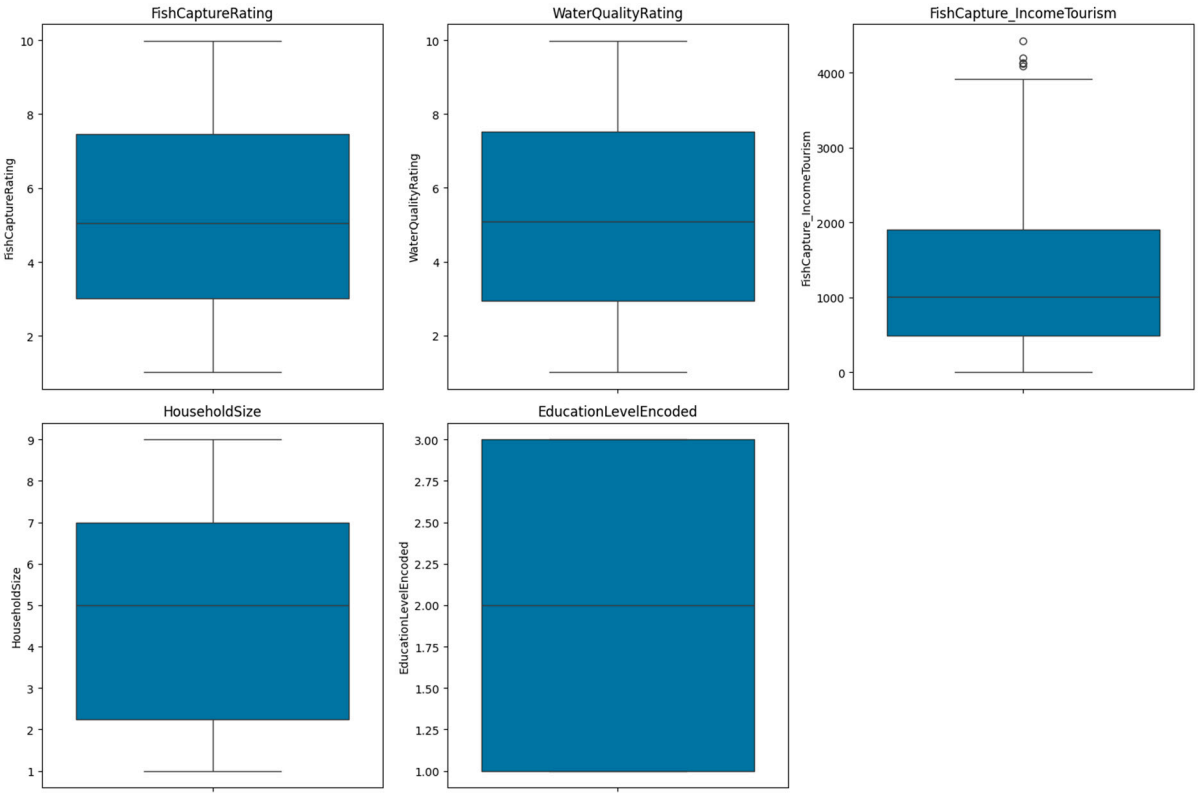

Figure 4. Boxplots showing the distribution of FishCaptureRating, WaterQualityRating, FishCapture_IncomeTourism, HouseholdSize, and EducationLevelEncoded. The circles in the FishCapture_IncomeTourism plot represent outliers, which are values outside the typical range. Source: Primary survey data.

Figure 5 depicts the perceived importance of various ecosystem services, represented along the vertical axis, with normalized ratings shown on the horizontal axis. A color bar to the right indicates the importance of these services, ranging from 0 (blue) to 1 (red). "Flood Control" is rated the highest, with a value of 1, highlighted in dark red, signifying its critical role in the community's perception. Services such as "Fish Capture", "Storm Protection", "Carbon Sequestration", and "Culture Heritage" fall in the mid-range, with normalized ratings between 0.6 and 0.7. On the other hand, services like "Activities Immersive Interactions", "Ground Water Recharge", and "Bequest Value" are rated with lower importance, shown in blue or lighter shades, with "Ground Water Recharge" receiving a value of 0, marking it as the least perceived. Services with values around 0.5, such as "Water Non-drinking", are perceived as moderately important. The x-axis contains diagonally displayed normalized ratings, showing that the ratings are closely spaced between 0 and 1. The figure illustrates the community's differentiated perceptions of ecosystem services,

with higher importance placed on protection and environmental regulation, while cultural and recreational activities receive lower importance.

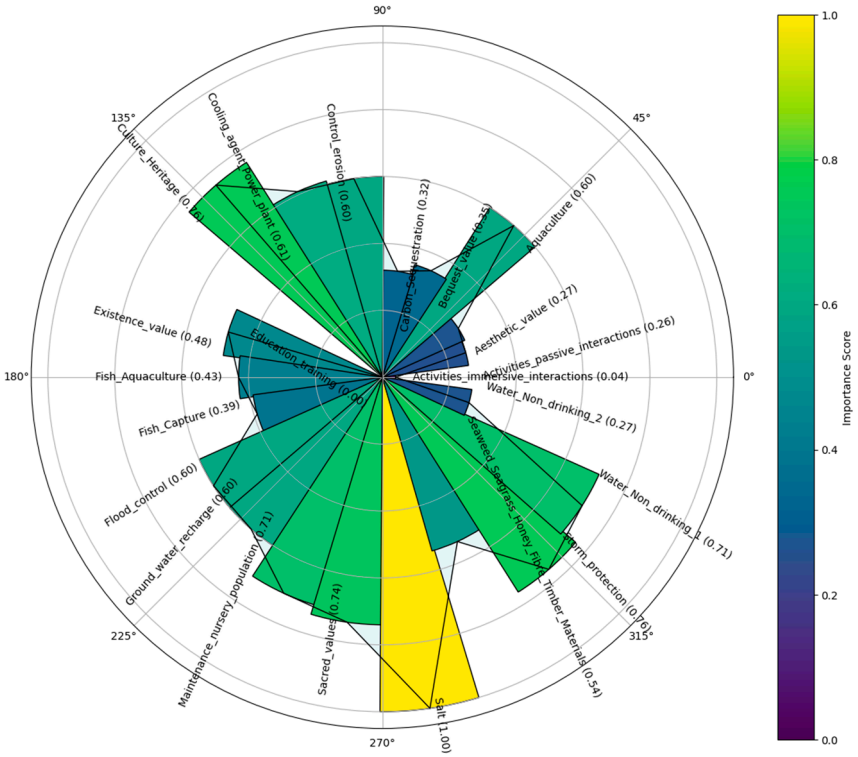

Figure 5. Community Perception of Ecosystem Services. Source: Primary survey data.

4. Conclusions and Recommendations

The current Coastal Ecosystem Services (CES) rating for the Gulf of Mannar presents a balanced distribution of importance across different services. However, this assessment may overlook the critical significance of fishing, which accounts for a substantial portion of the local economy. With 65% of the population directly employed in fishing and 20% engaged in related activities, fishing constitutes the primary livelihood for the region's coastal communities. This reliance underscores the need for a re-evaluation of the CES rating system, particularly in the context of fisheries, which may be undervalued in the current assessment.

The scientific literature and fish landing data suggest that fish stocks in the Gulf of Mannar are facing overexploitation. For instance, Ref. [9] highlights that marine catch rates along the Indian coast, including the Gulf of Mannar, have shown a decline, indicating pressures on fish populations. Additionally, reports from the Central Marine Fisheries Research Institute (CMFRI) show that annual fish landings have decreased in recent years, corroborating concerns raised by local fisherfolk about dwindling fish stocks. These data suggest the need for urgent action to reevaluate the ecosystem service contribution of fisheries to accurately reflect the resource depletion and its socio-economic implications.

The well-being analysis of the Gulf of Mannar communities indicates a significant relationship between household size, assets, and well-being. Larger households, despite having more labor resources, reported lower well-being scores, likely due to greater consumption demands. This finding aligns with socio-economic studies from small-scale fishing communities that associate larger household sizes with greater resource strain and vulnerability to economic shocks [57]. However, the current model assessing well-being needs refinement. Additional factors such as income diversification, education, health access, and social networks should be included to provide a more comprehensive picture of community well-being. Statistical models incorporating these variables could further elucidate the complex dynamics of socio-economic resilience in this region.

The sustainable management of the Gulf of Mannar's resources necessitates a multifaceted approach. Diversifying livelihoods—through activities like seaweed farming and ecotourism—has proven effective in reducing fishing pressure while enhancing income security in similar regions [24]. These alternative livelihoods not only alleviate the burden on overexploited fish stocks but also contribute to economic sustainability and resilience.

Community-based management (CBM) plays a critical role in this strategy by empowering local populations, fostering a sense of ownership over marine resources, and promoting sustainable fishing practices. Ref. [58]'s work on common-pool resource management highlights the importance of community participation in resource conservation. Empowering the Gulf of Mannar's fishing communities through capacity-building initiatives—such as training in sustainable fishing techniques and resource management—could further enhance community engagement. Evidence from CBM programs globally suggests that when local communities are given the tools, training, and authority to manage their resources, sustainable practices are more likely to take root and succeed in the long term [17]. Therefore, integrating CBM into the Gulf of Mannar's resource management framework, alongside livelihood diversification, can be instrumental in promoting both ecological sustainability and socio-economic well-being.

While the current CES rating provides a foundation for understanding the importance of ecosystem services, the specific significance of fisheries needs to be re-examined. A revised approach incorporating fish stock data, socio-economic variables, and community-based management strategies will offer a more accurate and sustainable path forward for the Gulf of Mannar.

Future research should focus on expanding data collection, enhancing feature engineering to capture nuanced socio-ecological dynamics, employing multivariate techniques like SEM, and integrating qualitative insights to provide a more comprehensive understanding of food security determinants in the Gulf of Mannar region. Regulatory measures such as bans on deforestation, shell collection, coral mining, and stringent controls on trawl boat operations and industrial effluents are critical for mitigating environmental degradation in sensitive ecosystems like the Gulf of Mannar. However, the enforcement of these regulations by governmental agencies can sometimes lead to conflicts, particularly with local communities whose livelihoods depend on accessing these resources. These communities may view such regulations as restrictive or unfair, especially if they are implemented without proper consultation or consideration of their socio-economic needs. This is where Community-Based Management (CBM) could play a crucial role. CBM emphasizes local participation and shared decision-making in managing natural resources. It allows communities to take an active role in the enforcement and monitoring of regulations, fostering a sense of ownership and responsibility. Involving local stakeholders in the development and enforcement of conservation policies can help reduce tensions, as communities are more likely to support measures that they have helped shape [59]. By integrating CBM with governmental regulations, a more collaborative and adaptive approach can be adopted. For example, instead of unilateral bans on activities like coral mining, a co-management system could be designed where sustainable practices are agreed upon, ensuring both environmental protection and livelihood security. This collaborative model could also involve alternative livelihood programs, compensating for the loss of income due to restrictions [58].

In this context, CBM provides a platform for aligning the interests of local communities with conservation objectives, ensuring that environmental regulations are seen as beneficial rather than punitive. This approach could potentially minimize conflict and promote long-term sustainability. Promoting sustainable development through responsible tourism, population growth control, and urban planning, while adhering to Coastal Regulation Zone (CRZ) rules, ensures integrated development aligned with environmental protection goals. These integrated strategies aim to enhance social equity, conserve ecological integrity, and promote economic sustainability for the long-term well-being of Gulf of Mannar communities.

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