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RESEARCH PAPER

Sustainable Harvests under Different Bio-economic Scenarios of Chilika Wetland's Fisheries

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Abstract: The primary goal of fisheries management is to control overfishing and unregulated fisheries to protect stocks and boost the value of fish resources. In this study, we compare harvesting and fishing efforts in the maximum economic yield (MEY), maximum sustainable yield (MSY), and open access (OA) scenarios using Gordon-Schafer's bioeconomic model to examine the economic status of Chilika's fisheries. This paper also measures the effectiveness of Chilika Lake's restoration measures. An independent sample t-test with bootstrap confidence intervals indicates the results' robustness and concludes that the fisheries' output has increased in the post-restoration period (2003–04 to 2020–21) in a statistically significant way. The estimated measures serve as the focal points for designing sustainable and optimal fisheries management strategies. They add to the ongoing research on stock evaluation, which helps determine harvesting effectiveness and strengthens the fishing stock to avoid exhaustion. Therefore, the expectation is that the outputs in the forms of optimal extraction and an enhanced management tool will improve livelihood opportunities and enhance other socioeconomic components of the fisheries sector. As a result, the findings will aid policymakers and other interested parties in creating a suitable harvesting strategy to attain economic optimality.

Keywords: Bioeconomic, fisheries, sustainable yield, Ramsar wetland

1. INTRODUCTION

Wetlands provide various ecosystem products and services that benefit humankind (Gardner and Finlayson 2018). They help maintain a diverse

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ecosystem and provide essential habitats for feeding and breeding for aquatic species, migratory birds, and other fauna. In addition to providing a means of subsistence and livelihoods for millions of fishers, wetlands play a significant role in water purification, hydrological regulation, carbon sequestration, climate regulation, and biodiversity conservation in addition to providing cultural and aesthetic services (Sukhdev *et al.* 2010). However, unsustainable harvesting, habitat degradation, loss of fishery resources, spawning, and the construction of nursery grounds worldwide has resulted in declining fishery yields. The prime intent behind designating a biodiverse wetland as a Ramsar site is to conserve the existing ecosystem from further damage and bring about overall sustainable development. The Ramsar Convention signed in 1971, officially referred to as the International Convention on Wetlands, primarily aims to promote the responsible utilization of wetlands while actively contributing to their preservation and maintenance (Ramsar 2023) However, studies such as Samraoui and Samraoui (2013), Geijzendorffer *et al.* (2019), Gaget *et al.* (2020), Gosh and Das (2020), and Mao *et al.* (2021) indicate how, in recent years, even these sites are being threatened despite significant protection efforts. This reveals how inefficiencies in the Ramsar Convention undermine the development of a strong conservation network. According to estimates from the United Nations Food and Agriculture Organization (FAO), the catch fisheries and aquaculture industry directly employs around 58.5 million people; indirectly, around 600 million people rely on the fisheries and aquaculture sector for a living (FAO 2020). Hence, sustainability is a significant concern raised in international agreements and guidelines pertaining to fisheries management. The sustainable use and conservation of sea and marine resources is the focus of Sustainable Development Goal (SDG) 14 of the United Nations, titled "Life Below Water" (Molony *et al.* 2022). The FAO's Code of Conduct for Responsible Fisheries (1995) too necessitates incorporating planning measures for fisheries' conservation and sustainable use (FAO 2020).

Fisheries, however, present the classic trade-off between profits and ecological deterioration. In the pursuit of economic goals—such as profit generation—social objectives such as employment, safe working conditions, and gender equality are undermined in fisheries, which also inadequately address their role in ecological deterioration (Kittinger *et al.* 2017; Farmery *et al.* 2019). In developing nations, overexploitation is driven by the commoditization of fish and the pursuit of economic development through industrialization and market expansion. According to a study by Sethi *et al.* (2010), a significant connection exists between demand and stock levels, whereby high prices due to high demand, and low extraction costs due to the availability of cheap labour in developing nations, results in over-extraction, and subsequently, lower fishery stock. Thus, prioritizing economic benefits necessitates larger and more frequent harvests, which eventually threaten ecological sustainability.

Uncontrolled access to the commons leads to a typical "tragedy of the commons" situation, wherein individual fisherfolk make decisions in their best interests, eventually reducing the stock of the resource and thus overall profits. Solutions to restrict access to the commons have been suggested, such as private or single ownership, but these have not been successful in preventing overfishing. In some situations, a single owner may find it economical to drive a fish stock to extinction (Clark 1973; Oosterveer 2008; Pauly *et al.* 2002; Costello *et al.* 2016). In some countries, fisheries management based on central government planning has failed to halt the degradation of fishery stocks. The most common approach is for the state to regulate resource access. It usually does this in three ways: first, control effort through boat registration, fishing permits, licensing fees, and taxes; second, regulate fishing gear type; third, impose seasonal limits, close access to the resource periodically, and protect a portion of the area for biodiversity conservation (Nagothu 2004). Thus, it is inevitable that fisheries must be managed such that there is a balance between the economy, ecology, and livelihoods, which implies that realising sustainable biological, social, and economic advantages from the abundant renewable aquatic resources available is the overarching purpose of fisheries management.

This study examines the economic principles central to fishery resource management to suggest a regulatory regime that can assure economic sustainability while utilizing fishery resources. Further, a thorough knowledge of bioeconomic resources and their management is required to encourage the sustainable development of fishery resources. Bioeconomic theory combines a fish species' biological and economic dimensions to explain stock, catch, and effort dynamics under various regimes and offers suggestions for the best stock management. The Gordon and Schaefer (1954) biomass approach to stock assessment and Beverton and Holt (1957) cohort analysis form the basis for various other optimization models in fisheries economics. However, the Gordon-Schaefer method has dominated fishery economics as it allows for empirical simplicity in comparison to a more in-depth, age-structured categorization of harvestable populations in situations where there is insufficient data and one is compelled to use models with a minimal number of parameters (Zimmermann, Steinshamn, and Heino 2011; Habib, Ullah, and Duy 2014). Standard approaches to fisheries' sustainable management include the MSY (maximum sustainable yield), MEY (maximum economic yield), and open access (OA) scenarios. These parameters predict over-exploitation situations and require information on the fishery's stock, catch, and fishing effort. Depending on the availability of empirical data, a suitable bioeconomic model that investigates the complexity of ecological mechanisms can be used to understand static and dynamic behaviours. This analysis can help in assessing the long-term sustainability of measures to increase fishers' profitability as per various social, economic, and ecological objectives.

The objectives of this article are as follows: 1) examine the evolution of Chilika's fishery resources and offer relevant policy recommendations to optimise for sustainable harvesting in the wetland; and 2) use Gordon-Schafer's bioeconomic model to examine the economic prospect of Chilikas' fisheries by comparing harvesting and fishing efforts in the MEY, MSY, and OA regimes. These biological measurements support ongoing research on stock evaluation, which aim at increasing harvesting effectiveness and strengthening the fishing stock to avoid the point of exhaustion. Chilika, declared as India's first "Ramsar site" in 1982, was chosen as the study area due to its significant biodiversity and ecological importance. The National Wetlands, Mangroves, and Coral Reefs Committee of the Ministry of Environment Forests (MoEFCC), Government of India, has also identified the lagoon as a priority site for conservation and management. Nalaban Island within the lagoon is notified as a bird sanctuary under the Wildlife (Protection) Act, 1972. Chilika was considered a dying lake in the late 1990s, and because of the alteration in its biological nature, the Ramsar Convention included it in the Montreux Record (threatened list) in 1993. However, following practical restoration work carried out by the CDA and the state government, the lake was the first in Asia to be removed from the Montreux Record in 2002 (CDA 2017). Chilika also presents a case where remunerative fishing and state intervention attract outsiders to the area, causing damage and making local community management challenging.

The paper is structured as follows: Section 2 provides a detailed description of the study area along with the evolution of fishery resources. Section 3 discusses the chosen bioeconomic model, the results of which are presented in Section 4. Section 5 concludes the study with discussions and policy implications.

2. DESCRIPTION OF THE STUDY AREA

Figure 1: Map of Chilika Lake

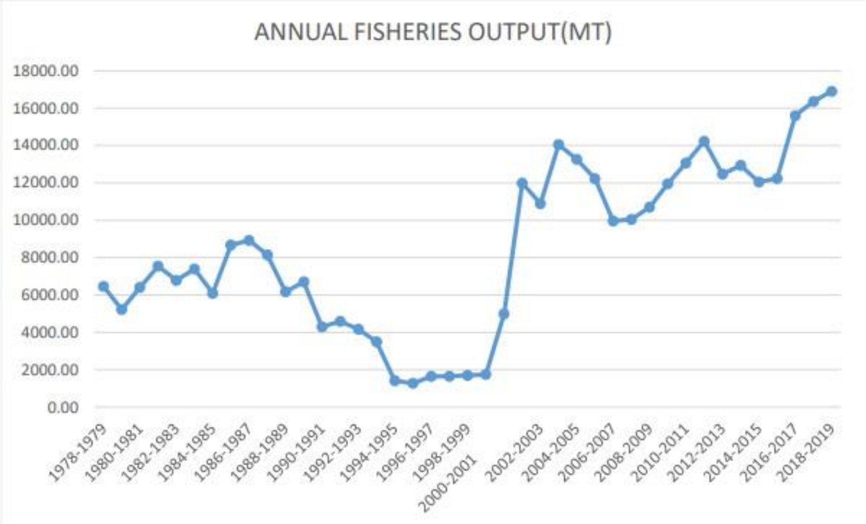
Source*:* CDA website (*https://www.chilika.com/how-to-reach.php*)

Chilika, one of the largest brackish water lagoons, features a rare combination of fresh water, brackish water, and marine environments and is in the state of Odisha along the Bay of Bengal around latitudes 19°’28’ and 19°’54’ N and 85°’5’ and 85°’38’E (Figure 1). This unique combination of factors have given it a rich biodiversity and a highly productive ecology, with fishery resources offering attractive advantages. Irregular water channels and several tiny, sandy, and transitory islands connect this pear-shaped lagoon to the sea. The lagoon is a significant migratory waterfowl wintering area renowned for having a diverse range of species, including Irrawaddy dolphins and several rare, vulnerable, and endangered species on the IUCN Red List of Threatened Species. The lagoon is one of Odisha’s primary sources of capture fisheries (Figure 2), and over 0.15 million commercial and subsistence fisherfolk who live in and around Chilika lagoon depend on it for their nutritional and economic security (Figure 3) (CDA 2017, 2022). The annual fisheries output of Chilika majorly comprises fish, prawn/shrimp, and crab. Due to its distinctive hydrology, which combines brackish and riverine features, its products are in great demand. In 1978–79, the total output was 6,454 million tons (MT), valued at ₹89.1 million. Of this, shrimp accounted for 1,869 MT, worth ₹51.2

million. However, later periods (1988–2001) witnessed a steady decline, mainly due to the lake's health deterioration. The site was included under the Montreux Record from 1993–2002, and major restoration works were undertaken to rehabilitate the lake to its original state. Thus, from Figure 2, it is clear that this period witnessed the least amount of total fisheries yield. After the restoration period, output steadily increased relative to the earlier phase, but there have been fluctuations in yield—studies such as Sahu, Pati, and Panigrahy (2014), Kankara and Panda (2020), and Finlayson *et al.* (2020) indicate that hydrological changes due to natural and anthropogenic factors impact the productivity of the lake due to varying sediments and salinity levels.

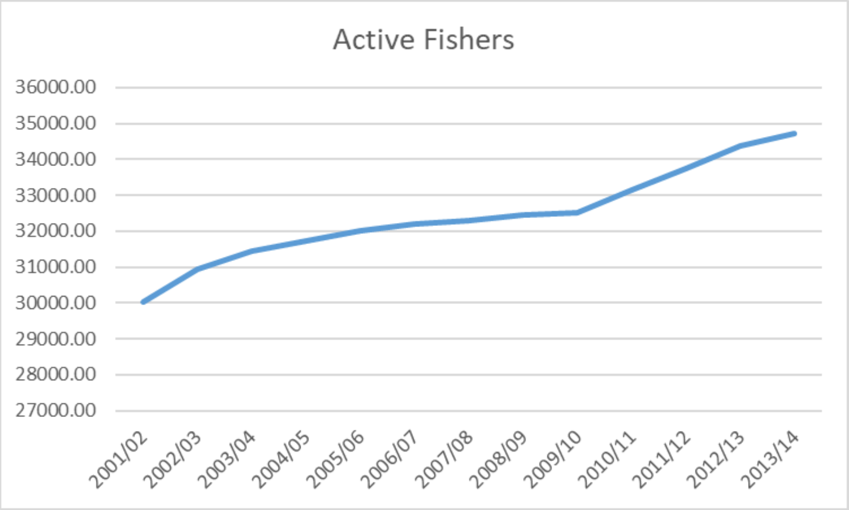
According to the CDA's report, compared to yearly landings in 2016, average fish landings in 2017–18 totalled 16,657.3 tonnes, an increase of 18.4%. The average landing value for 2017–2018 was ₹2,424.8 million, a 27.5% rise over the catch value for the previous year. The predicted average per capita income of active fisherfolk for 2017–2018 was ₹59,141, a 5.5% increase over the previous year. Fish, prawn, and crab made up 69.7%, 28.4%, and 1.9% of the average annual landing during these years.

Figure 2: Annual Fisheries Output (1978–2019)



Source: Fisheries Department, Government of Odisha

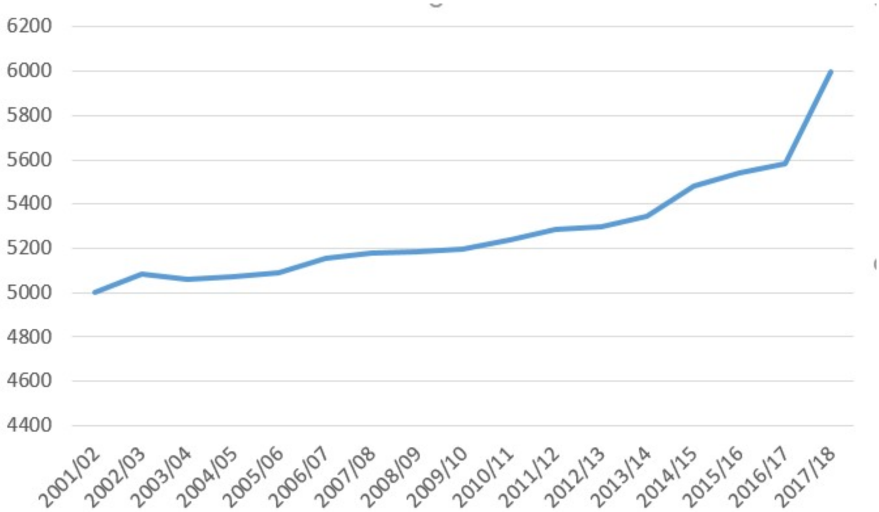
Figure 3: Number of Active Fishers (2001–14)



Source: CDA

The lake is surrounded by about 132 fishing villages of varying sizes, and 30% of the fishing village population is actively involved in fishing (Sekhar 2004). Figures 3 and 4 indicate that the number of people involved in fishing and the number of boats has also increased. In 2016, the average per capita income of active fishers in the region was estimated to be ₹56,035 (CDA 2017).

Figure 4. Number of Fishing Boats Used for Regular Fishing (2001–18)



Source: CDA

Table 1 summarizes the evolving nature of fishing undertaken in Chilika. Sekhar (2004) and Iwasaki and Shaw (2009) note that the lake was part of zamindari holdings until the 1880s, and they leased out access rights to the surrounding fishing families in exchange for small token payments. The British maintained this arrangement in India, and the state government took over ownership post-1950. Leases were allocated through an auction system and were restricted to local fisherfolk. The local fishing community had access rights to fisheries till the late 1980s; these communities respected seasonal limits for fishing. The fishing communities collectively enforced boundary rules to restrict access to the lake and formed guiding principles for harvesting—such as restrictions on where to fish, size limitations, and seasonal closures to allow juvenile stocks to grow, thereby avoiding stock extinction. However, as several stakeholders laid claim to the resource, conflicts among various stakeholders took place.

Chilika Lake presents a case of how a divergence of interests leads to the disintegration of prevalent social and economic structures and damages to the natural resource base. In his study, Sekhar (2004) reports that traditional fisherfolk fished sustainably as they used localized gear made of local materials, and the gear type depended on the species and area fished. However, external parties (various state departments), in the name of development, have introduced more mechanized fishing boats and gear, which has led to the overexploitation of the fishery resource and increased resource conflicts due to a lack of respect for resource boundaries and access norms and disturbance of breeding areas for commercial advantage. Further, studies such as Samal (2002), Adduci (2009), Nayak and Berkes (2011), Nayak (2012), and Das (2014) note that fishing in Chilika is predominantly small scale in nature; as a means to provide the fisher community with an alternative source of income, the state government promoted shrimp aquaculture through initiatives like the "Economic Rehabilitation of the Poor" programme. However, this had the opposite effect of what was intended. Not only did it have a detrimental effect on the local fisher community, but it also led to significant environmental damage. The timeframe shown in Table 1 also demonstrates how the rapid expansion of aquaculture in the region led to the socioeconomic decline of the traditional fishing population that depended on the lake. Kadekodi and Gulati (1999), Kadekodi and Nayampalli (2003), Mohapatra *et al.* (2007), and Mishra *et al.* (2019) indicate that the growth of shrimp farming intensified lake degradation by altering its hydrological balance. It hinders the free water and tidal migration of species—including juveniles,

Table 1. Timeline of Changes in Fishing Policies with Respect to Chilika and Their Structural Implications

Timeline	Fishing Rights Situation	Structural Implications
Colonial rule (before 1952)	Proprietors included rajas, zamindars, local landowners, and the government.	Strict norms based on caste-defined fishing rights and entitlements.
Anchal Adhikari (1953–1959)	Open auction mechanism, primarily employing local fishers.	The lease system and the strict caste-based fishing rights granted exclusive rights and preserved the interests of traditional fisherfolk.
Revenue collectors (1959)	Leases are mainly given primarily to fisherfolk cooperative groups.	In addition to enabling higher economic gains to be distributed fairly among the fisherfolk, community-based structures also reduced disputes, preserved sound ecological health, and provided a strong resource base.
The late 1980s to 1993	Promotion of aquaculture farms, especially shrimp farming. However, the plan was withdrawn owing to protests by fisherfolk.	Exclusion of traditional fishers as historical fishing grounds shrank due to changes in land-use patterns and resource reallocation towards shrimp farming and other uses.
Fishing lease guidelines (1991)	Fishing rights were officially granted to both non-fisherfolk and fisherfolk.	Serious concerns involving access and entitlements were brought on by the loss of the institutional base, illegal encroachment, and unfavourable leasing policies.
Orissa High Court’s decision (1993)	30% of fishing rights were given to non-fisherfolk.	Institutional changes and worldwide increasing demand and pricing of shrimp have resulted in increased resource degradation, biodiversity loss, and fishing productivity.
Supreme Court’s decision (1996)	Aquaculture is to be prohibited within 1,000 metres of the Chilika lagoon.	
Orissa legislative assembly’s	Orissa Fishing in Chilika Lake Bill failed to pass due to opposition from fisherfolk.	

decision (2002)

Source*:* Revised from Iwasaki and Shaw (2009)

whose sustenance is important for individual species to not become extinct—and causes increased silting, leading to reduced lake area.

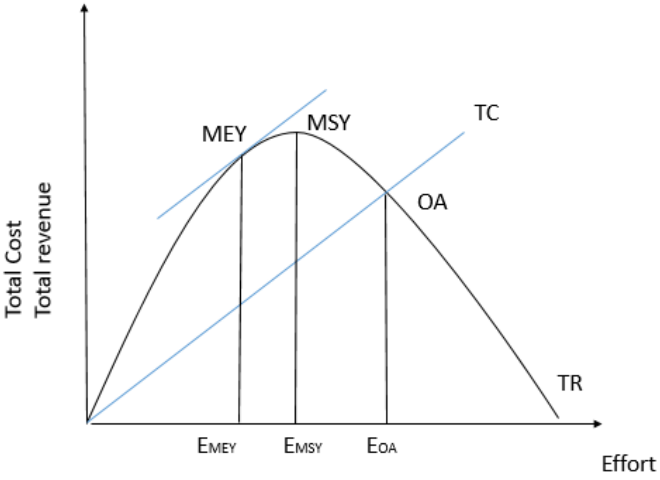
The declaration of the lake as a Ramsar site positively impacted fishery resource augmentation and a dramatic rise in fish landings has been observed. According to Ghosh, Pattnaik, and Ballatore (2006), the costs incurred in managing Chilika are taken care of by both the state and central government via funding allocated for specific projects. When it comes to financial aid from the latter, it is primarily in the form of support rendered by MoEFCC's wetland-specific National Plan for Conservation of Aquatic Ecosystems. As part of their efforts to restore the lagoon, the CDA was awarded a "special problem grant" from the Ministry of Finance, totalling ₹270 million under the 10th Finance Commission (1996–2000). Furthermore, they were awarded an additional amount worth ₹300 million through the 11th Finance Commission (Ghosh *et al.* 2006). Moreover, it is worth noting that the Orissa Water Resource Consolidation Project (OWRCP), backed by the World Bank, has acknowledged the significance of Chilika Lake by including it as a constituent of the project. This move has facilitated the allocation of funds for conducting hydro-biological surveillance of the lagoon. A significant portion of the funds was directed towards maintaining hydrological regimes essential for maintaining ecosystem connectivity with the Bay of Bengal and ensuring that the right salinity and water composition levels are maintained. This was done by dredging lead channels and opening a new mouth to the lake; apart from that, the remaining portions went into wetland monitoring/evaluation as well as fisheries development or livelihood improvement, respectively (Finlayson *et al.* 2020). Ghosh, Pattnaik, and Ballatore (2006) and Mohanty *et al.* (2008) also note that when the mouth of the channel was opened, there were changes in tidal movement that resulted in significant sediment flushing. This deepened the waterway and allowed for quicker freshwater discharge through the new opening. The restoration of salinity levels through this process improved auto-recruitment from the ocean and allowed for free-breeding migration. However, on the negative side, substantial evidence suggests that inland and small-scale coastal fisheries have declined due to the modification, overfishing, and other human activities (Kadekodi and Gulati 1999; Adduci 2009). During the post-intervention period, the average annual fish landings were 12,070.54 metric tonnes, which almost matched the MSY level predicted by the Central Inland Fisheries Research Institute (CDA 2013). According to CDA's

Chilika Health Report (CDA, 2017), the total annual fish landing (fish, shrimps, and crabs) from the lake in 2016 amounted to 14,067.50 MT, equivalent to ₹1,901.96 million (see Figure 2 for the annual fisheries output from the lake).

3. MODEL DESCRIPTION

The literature on the economic performance of fishery management strategies suggests that the surplus production methodology of the bioeconomic model of fishery resources helps in determining sustainable harvest levels for a given effort and is regarded as a helpful tool for making an initial approximation even in conditions of time or data constraints (Dowling 2016; Honey *et al.* 2010; Habib *et al.* 2014). The biological linkages between fish stock growth and catch effort serve as the foundation for the surplus production model. It is based on the simplified stock–growth relationship that produces a positive rate of growth or surplus output (Coppola and Pascoe 1998). According to this theory, if the stock of fish population is not harvested, the uncaught population will gradually tend toward the maximum carrying capacity given a particular environment and a finite food source. As the population grows, surplus production is subsequently generated, which increases at a decreasing rate. However, this surplus output decreases at the point of maximum stock (corresponding to MSY as in Figure 5), because after this point, recruitment and growth of the population would be counterbalanced by natural mortality. Hence, beyond the MSY, the rate of increase of the fishery stock and the excess output becomes negative. The bioeconomic model thus offers a comprehensive method for assessing efficient fisheries management plans.

Figure 5. Depiction of the Gordon-Schafer's Bioeconomic Model



Source: Adapted from Gordon (1954) and Schaefer (1957)

The terms MEY and MSY refer to two distinct fisheries objectives that serve as the foundation for determining effective management strategies. OA denotes a situation where a shared pool resource and a lack of property rights result in no restrictions on harvested quantity. This is found to be socially inefficient as it results in suboptimal levels of outcome despite higher efforts compared to other scenarios. It thus results in lower catch levels with higher costs when compared with MSY and MEY.

The Gordon-Schaefer (GS) model is often used to identify the underlying relationship between the three management scenarios (Gordon 1954; Schaefer 1957). The model's ability to provide preliminary recommendations for both single-species and multi-species fisheries while only requiring limited data is a significant benefit, especially because the available data in the public domain captures only boat numbers and not changes in fishing intensity over the years. Further, due to complex biological and technological interactions, and the prevalence of predominantly small-scale fishing in the lake region, we believe that alternative fishing techniques or equipment will have similar results and that the same fishing effort would be utilized for harvesting a variety of species. Hence, the simplest GS, which assumes homogenous boats and a single stock, is utilized in this study to give a broader perspective on the fishing status in Chilika. Thus, in this study, we use the GS model to estimate the optimal levels of yield and effort for fisheries extraction in the Chilika wetland. The GS model is based on the following logistic equation describing a parabolic curve as a function of stock:

$$F(X) = rX(1 - X/K) \tag{1}$$

Where,

F(X) is the surplus biomass growth per unit of time.

X is the biomass of the given stock.

K and *r* refer to the carrying capacity and rate of intrinsic growth of the stock.

The harvest rate is given by the following Schaefer's catch function:

$$H(E, X) = qEX \tag{2}$$

E denotes the fishing effort and *q* is the catchability coefficient. Sustainable yield is then when the surplus growth equals the harvest rate.

$$\delta x/\delta t = F(X) - H(E, X) = 0 \tag{3}$$

Based on (1) and (2):

$$\delta x/\delta t = qEX = rX(1 - x/K) \tag{4}$$

and solving for *X* at equilibrium:

$$X = K(1 - qE/r) \tag{5}$$

Hence, eq. (2) then becomes:

$$H(E) = qKE(1 - \frac{qE}{r}) = qKE - \frac{q^2KE^2}{r} \tag{6}$$

Dividing both sides by (*E*) gives:

$$CPUE = \frac{H}{E} = qK - \frac{q^2KE^2}{r} \tag{7}$$

Eq. (8) depicts the total revenue function at the equilibrium:

$$TR(E) = p.H(E) \tag{8}$$

Where *p* is assumed to be a constant price per unit harvest:

$$TC(E) = c.E \tag{9}$$

Eq. (9) gives the total cost of fishing effort with *c* denoting per unit cost of effort. Obtaining the equilibrium resource rent from eqs. (8) and (9):

$$\prod (E) = TR(E) - TC(E) \tag{10}$$

Assuming average revenue at OA equilibrium to be *AR* = *TR*/*E* and *AR* equal to marginal cost (*MC* = '*TC*' (*E*):

$$\frac{pH}{E} = c; \frac{H}{E} = \frac{c}{p} \tag{11}$$

We may determine the fish stock's OA equilibrium level by considering the unit cost of harvest and the resource rent per unit harvest. Thus using eqs. (2) and (9), the unit cost of harvest is as follows:

$$C(X) = \frac{TC(E)}{H} = \frac{cE}{qEX} = \frac{c}{qX} \tag{12}$$

This shows that as stock size increases, the unit cost of harvest reduces. Further, the resource rent per unit of harvest then becomes:

$$b(X) = p - \frac{c}{qX} \tag{13}$$

The long-term harvest function is denoted by:

$$H(E) = aE + bE^2 \tag{14}$$

and CPUE is denoted as follows:

$$CPUE = a + bE \tag{15}$$

where CPUE = H/E, $a = qK$, and $b = -aq/r$. Thus, the parameters a and b are obtained from the OLS regression of CPUE upon effort.

Eq. (13) is then used to calculate effort at MSY by calculating the partial derivative of H with respect to E and bringing it equal to zero:

$$E_{MSY} = -\frac{a}{2b} \tag{16}$$

and the output at MSY is:

$$MSY = \frac{-a^2}{4b} \tag{17}$$

According to the OA, total fishing costs equal total revenue from the fishery ($TR(E) = TC(E)$). As a result, the effort at OA yield may be calculated using the Gordon-Schaefer model by equating $MC = AR$, hence:

$$c = \frac{pH(E)}{E} \tag{18}$$

$$c(E) = pH(E) \equiv E_{OA} = \frac{c/p - a}{b} \tag{19}$$

The maximum economic return is reached for positive economic rent at a reduced total fishing effort, lower than $E(OA)$. MEY is accomplished at a profit-maximizing level of effort:

$$E_{MEY} = \frac{c/p - a}{2b} \tag{20}$$

The impact of restoration measures implemented during 1992–93 and 2002–03 as part of Chilika Lake being classified under the Montreux Record has been captured by performing an independent t-test for these periods. The base period selection indicates the period during which severe measures to rehabilitate the lake to its original state were undertaken. As stated earlier, in 2002, the lake was declared successfully restored and subsequently removed from the Montreux Record. Further, economic considerations are found to be mostly ignored in most studies on surplus production models. Differing consumer demand and supply responses can notably impact the fishery stock's exploitation rate.

In the context of Chilika, demand for its fishery products is mainly driven by the distinctive quality and flavour that these species have due to the brackish features of the water. Studies such as Gudmundsson and Wessells (2000), Courchamp *et al.* (2006), Hall, Milner-Gulland, and Courchamp

(2008), and Booth, Squires, and Milner-Gulland (2019) indicate how perceived rarity affects consumer behaviour, thereby influencing prices through changes in demand. The cost of extraction also plays a role in influencing the sustainability of the resource. Changes in costs are driven by expenses incurred towards the type of gear, boats and their maintenance, fuel costs, lease fees, costs incurred in setting up storage facilities, etc. Habitat degradation driven by climate change and anthropogenic factors can also increase the cost of harvesting through its impact on stock levels. The following five scenarios indicate how bioeconomic estimates and profits are impacted by changes in prices and how costs are modelled in this study. It is to be noted that, although choosing a 10% change may seem arbitrary, it offers the right amount of significance to affect the results without making it unfeasible or unrealistic. This approach facilitates a constructive appraisal of the model's sensitivity by not introducing undue instability or volatility. The five scenarios are as follows:

S0: Baseline, denoting the current situation
S1: Cost increases by 10% + Price is the same
S2: Cost reduces by 10% + Price is the same
S3: Cost is the same + Price increases by 10%
S4: Cost is the same + Price reduces by 10%

4. DATA AND RESULTS

The data used to obtain the sustainable catch level using the GS bioeconomic model was obtained from the CDA and Odisha Fisheries Department. The data for the bioeconomic model was for the period 2001–18, and the data on the evaluation of restoration efforts was available for the period 1978–79 to 2000–21. Catch data was proxied by the total landings for the given period. The effort was calculated in terms of the number of boat days in a year and the number of boats deployed for fishing. The given data was normalized and brought to a units-per-day basis. Since there was a lack of secondary data on input costs, the cost of fishing effort was calculated based on the fuel price and quantity of fuel consumed on a fishing day (i.e., 3.7 litres of diesel per fishing trip and the price of fuel in 2018 was between ₹55–₹62) and the minimum daily wage rate earned per fishing day (₹200 as per MGNREGA). The unit cost of fishing effort and the unit price of the harvest in Chilika is thus estimated to be ₹52/kg (= (3.7*60) + 200 = ₹422/8.11) and ₹151.32/kg (= (2474.1*1000000) / (6000*336) = ₹1227.23/8.11), respectively, in 2018.

Table 2: Key Statistics Related to Chilika Lake

	2001/02	**2017/18**
Number of fish landing centres/sampling stations	17	34
Number of fishing boats used for regular fishing during the year	5,000	6,000
Annual landing (fisheries output) in tonnes	11,988.88	16,358.34
Total catch value in million rupees (nominal)	571.60	2,474.10
Average CPUE (Kg/boat-day)	6.950	8.11
Total number of fishing days	345	336

The surplus production assessment method uses catch per unit effort (CPUE) as a measure of stock abundance. In the case of Chilika, the fish CPUE trend had a significant drop that started in 2005–06, followed by a rise that is found to have persisted. However, the fluctuations are not drastic and are between the 6–8 CPUE range (Table 2). The effort at maximum sustainable yield (MSY) based on the regression coefficients is 0.655 kg/boat/day, and that of maximum efficient yield (MEY) and open access (OA) are 0.64 and 1.29 kg/boat/day; profits estimated per unit at MSY is ₹1,207.63, at MEY is ₹1,199.67, and at OA is ₹73.82. Comparing the CPUE and effort shows that the number of boats has increased over the years, but the CPUE remains more or less the same. This could indicate the presence of unsustainable fishing methods where the effort burden is placed on smaller fish varieties, which does not significantly contribute to total yield or weight, thereby resulting in a reduced CPUE. This situation could further worsen if the continuous increase in fishing efforts persists without proper regulatory measures. Additional increases in fishing efforts would negatively impact the fish population, and neither of the reference points (MSY and MEY) will be in an equilibrium state.

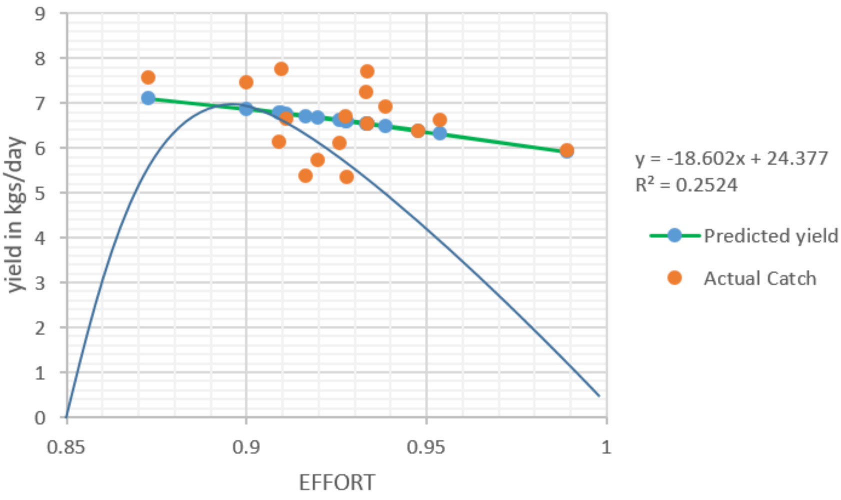
Regression results for the GS model are depicted in Figure 6 and through equation 21. Regression of CPUE on effort shows a downward sloping linear trend (negative slope coefficient b), indicating that a higher effort would result in a lower yield after a specific time as the stock size would be limited. The estimates are significant at a 10% significance level, and the model R^2 value suggests that changes in effort levels explain a 25% variation in the catch. The GS curve for the Chilika fishery resource can be indicated as follows:

$$H(E) = 24.377E + (-18.602E^2) \quad (21)$$
$$\qquad (0.006) \qquad\qquad (0.039)$$

The parameters *a* and *b* generate the predicted yields given the effort levels. These are then matched with Gordon-Schafaer's production curve, which traces an inverted-U shape, indicating the relationship between regeneration capacity and the sustainable harvesting rate.

The projected MSY was obtained using the regression coefficients in the GS model, and the corresponding effort levels were compared with the actual catch and effort data to determine if present fish harvesting techniques are ecologically sustainable (Figures 6 and 7). Figures 6 and 7 show that the actual catch rates are mostly higher than sustainable levels. Upon analysing the actual catch vis-a-vis predicted catch values for the same given levels of effort, it can be seen that the harvesting trend has remained more or less the same as that of the sustainable levels, with only slight variations biologically.

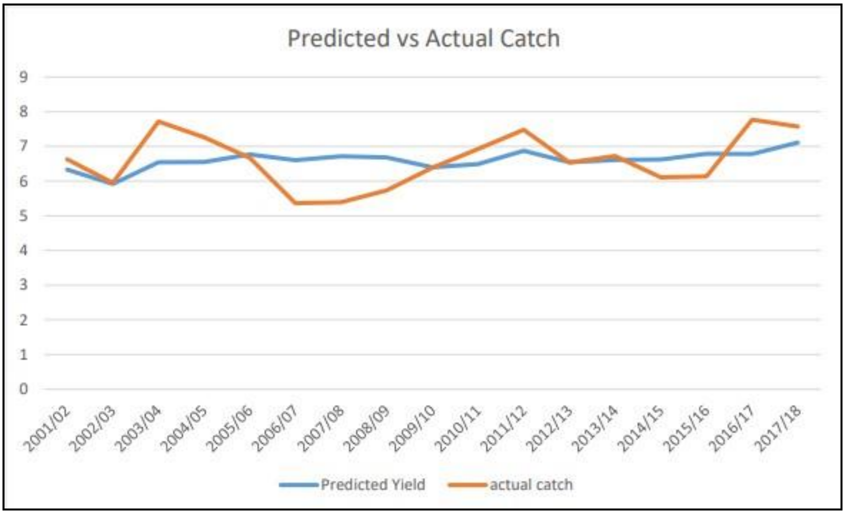
Figure 6: Regression of CPUE upon Effort and Actual Catch and Predicted yield with Respect to the Effort–Harvest Relationship



Source*:* Author's analysis

An independent sample t-test is conducted to compare the impact of restoration for the periods before and after when the site was declared out of the Montreux Record (Table 3). In addition, for higher accuracy, a BCa 95% confidence interval is also obtained with 1,000 bootstrap samples using the bias-corrected accelerated (BCa) bootstrapping technique. There are significant differences (t(df = 40) = −9.71, p = 0.001) in the fisheries output with mean landings for the period before restoration (M = 5,311.61, SD = 2,832.46, BCa 95% confidence interval: 4,181.24 to 6,549.75) found to be lower than in the period after 2003 (M = 13,065.31, SD = 2,134.49, BCa 95% confidence interval: 12,018.84 to 14,163.17). The magnitude of the difference in the means (mean difference = −7,753.69) is significant. Thus, the model suggests that restoration efforts have positively impacted the level of fisheries output. However, Pauly *et al.* (2013) argue that fisheries output need not necessarily correlate with stock abundance and reflect better fisheries' health. Various external factors beyond fish availability may also influence catch size—from shifting policies to revamped management strategies. They further add that, though this measure should be used with caution, it is also worth noting that for most species of fish, declining trends might go unnoticed without information on actual catch levels.

Figure 7: Actual Catch vs. Predicted Sustainable Yield Values



Source*:* Author's analysis

The different scenarios with varying per unit harvest price and cost per unit effort were analysed. The effects of the cost and price variations on the predicted parameters of MSY, MEY, and OA were observed. It is to be noted that these observations denote the impact under the assumption that intrinsic growth and the carrying capacity of the lake are constant. Table 4 summarizes the impact of changes in costs and prices upon harvest levels and per-unit profits. In S1, when costs increase by 10% and prices remain at the base level (S0), the harvest goes up by 0.69% for the given level of effort, whereas the average change in profits declines by 2.36% at the MEY level. In the case of OA, both harvests and profits decline when compared to the S0 scenario. In S2, when costs reduce by 10%, profits decline further by 1.79%, despite an increase in harvests by 0.7%. In scenario S4 (where costs do not change, but prices decline by 10%), there is a 12.77% decrease in profits compared to the base scenario, despite the harvest rate being the same. In general, the situation of OA for different scenarios was unsustainable from an economic point of view. S3, where the prices increased by 10% with costs remaining the same, was found to be favourable as the overall profits went up by 7.48% with a slight increase (0.24%) in harvest rates.

Table 3: Results of the Differences in Total Output Before and After Restoration of the Lake (Independent Sample T-test with Bootstrapping Confidence Intervals)

Variables	N	Mean	SD	Mean difference	t	p	BCa 95% CI
Before	24	5,311.61	2,832.46	−7,753.69	−9.71	0.001	4,181.24 – 6,549.75
After	18	13,065.31	2,134.49				12,018.84 – 14,163.17

bootstrap results are based on 1,000 bootstrap samples; BCa: bias-corrected accelerated;

Before the restoration period (1978–79 to 2002–03); after the restoration period (2003–04 to 2020–21)

Source: Author's analysis

5. DISCUSSION AND CONCLUDING REMARKS

Bioeconomic models play an essential role in fishery harvesting management by prioritizing three key scenarios: MSY, MEY, and OA (Seijo 2001). These impactful strategies help enhance the sustainability and optimization of fisheries management practices and help raise awareness among stakeholders directly impacted by it. The unique perspectives presented by each scenario enable deeper insights that can promote more informed approaches towards managing Chilika Lake's precious resources. MSY seeks ecological sustainability while prioritizing species conservation, whereas OA favours economic efficiency by establishing a necessary balance between costs and profits while determining harvest rates. Finally, MEY focuses on providing a middle ground where both ecological sustainability and economic efficiency are regarded equally. Policymakers and fishery managers should take into consideration all three scenarios to ensure the sustainability of Chilika Lake and a profitable future for fishing communities. In this study, we used CPUE and fishing efforts to analyse the stock abundance and sustainability of the present harvesting techniques employed in Chilika. The GS model ignores biological cycles, such as those

Table 4: The Results of Different Scenarios of Harvests, Corresponding Effort, and Profits at the MSY, MEY, and OA Levels in Reaction to Changes in Prices and Costs

Scenario	Cost per unit effort (Rs/kg)	Price per unit harvest (Rs/kg)	Effort (kg/boat/day)		Harvest (kg/boat/day)		% Change	Profits (Rs/kg/boat/day)	% Change
S0	52	151.32	E(MSY)	0.655	H(MSY)	7.982	-	1,207.63	-
			E(MEY)	0.645	H(MEY)	7.929	-	1,199.67	-
			E(OA)	1.291	H(OA)	0.490	-	73.81	-
S1	57.2	151.32	E(MEY)	0.645	H(MEY)	7.984	0.69	1,171.26	−2.36
			E(OA)	1.290	H(OA)	0.487	−0.62	0.35	−99.51
S2	44.1	132	E(MEY)	0.647	H(MEY)	7.985	0.70	1,178.11	−1.79
			E(OA)	1.294	H(OA)	0.388	−20.87	−2.87	−103.8
S3	49	145.2	E(MEY)	0.646	H(MEY)	7.948	0.24	1,289.46	7.48
			E(OA)	1.293	H(OA)	0.403	−17.75	−0.5	−100.6
S4	49	118.8	E(MEY)	0.644	H(MEY)	7.929	0	1,046.37	−12.77
			E(OA)	1.289	H(OA)	0.492	0.362	−0.34	−100.4

Different scenarios: S0: Baseline, denoting the current situation; S1: Cost increases by 10% + Price are same; S2: Cost reduces by 10% + Price is same; S3: Cost is same + Price increases by 10%; S4: Cost is same + Price reduces by 10%.

(Note: As per eq. 16, MSY would not get impacted by changes in costs and prices; hence it remains the same in the rest of the scenarios.)

Source: Author's analysis

brought on by variations in recruitment (i.e., transitioning from very small and surviving to becoming old fish), and assumes that the resource responds instantly to changes in effort and total costs grow linearly as effort increases (Seijo 2001; Hilborn and Walters 2013). Therefore, this study takes into consideration the classical GS model which assumes linearity or direct proportionality in stock size, fishing effort, and catch values. For the specified research period, the study found that MSY and MEY for the GS model of the Chilika fishery had similar outcomes with only minor fluctuations. However, it is interesting to note that effort as a function of boat numbers grew while the annual number of fishing days remained constant. It is also to be noted that there has been little distinction between outcomes of OA under different scenarios over the years. MSY does not indicate effective harvesting from an economic perspective, as efficiency is defined as maximizing the net profit from the use of economic resources or maximizing resource rent (Holma *et al.* 2019; Grafton, Kompas, and Hilborn 2007). Therefore, MEY is usually regarded as an appropriate reference point for fisheries management. However, in the case of Chilika, it is found that both MSY and MEY are occurring at nearly the same point with significantly less difference. This indicates that the economic efficiency of the sustainable yield curve is the same as that of harvesting at the profit-maximizing point. This could be concerning if fishing is characterized by smaller pelagic and demersal fishery, with the burden on smaller varieties.

Further, there are no reports of fisherfolk discarding bycatch from Chilika, which can indicate biological overfishing. However, based on the results presented in the paper, it is not severe for the fishery resources. A fishery endeavour cannot be considered sustainable if the overall catch exceeds the MSY level. The MEY strategy is best described as one that considers the economic efficiency of the sustainable yield curve, and pursuing this objective—or at least analysing it for every specific fishery species—has several advantages. Given this backdrop, the results of the current model reveal that the Chilika fishery is at a critical stage as both the MSY and MEY have been reached, and resource depletion is quite likely if it is not managed going forward. Larkin *et al.* (2011) suggest that among the reference points, it is important to prioritise MEY, as this approach is responsive to variations in economic conditions and is more efficient as it minimizes harvesting costs. Further, the results obtained under OA conditions also indicate that unless managed efficiently, resources will probably be over-exploited. We believe that the shifting governance structure and the subsequent changes in fishing policies in Chilika—which are more oriented towards the privatization of the lake's resources (e.g., growing demand for shrimp aquaculture)—have in fact disrupted the ecological balance even more. Further, the evolution of Chilika's fisheries demonstrates that, despite its potential for discrimination, the earlier caste-based fishing encouraged collective management of the lake's resources, hence preventing undue pressure on resources (Nayak and Berkes 2011, 2014; Sekhar 2007). Also, studies such as Ostrom (2009) and Folke *et al.* (2005) have established that the success or failure of the sustainable use of common areas is correlated with institutional and governance structures. In addition, we must consider factors such as emerging technologies, changing knowledge patterns, as well as shifts in power dynamics, all of which affect how the lake's resources are utilized. Therefore, to avoid the rapid depletion of the lake's resources, it is critical to emphasize collaborative practices while striving for collective governance when managing Chilika Lake. Hence, we stress on inclusive management strategies that consider local community support for restoration of the lake and concerted actions towards the efficient usage of its assets.

From the results of the different scenarios analysed, it can be concluded that given the biological parameters, ensuring that the fish stock does not reach the critical limit or get exhausted would entail policies that target harvest rates and prices. Strict measures should be in place to ensure a specific quantity of catch. However, being a common pool resource, this would be difficult to implement in the case of Chilika. Practical solutions to this could be limiting the number of boats, regulating the number of fishing licenses and fishing days, monitoring the market for the final products, and providing access to credit facilities for fishers and alternative employment opportunities. Also, international agreements like the Ramsar Convention may offer vital resources for nations stepping up their conservation efforts. Most of these international accords rely on non-binding measures for protection. Hence, many times, their goals get compromised either due to weak management strategies (Munguía and Heinen 2021) or due to the ineffectiveness of the government (Pomeranz *et al.* 2021). As the Ramsar Convention seeks to establish a global cooperation network, its implementation should serve as a role model. This is especially critical given that the network aims to sustain vital habitats for endemic and migratory species, directly enhance human livelihoods, and preserve wetlands as an integral part of local cultures. This is necessary to preserve the Ramsar Convention's integrity and increase public perception.

The analysis has implications for small-scale fishers as well. Small-scale fisheries are characterized by the following: little technological sophistication, lower capital–output ratio, labour-intensive production, the presence of manual labour and part-time fishing, a large number of traditional boats targeting a diverse range of species, poor economic returns, and a complex production process affected by the culture and customs of small-scale fishing communities (Tietze 2016). Consequently, fisheries of such scale are mostly undervalued and unregulated (Mills *et al.* 2011). The general effects of fishing on ecosystems are made worse by the complacent perception that this sector has a more negligible impact than industrial fisheries, especially considering that small-scale fisheries frequently occur in sensitive regions like mangroves (Hutchison, Spalding, and Ermgassen 2014). Hence, ignoring its effects and interlinkages increases the vulnerability of fisheries to climatic and global changes. For instance, already poor fisherfolk may get loans they cannot pay to counter decreased yield by increasing their effort and catch. This might result in the overfishing of species that fetch higher market prices. The ecology thus suffers from this kind of endeavour, which has detrimental effects on local livelihoods (Salayo *et al.* 2008). Given this context, maintaining socioeconomic benefits and conserving fishery resources in an ecologically sensitive area like Chilika is crucial in global and local contexts. Failing to protect such small-scale fisheries would not only negatively impact the locals' ability to support themselves, but it would also have a detrimental effect on the ecological characteristics of the lake.

In conclusion, fisheries management is better understood by evaluating changes in fishery output. For instance, the slight alterations noted in this study's analysis could represent the start of far more severe adverse effects on the species and the people who depend on fishing, such as fishers and all other users of the fish value chain. Furthermore, the lack of timely interventions and management of a common pool resource like Chilika may increase the strain on natural resources to meet the demands resulting from its products. Identifying the changes the fisheries sector goes through in ecologically sensitive areas also has social implications because stock depletion may result in food loss and revenue loss. This study was able to account for the economic contributions made by fisheries to the local economy; a further improvement to the analysis would be to capture the damage to stocks that fisheries cause or its net social impact on the local economy.

Though this study does not measure stock levels in light of the regeneration rates of individual species, studies such as Coppola and Pascoe (1998), Holma *et al.* (2019), and Grafton, Kompas, and Hilborn (2007) indicate that the stock gets depleted in the long run if the harvested levels are higher than the regenerating capacity. This can be a severe cause of concern in the case of Chilika as it would not only impact ecological diversity but also negatively impact the dependent fisher community. Lastly, the results should be viewed as the upper bound in this case, as the model considered in this study does not account for ecological complexities and environmental uncertainties due to the paucity of information. This study employs the classical Gordon-Schaefer model in its simplest form as it is easily adaptable to suit different fisheries' requirements owing to its broad application range. By revealing the standard tradeoffs between fishing effort management decisions versus supplying sustainably desired yields without considering any fish species or other peculiarities relevant to fisheries operations, this approach is beneficial during initial assessments, besides being an excellent benchmark for complex modelling techniques. Future studies can consider stock assessments that include non-linear relationships between variables and species specificness and which also encompass spatial dimensions for precision analysis. The study currently ignores the real economic opportunities that multiple stakeholders face and the dynamics of biological populations and parameters, which are subject to uncertainty. Hence, further improvement is needed in this area. Though the data requirements are high, the study needs to consider ecosystem-based management approaches that emphasize ecological, economic, and social objectives for the present and future generations.

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Data Availability statement: The data used to support this research is not provided in a repository as it can be downloaded from the original sources mentioned in the paper.

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