

Original Research Articles

Evaluation of the efficacy of implementing Ecosystem-Based Management (EBM) strategies within fisheries across the middle and lower Yangtze River basin lakes in China

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To mitigate the decline of fishery resources and the exacerbation of water pollution in Chinese lakes and to enhance the potential and sustainable use of lake fisheries, the Chinese government has actively implemented principles and models of ecosystem-based lake fishery management. This includes promoting ecological aquaculture techniques and the “retiring pens to restore lakes” policy. To assess the effects of ecosystem-based management on Chinese lake fisheries, data from 2007 to 2020 were collected for the Qiandao Lake, Tai Lake, Hongze Lake, Luoma Lake, and Gaobao Lake in the middle and lower reaches of the Yangtze River. The study employed Data Envelopment Analysis (DEA) to assess fishing efficiency through a static input-output efficiency model. Additionally, the Malmquist index and distance functions were used for a dynamic comparison of total factor productivity (TFP) across the five lake management models. The results indicate that trends in technological progress, scale efficiency, and TFP were consistent across the lakes from 2013 to 2020. Qiandao Lake, Tai Lake, and Hongze Lake showed a positive average annual growth rate in TFP, with Qiandao Lake having the highest average annual growth rate of 13.2%. In contrast, Gaobao and Luoma Lakes experienced a negative growth rate in TFP. Furthermore, Qiandao Lake exhibited significantly higher technical efficiency than the other four lakes, effectively achieving an efficient state, followed by Hongze Lake. The study demonstrates that technological progress and variations in scale efficiency are the primary factors driving the increase in TFP in fisheries. Promoting ecosystem-based “fishing for water conservation” aquaculture techniques and restricting aquaculture scale through the “retiring pens to restore lakes” policy contribute to enhancing TFP in ecological fisheries.

INTRODUCTION

The fisheries sector and fishery economy are paramount to socio-economic development and public welfare in countries with large populations.¹ As a leading fish-producing nation, China contributes approximately one-third to global aquatic product output, with its freshwater product output constituting over half of the global freshwater product volume.² The intensive development of freshwater fisheries, particularly the swift expansion of aquaculture, has led to the extensive exploitation of significant water bodies, including lakes and reservoirs. China boasts 2,693 natural

lakes, each larger than 1.0 km², and an area of 81,400 km². Out of this, 18,700 km² are deemed suitable for aquaculture. Additionally, aquaculture-friendly reservoirs span 20,000 km², representing over 70% of the nation's inland-capable waters.³ Predominantly situated in subtropical and temperate zones, China's lakes provide unparalleled conditions for nurturing freshwater fisheries. In 2022, lake fisheries accounted for 18% of China's freshwater fishery production, underscoring their critical role.⁴

Urbanization has driven the aggregation of urban populations, increasing the demand for recreational fisheries, which has led to the rapid development of aquaculture and

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recreational fisheries, evolving from small-scale family operations to large-scale farming by fisheries cooperatives. Moreover, as a significant population moves to urban areas, many fishers are transitioning to other professions and settling ashore, gradually decreasing lake fishermen. This transition brought about by urbanization leads to a natural change in the pattern and structure of lake fisheries.

However, China's accelerated economic progression and rapid industrial and agricultural advancement have exacerbated water pollution, perpetuating a yearly reduction in lacustrine fishery resources and diminishing fishery outputs. Fish play a regulatory apex role within lacustrine ecosystems, intricately linked to other biotic components through the food web. Alterations in fish populations and their decline precipitate the deterioration of lake ecological functions. Concurrently, the proliferation of intensive lake aquaculture has increased the influx of allochthonous nutrients, expediting the eutrophication of these aquatic ecosystems.^{5,6}

Examining the global trajectory of lake fisheries development, it becomes apparent that since the 1950s, a common trend has emerged characterized by the depletion of natural fishery resources, environmental degradation, and climatic changes. These challenges, coupled with the limited availability of fishery resources, have catalyzed the rapid advancement of aquaculture within lake fisheries. Aquaculture has become the predominant form of fisheries in lakes, with efficient intensive farming techniques such as cage aquaculture and factory-based fish farming gradually evolving in certain countries. Countries at the forefront of advanced intensive aquaculture include Japan, Europe, and the United States. The US introduced cage fish farming technology in 1964, achieving a maximum 600 kg/m³ yield. By the mid-1960s, the successful introduction of Coho salmon into the Great Lakes was reported. In addition to conservation efforts to maintain and protect the ecological environment from degradation, the development of recreational fishing has emerged as another hallmark of lake fisheries in developed countries. The US began promoting recreational lake fishing in the 1920s, a form of fisheries renowned for its broad participation, environmental conservation, and substantial economic benefits.⁷ By the early 1980s, participation in freshwater recreational fishing in the US exceeded 20 million individuals. Lake stocking in the US gradually became a service industry supporting recreational fishing.⁸

Despite differences in the status of fisheries resources, the intensity of development and utilization, and focus points in fishery resource management between foreign countries and China, the experiences and practices of foreign fishery resource management are worthy of our consideration and emulation.

Fisheries constitute a critical function of lake ecosystems, significantly influencing their ecological progression and serving as a cornerstone for lake management and ecosystem restoration efforts.⁹ The essential criteria for managing China's inland aquatic resources stipulate the imperative to preserve water quality, accommodate fishery interests, pursue moderate development, and ensure sus-

tainable usage. The urgency of implementing ecological restoration in lakes is paramount; it encompasses safeguarding the aquatic environment and reversing the negative trends impacting fishery resources alongside their ongoing preservation.¹⁰ Globally endorsed, ecosystem-based fishery management is a strategic and effective method to expedite the recuperation of overharvested fishery stocks, avert further ecological deterioration, and facilitate the enduring sustainable exploitation of these resources. This management paradigm involves a holistic approach that incorporates living and non-living components, human dimensions, and the myriad interactions therein, spanning the spectrum of extant yet-to-be-discovered factors within an ecologically significant context.

LITERATURE REVIEW

Numerous scholars have deconstructed total factor productivity (TFP) to further our understanding of its components, such as the rate of technical contribution and efficiency. Robert Solow pioneered in this field, using the growth rate equation to evaluate technological advancement in the United States, enriching our grasp of technology's influence on economic expansion.¹¹ He posited that TFP is the segment of output growth persisting after the deduction of factor growth, effectively encapsulating the yield of technological progression. Furthermore, Solow explored how to gauge production efficiency with fixed factor inputs.

Data Envelopment Analysis (DEA) was introduced in 1978 by Charnes et al. as a technique for appraising the effectiveness of decision-making units. Farrell was at the forefront of measuring TFP through Stochastic Frontier Analysis (SFA), which scrutinizes input factors, outputs, and technical efficiency via frontier production functions.¹² Christensen et al. advocated for the translog production function to quantify narrowly defined technical progress.¹³ Moreover, Kumbhakar et al. dissected TFP growth by employing theories of economic growth, estimating the impact of such progress, enhancements in technical efficiency, and scale efficiency on China's economic development.¹⁴

Cinemre et al. employed DEA to assess the technical, resource allocation, and cost efficiencies of tilapia aquaculture in the Turkish Black Sea region with a comprehensive analysis.¹⁵ Similarly, Alam et al. utilized SFA to investigate technical efficiency and the principal factors influencing inefficiency in genetically modified tilapia aquaculture in Bangladesh.¹⁶

The studies mentioned above offer valuable insights into fisheries' technical efficiency and scale returns. Nevertheless, the focus within China's fisheries management research, particularly concerning fishing and aquaculture, is often limited to efficiency evaluations with incomplete input and output indicators and predominantly qualitative in nature. Addressing this gap, this article analyzes output efficiency in terms of fisheries technical efficiency (static) and TFP (dynamic) for five lakes in the Yangtze River's middle and lower basins over the period 2007-2020. This is

achieved using DEA and the Malmquist index method after the application of ecosystem management.

This research evaluates output efficiency with carefully chosen indicators and considers three primary inputs: labor, capital, and natural resources. In its comprehensive appraisal of lake fisheries efficiency, the study further delineates the technical efficiency of the five lakes and elucidates the reasons behind diminishing scale returns in fisheries. It also scrutinizes existing issues within these lakes, aiming to inform factor allocation strategies for Chinese lake fisheries, enhance the efficiency of ecosystem management methods, promote sustainable and high-quality lake fisheries development, and support the government in crafting enduring policies for the sustainable growth of fisheries.

MATERIALS AND METHODS

DATA SOURCES

The data for this study were collected between 2020 and 2023 through a series of surveys conducted at the Qiandao Lake Development Group in Hangzhou, the Taihu Lake Fisheries Management Committee Office, the Jiangsu Freshwater Fisheries Research Institute, the Gaobao Shaobo Lake Fisheries Management Committee Office, and the Luomahu Fisheries Management Committee Office, among other fisheries management organizations in Jiangsu Province. These surveys compiled fisheries' production values (including fishing and aquaculture), lake phosphorus content, and the number of laborers and boat horsepower from five lakes from 2007 to 2020. Bound by the Land and Resources Data Confidentiality Agreement in China, data research can only be published up to 2020. The processed survey data regarding input-output indicators are detailed in the appendix, along with the survey inventory.

METHODS

(A) DEA-CCR MODEL

Data Envelopment Analysis (DEA), formulated by American operations researchers Charnes, Cooper, and Rhodes in 1978, is commonly called the CCR model.¹⁷ It is an analytical methodology that assesses the relative efficiency of Decision-Making Units (DMUs) by utilizing input and output data. The model is designed to compute comprehensive technical efficiency predicated on the premise of constant returns to scale, hence its alternate designation as the Constant Returns to Scale (CRS) model.

Assuming there are n Decision Making Units ($DMU_j (j = 1, 2, \dots, n)$), the input for DMU_j is denoted as $x_j = (x_{1j}, x_{2j}, \dots, x_{mj})^T$, and the output is denoted as $y_i = (y_{1j}, y_{2j}, \dots, y_{tj})^T$, with m being the number of input indicators and t the number of output indicators. Additionally, it is given that $x_j, y_j \geq 0$. The CCR (Charnes, Cooper, and Rhodes) model, which incorporates non-Archimedean infinitesimals, is presented as follows:

$$\begin{aligned} \min & \left[\theta - \varepsilon \left(\sum_{r=1}^t S_r^+ + \sum_{i=1}^m S_i^- \right) \right] \\ & \sum_{j=1}^n \lambda_j x_{ij} + S_i^- = \theta x_{ij0} \\ & \sum_{j=1}^n \lambda_j y_{rj} - S_r^+ = y_{rj0} \\ & \lambda_j \geq 0, j = 1, 2, \dots, n \\ & S_i^- \geq 0, S_r^+ \geq 0 \end{aligned}$$

In the specified model, x_{ij} denotes the input quantity of the factor i for j^{th} the Decision Making Unit (DMU), while y_{rj} denotes the output quantity of the r factor for the same DMU . Slack and surplus variables are represented by S_i^- and S_r^+ respectively, highlighting instances of input excess and output deficit. The non-Archimedean infinitesimal, ε typically set to $\varepsilon = 10^{-6}$. Additionally, λ_j , S_i^- , S_r^+ and θ are the parameters requiring estimation.

The economic rationale behind the CCR model is articulated as such: when $\theta = 1$ and $S_i^- = S_r^+ = 0$, the DMU in question is deemed DEA-efficient concerning overall technical efficiency. By defining as $x_0^* = \theta x_0 - S_i^-$, $y_0^* = y_0 + S_r^+$, the point (x_0^*, y_0^*) is established as the projection of (x_0, y_0) onto the efficient frontier. This indicates that, compared to the original DMU , the adjusted DMU achieves DEA efficiency.

(B) DEA-BCC MODEL

The CCR model assumes that all Decision Making Units ($DMUs$) operate under conditions of constant returns to scale. This assumption may not accurately reflect the current production characteristics of the lake fishery. In 1984, Banker, Charnes, and Cooper introduced the BCC model, which accommodates variable returns to scale. This model adds a convexity constraint, $\sum_{j=1}^K \lambda_j = 1$ to the foundation established by the CCR model, while all other aspects remain unchanged.¹⁸ The specific formula is as follows:

$$s.t. \begin{cases} \min \theta_c \\ \theta_c X_0 - \sum_{j=1}^K \lambda_j x_j \geq 0 \\ Y_0 + \sum_{j=1}^K \lambda_j y_j \geq 0 \\ \sum_{j=1}^K \lambda_j = 1 \\ \lambda_j \geq 0 (j=1, 2, \dots, K) \end{cases}$$

The second phase involves processing slack variables to optimize efficiency and identify paths for efficiency enhancement. The DEA model for the second phase is as follows:

$$\begin{aligned} \min & - [\theta_c - QT * OS + WT * IS] \\ s.t. & \begin{cases} \sum_{j=1}^K \lambda_j y_j - OS = y_0 \\ \sum_{j=1}^K \lambda_j x_j - IS = \theta_c X_0 \end{cases} \end{aligned}$$

(C) THE MALMQUIST INDEX

The DEA (Data Envelopment Analysis) model is a static analytical method that evaluates the efficiency of decision-making units by comparing their input and output envelopment surfaces (cross-sections). It is only capable of comparing the efficiency among decision-making units (e.g. sample lakes) within the same period. It does not compare the efficiency of decision-making units across different periods. In 1994, Rolf Färe, Shawna Grosskopf, and oth-

Table 1. Input and output quantity of five lakes (after data processing)

Year	Lake	Production value	Lake phosphorus content	Fishermen population	vessel horsepower	Year	Lake	Production value	Lake phosphorus content	Fishermen population	vessel horsepower
2007	Taihu	0.026	0.126	0.179	0.032	2012	Taihu	0.032	0.129	0.183	0.019
	Qiandao	0.181	0.186	0.644	0.035		Qiandao	0.132	0.192	0.648	0.029
	Hongze	0.044	0.095	0.020	0.016		Hongze	0.048	0.095	0.020	0.016
	Luoma	0.024	0.158	0.011	0.024		Luoma	0.016	0.161	0.030	0.027
	Gaobao	0.140	0.121	0.635	0.023		Gaobao	0.046	0.144	0.547	0.026
2008	Taihu	0.026	0.128	0.187	0.029	2013	Taihu	0.031	0.122	0.161	0.057
	Qiandao	0.168	0.182	0.652	0.027		Qiandao	0.130	0.194	0.655	0.057
	Hongze	0.040	0.070	0.020	0.016		Hongze	0.034	0.059	0.020	0.016
	Luoma	0.023	0.155	0.012	0.028		Luoma	0.016	0.175	0.031	0.028
	Gaobao	0.098	0.122	0.643	0.029		Gaobao	0.043	0.040	0.496	0.027
2009	Taihu	0.031	0.138	0.185	0.030	2014	Taihu	0.028	0.131	0.162	0.019
	Qiandao	0.157	0.180	0.656	0.027		Qiandao	0.128	0.193	0.659	0.030
	Hongze	0.038	0.030	0.020	0.016		Hongze	0.017	0.047	0.020	0.016
	Luoma	0.018	0.151	0.020	0.027		Luoma	0.014	0.163	0.031	0.027
	Gaobao	0.128	0.123	0.684	0.029		Gaobao	0.043	0.126	0.467	0.027
2010	Taihu	0.043	0.129	0.203	0.025	2015	Taihu	0.028	0.118	0.163	0.018
	Qiandao	0.154	0.187	0.653	0.028		Qiandao	0.098	0.191	0.653	0.065
	Hongze	0.041	0.060	0.020	0.016		Hongze	0.016	0.110	0.021	0.016
	Luoma	0.015	0.141	0.023	0.027		Luoma	0.014	0.168	0.031	0.028
	Gaobao	0.058	0.124	0.578	0.026		Gaobao	0.034	0.127	0.430	0.027
2011	Taihu	0.033	0.134	0.197	0.019	2016	Taihu	0.017	0.116	0.164	0.018
	Qiandao	0.131	0.191	0.655	0.028		Qiandao	0.094	0.193	0.644	0.028
	Hongze	0.049	0.020	0.020	0.016		Hongze	0.015	0.047	0.021	0.016
	Luoma	0.022	0.129	0.024	0.027		Luoma	0.013	0.141	0.031	0.027
	Gaobao	0.052	0.122	0.587	0.024		Gaobao	0.043	0.134	0.406	0.029
Year	Lake	Production value	Lake phosphorus content	Fishermen population	vessel horsepower	Year	Lake	Production value	Lake phosphorus content	Fishermen population	vessel horsepower
2017	Taihu	0.023	0.117	0.163	0.018	2019	Taihu	0.036	0.121	0.163	0.018
	Qiandao	0.085	0.192	0.670	0.026		Qiandao	0.027	0.187	0.649	0.027
	Hongze	0.014	0.183	0.021	0.016		Hongze	0.020	0.129	0.021	0.017
	Luoma	0.013	0.144	0.031	0.027		Luoma	0.017	0.129	0.036	0.028
	Gaobao	0.033	0.137	0.405	0.029		Gaobao	0.033	0.133	0.421	0.026

2018	Taihu	0.032	0.121	0.163	0.018	2020	Taihu	0.036	0.125	0.163	0.018
	Qiandao	0.032	0.191	0.647	0.026		Qiandao	0.024	0.185	0.647	0.028
	Hongze	0.018	0.124	0.021	0.017		Hongze	0.019	0.138	0.021	0.018
	Luoma	0.015	0.142	0.034	0.027		Luoma	0.020	0.157	0.059	0.028
	Gaobao	0.033	0.135	0.417	0.026		Gaobao	0.034	0.132	0.425	0.025

Data sources: The original data comes from the fisheries management committees of Taihu Lake, Hongze Lake, Luoma Lake, Gaobao Lake, and the Qiandao Lake Development Corporation.

ers introduced the Malmquist index,¹⁹ originally proposed by Sten Malmquist in 1953, into total factor productivity growth research to analyze cross-sectional data from different periods.²⁰ The Malmquist productivity efficiency index is defined using a distance function, with the formula for calculating the total factor productivity growth Malmquist index as follows:

$$M_0(x_{t+1}, y_{t+1}, x_t, y_t) = \sqrt{\frac{d_0^t(x_{t+1}, y_{t+1})}{d_0^t(x_t, y_t)} \times \frac{d_0^{t+1}(x_{t+1}, y_{t+1})}{d_0^{t+1}(x_t, y_t)}} \quad (1)$$

In this context, (x_{t+1}, y_{t+1}) and (x_t, y_t) denote the input and output vectors at periods $t+1$ and t , respectively; d_0^t and d_0^{t+1} represent the distance functions with respect to technologies T_t and T_{t+1} , respectively. The Malmquist index can be decomposed into changes in technical efficiency change (TEC) under the assumption of constant returns to scale and technological progress change (TP), with the specific decomposition formula as follows:

$$\begin{aligned} M_0(x_{t+1}, y_{t+1}, x_t, y_t) &= \frac{d_0^{t+1}(x_{t+1}, y_{t+1})}{d_0^t(x_t, y_t)} \\ &\times \sqrt{\frac{d_0^t(x_{t+1}, y_{t+1})}{d_0^{t+1}(x_{t+1}, y_{t+1})} \times \frac{d_0^t(x_t, y_t)}{d_0^{t+1}(x_t, y_t)}} \\ &= TEC \times TP \end{aligned} \quad (2)$$

To reveal the impact of variable returns to scale (VRS), the technical efficiency change index within the Malmquist index, as referred to by equation (2), can be further decomposed into pure technical efficiency change (PTEC) and scale efficiency change (SEC). Pure technical efficiency refers to the level of technical efficiency achieved under the assumption of variable returns to scale (VRS), after removing the impact of scale efficiency; scale efficiency change is the ratio of technical efficiency change to pure technical efficiency. A scale efficiency value closer to 1 indicates an approach to the optimal scale, while a lower scale efficiency suggests that the inputs have not reached the optimal scale at a certain level of technology. Consequently, equation (2) can be further decomposed as follows, the Malmquist productivity index can be expressed as follows:

$$M_0(x_{t+1}, y_{t+1}, x_t, y_t) = TEC \times TP = TP \times PTEC \times SEC \quad (3)$$

According to the definition and computation of the Malmquist index, it carries significant economic implications. If the Malmquist index is greater than 1, it implies that the Total Factor Productivity (TFP) is on an upward trend, indicating an improvement in productivity. If the Malmquist index equals 1, it indicates that the Total Factor Productivity (TFP) is constant, suggesting stability in productivity levels. If the Malmquist index is less than 1, it suggests that the Total Factor Productivity (TFP) is declining, indicating a reduction in productivity levels. Similarly, the components of the index such as TEC (Technical Efficiency Change), TP (Technological Progress), PTEC (Pure Technical Efficiency Change), and SEC (Scale Efficiency Change) have analogous economic meanings.

INDICATOR SELECTION

This study selects input and output indicators based on their scientific relevance and availability (see Table 2). When calculating the overall output efficiency of the five

lakes, the number of fishermen and the horsepower of the vessels are chosen as input indicators. The output indicators selected are the value of fishery production and the phosphorus content. (Refer to Table 2)

(A) INPUT INDICATORS

According to economic theory, the primary factors of production include labor, natural resources, and capital. In this study, the number of workers in the lake fisheries sector is used as an indicator of labor input, and the total area of the lakes serves as an indicator of natural resource input. To limit the number of variables, the area of the lakes is divided by other investments. Since fishing boats represent a significant fixed asset investment in fishery production, the power output of the fishing vessels is selected as the indicator for capital input in the fisheries sector.

(B) OUTPUT INDICATORS

In assessing the technical efficiency of fisheries, the industry's output value and production volume are commonly employed as output indicators. Lake fisheries managed based on ecosystem principles strive for a harmony between economic and ecological benefits. Lake ecology constitutes a complex system. The most direct impact of aquaculture on aquatic ecosystems is the eutrophication of water bodies caused by improper farming practices, leading to the enrichment of nitrogen and phosphorus nutrients, which in turn stimulates rapid growth of algae and other plankton. This reduces the dissolved oxygen in the water, resulting in water quality degradation. A primary ecological goal of lake fisheries is to reduce the nitrogen and phosphorus content in lakes. As such, the total output value of lake fisheries and the phosphorus content in lake water are selected as output indicators.

Given the interrelation between the phosphorus content indicator and management objectives, data processing on the phosphorus content indicator has been performed. This involves subtracting the phosphorus content measurements at different times for each lake from a maximum value of 2mg/L, ensuring the consistency of the two output indicators Y1 and Y2, with higher values being preferable.

RESULTS AND ANALYSIS

Using DEAP Version 2.1 software, we can calculate the pure technical efficiency, total factor productivity, and total factor productivity efficiency of the five lakes, which allows for an evaluation and analysis of their output efficiency.

PURE TECHNICAL EFFICIENCY

Based on the input and output values from the processed survey data, and employing the DEA-BCC model, the DEAP Version 2.1 software was utilized to calculate and analyze the comprehensive technical efficiency and pure technical efficiency of five lakes in the middle and lower reaches of the Yangtze River — Taihu Lake, Qiandao Lake, Hongze

Table 2. Input and output indicators

<i>Input indicators</i>	<i>Output indicators</i>
Number of fisherman/Lake areaX1	Fishery production value Y1
Number of fisherman in Lake/Lake areaX2	phosphorus content Y2
Vessel horsepower(Kw)/Lake areaX3	

Table 3. Technical efficiency of five lakes

Year	Taihu	Qiandao	Hongze	Luoma	Gaobao
2007	0.257263696	1	0.956521739	1	1
2008	0.280452494	1	0.782122905	0.857990674	0.531572687
2009	0.320046932	0.942623904	0.451485149	0.586733002	0.622984491
2010	0.462840745	1	0.726199262	0.459400899	0.429827984
2011	0.473778216	1	1	0.533517797	0.422656782
2012	0.456334694	1	1	0.519587629	0.413375379
2013	0.18393025	1	0.66182778	0.596169008	0.170766043
2014	0.436560601	1	0.412813227	0.485716182	0.358025568
2015	0.422706473	0.59172963	0.538926387	0.50512334	0.31245595
2016	0.302515707	1	0.373927892	0.371410264	0.364402198
2017	0.372828903	1	1	0.381524442	0.308881786
2018	0.447334694	1	0.38626387	0.596169008	0.413375379
2019	0.533517797	0.971410264	0.386733002	0.734517796	0.459400899
2020	0.302515707	1	0.374967892	0.371410264	0.364402198
AVERAGE	0.375187636	0.964697414	0.646556365	0.590339465	0.440866239

Lake, Luoma Lake, and Gaobao Lake — over the period from 2007 to 2020.

Table 3 reveals that between 2007 and 2020, Taihu Lake's comprehensive technical efficiency ranged from 0.2573 to 0.5335, with an average of 0.3752. Qiandao Lake's comprehensive technical efficiency varied between 0.5917 and 1.0000, averaging 0.9647, making it the leader among the five major lakes with a perfect efficiency score of 1 according to DEA analysis. This demonstrates Qiandao Lake's leading position in applying "water-conserving fisheries" technology based on ecosystem management, indicating the effective extent to which fishery technologies are disseminated and adopted. Over the same period, Qiandao Lake's scale efficiency in fisheries outperformed the other four lakes. Hongze Lake's efficiency ranged from 0.3739 to 1.0000, with an average of 0.6466, while Luoma Lake varied between 0.3714 and 1, averaging 0.5903. Gaobao Lake's efficiency was between 0.1708 and 0.6230, with an average of 0.4409.

Table 4 highlights that Qiandao Lake's pure technical efficiency significantly surpasses the other lakes, achieving an efficient status, followed by Hongze Lake. This paper posits that aside from Qiandao Lake, which has successfully integrated economic and ecological benefits in its fisheries, there are no significant differences in the fisheries of the other lakes. The relatively high efficiency of Hongze Lake, compared to the others (excluding Qiandao Lake), could be attributed to its focus on farming species with higher

economic value, such as the Chinese mitten crab. On the other hand, the lower production efficiency of Taihu Lake is mainly due to limitations on farming scale, decreased production, and overfishing. Although overfishing has maintained high catch volumes, it has led to a decline in the quality of aquatic products, decreasing their value and making the fishery's contribution to water quality improvement less apparent.

In the context of severe eutrophication currently afflicting the lakes of the middle and lower reaches of the Yangtze River, the establishment of lake product branding and the extension of the industry chain are of particular importance. The organic fish brand from Qiandao Lake has been notably successful, achieving a significant market premium. Liu Qigen's research²¹ on the "conservational aquaculture" of Qiandao Lake reveals that the water source replenishment, after undergoing purification by the lake's ecosystem, showed a significant reduction in water quality indicators such as nitrogen and phosphorus, with the average reduction rate of total nitrogen being 21.9% and that of total phosphorus 18.6%. Consequently, the implementation of ecosystem-based management has evidently led to substantial improvements in the aquatic environment. It is clear that the adoption of the "conservational aquaculture" model in Qiandao Lake has achieved the objectives of sustainable fisheries development, with simultaneous increases in economic output and ecological environmental enhancement.

Table 4. Total factor productivity of fishery in five lakes

Year	Technical Efficiency (TEC)	Technological Progress (TP)	Pure Technical Efficiency (PTEC)	Scale Efficiency (SEC)	Total Factor Productivity (TFP)
2007-2008	0.954	0.957	0.986	0.967	0.913
2008-2009	1.049	0.891	1.039	1.009	0.935
2009-2010	1.014	0.988	1.028	0.986	1.002
2010-2011	1.022	0.995	1.004	1.018	1.017
2011-2012	1.023	1.059	0.998	1.025	1.083
2012-2013	0.815	0.717	0.823	0.99	0.585
2013-2014	1.186	1.052	1.194	0.993	1.248
2014-2015	1.026	0.835	1.024	1.002	0.856
2015-2016	0.985	1.039	0.975	1.011	1.023
2016-2017	0.817	1.311	0.891	0.917	1.071
2017-2018	1.156	0.815	1.190	0.971	1.094
2018-2019	0.942	1.049	0.854	1.103	0.987
2019-2020	1.030	1.049	0.854	1.103	1.037
AVERAGE	0.996	0.968	1.003	0.993	0.964

TOTAL FACTOR PRODUCTIVITY (TFP) AND ITS COMPOSITION

Utilizing survey data on fisheries inputs and outputs from five lakes between 2007 and 2020, this study employs the Malmquist index method and analyzes the data using DEAP Version 2.1 software. It calculates the changes and decompositions in Total Factor Productivity (TFP) efficiency of lake fisheries for 2007-2022, as detailed in Table 4, and the changes and decompositions in TFP, as presented in Table 5, facilitating a comparative analysis.

Overall, with the exception of the notably anomalous data for the years 2012-2013, the Total Factor Productivity (TFP) of fisheries across the five lakes has been on a marginal increase. Excluding these outliers, the TFP index for lake fisheries post-2013 stands at 1.045, indicating a phase of marginal productivity gains. Between 2013 and 2020, the trends in technological progress, scale efficiency, and TFP have been consistent, signifying that advancements in technology and changes in scale efficiency have been the primary drivers of TFP growth in the fisheries sector in recent years. This suggests that the ecological aquaculture technologies promoted by the fisheries authorities and the “retiring pens to restore lakes” policies that restrict farming scale have been beneficial in enhancing the TFP of eco-friendly fisheries.

Although the average value of pure technical efficiency was generally above 1, it fell to 0.96, less than 1, during the period from 2014 to 2020, indicating a negative growth rate. Similarly, the pure technical efficiency was less than 1 over the same period, yet the scale efficiency was above 1. This implies that the increases in planning efficiency were somewhat constrained by the negative growth in pure technical efficiency. Given that technological progress during this phase was greater than 1, at 1.02, it appears that the technical potential of lake fisheries has not been fully realized.

The Malmquist index and its decomposition indicators have been applied to calculate the TFP of fisheries in the five lakes from 2007 to 2020, with the results presented in Table 5.

The annual growth rates of Gaobao Lake and Luoma Lake were negative, indicating a phenomenon of lake desertification in Gaobao Lake in recent years, which has been a definite sign of the negative growth in total factor productivity. In contrast, Qiandao Lake, Taihu Lake, and Hongze Lake exhibited positive annual growth rates in total factor productivity, with Qiandao Lake experiencing the highest average annual growth rate of 13.2%. The increase in technical efficiency at Qiandao Lake, primarily driven by advancements in pure technical efficiency, significantly contributed to the growth in its total factor productivity. This aligns with the practical developments in Qiandao Lake’s fisheries, where the adoption of large-scale net fishing techniques has substantially reduced labor efforts, and institutional innovations have enhanced stocking efficiency—all attributed to improvements in pure technical efficiency. However, the dispersed family-based management model has struggled to develop labor-saving fishing technologies or to improve the efficiency of enhancement and stocking.

CONCLUSION

This study employs Data Envelopment Analysis (DEA) and the Malmquist productivity index to assess and compare the technical efficiency and Total Factor Productivity (TFP) indices of fisheries in the five major lakes of the middle and lower reaches of the Yangtze River in China from 2007 to 2020.

The results indicate that :(1) during this period, the average pure technical efficiency of fisheries in Taihu, Qiandao, Hongze, Luoma, and Gaobao lakes was 0.3751, 0.9647, 0.6466, 0.5903, and 0.4409, respectively. Qiandao Lake ex-

Table 5. Average fishery total factor productivity of five lakes from 2007 to 2020

Lake	Total Factor Productivity	Technological Progress	Technical Efficiency	Pure Technical Efficiency	Scale Efficiency
Qiandao	1.132	1.016	1.106	1.099	1.005
Taihu	1.028	1.036	0.992	1.000	0.992
Luoma	0.959	0.996	0.992	1.033	0.989
Hongze	1.077	1.077	1.000	1.000	1.000
Gaobao	0.994	1.007	1.000	0.998	1.004

hibited the highest pure technical efficiency, closely followed by Hongze Lake, suggesting that Qiandao Lake sets the benchmark in overall fishery production levels and technical expertise within the sector.

(2) A comprehensive analysis of the TFP, technological progress, technical efficiency, pure technical improvement, and scale efficiency of the five lakes from 2013 to 2020 revealed that changes in scale efficiency were primarily driven by technological progress. Trends in technological progress, scale efficiency, and TFP were consistent, with technological advancement being the primary catalyst for TFP growth in fisheries. This underscores the effectiveness of policies that both promote ecological aquaculture technologies and limit farming scale through initiatives like “retiring pens to restore lakes,” which have been beneficial for enhancing the TFP of ecological fisheries. Between 2014 and 2020, pure technical efficiency was found to be less than 1, whereas scale efficiency exceeded 1, indicating an underutilization of technological potential within lake fisheries.

(3) Gaobao and Luoma lakes experienced negative annual growth rates, with lake desertification in Gaobao Lake emerging as a significant contributory factor. Conversely, Qiandao Lake achieved the highest annual growth rate at 13.2%, attributed mainly to labor-saving large-net fishing techniques and improvements in pure technical efficiency, as well as efficiency gains driven by institutional innovation

POLICY IMPLICATIONS

Based on the preceding research findings, the following recommendations are proposed to improve the fishery practices in the lakes of the middle and lower Yangtze River.

Over-intensive fishing efforts have been identified as the primary cause of the inefficient comprehensive technical efficiency and diminishing returns to scale in fisheries such as Tai Lake, Gaobao Lake, and Shaobei Lake. Therefore, it is advised that the lakes in the middle and lower reaches of the Yangtze River, with the exception of Qiandao Lake, should adopt an ecosystem-based, ecology-prioritized fishery development model. This model centers on the protection of the ecological environment, the conservation and integrated use of aquatic biological resources, and the implementation of “water-conserving fisheries.” It aims to achieve high-quality and sustainable development through harmonization of aquatic ecological protection and fishery production. The technical measures for artificial conservation and protection of the ecological environment, includ-

ing fishery resource structure, fishery resource stock control, annual fishing quotas, fishing gear restrictions, fishing size and species controls, and resource enhancement through restocking, should all be dynamically set based on the current water quality status and ecological environment management objectives. A quantifiable management indicator system should be established to scientifically guide the dynamic setting of these measures. The relationship between fisheries and water resources should form the basis for a rational input-output regime, thereby enhancing the efficiency of fishery resources and addressing the issue of diminishing returns to scale. Concurrently, an adaptive management system for the ecological risks associated with stock enhancement and release should be constructed. In addition to considerations of fry cultivation, inspection and quarantine, and ecological environment monitoring, attention must also be given to the protection of aquatic biodiversity and the risk of invasive species introduction.

With the rapid advancement of science and technology, various techniques such as Geographic Information Systems (GIS), hydroacoustic detection, and fish tagging are increasingly being applied in the field of lake fisheries, aiming to achieve the goals of rational utilization of fishery resources, reduction of production costs, and improvement of the ecological environment. GIS can be employed in constructing lake fishery models, long-term resource monitoring and management, enhancement scheme determination, and quota management. Hydroacoustic methods, characterized by their speed and effectiveness as well as their wide surveying range, can be utilized to assess the spatial distribution of lake fishery resources. Fish tagging technologies, including external tagging, fluorescent pigment marking, genetic tagging, stable isotope analysis, passive integrated transponder (PIT) tags, and biotelemetry tagging, can be applied in the research and management of lake fisheries.

To achieve a fishery development model prioritizing ecosystem ecology in the middle and lower reaches of the Yangtze River, it is necessary to implement input-output control management at the technical level through management systems, comprehensively consider the integrated model of lake fishery development and water environment protection, and adopt the “fish for water management - water conservation fisheries” development concept seen in Qiandao Lake. This involves the reasonable arrangement of aquaculture species and the construction of aquatic plant purification systems. Releasing a reasonable number and size of silver and bighead carp in the lake to enhance the

water purification capacity, achieving multi-level nutrient utilization, and in-situ remediation of aquaculture pollution are also crucial. Meanwhile, with the protection of the lake water environment as a premise, it is essential to control and reduce the aquaculture area according to the environmental capacity, decrease the input of exogenous nutrients, and ensure that the fisheries development model in the lake water source areas implements an environmentally friendly approach to fisheries development and precisely control over fishing output should be exerted through the issuance of fishing quotas, complemented by a fishing license system to control fishing efforts. The apportionment of fishing quotas should be designed to consider both commercial fishing and the upgrade of fishing industries, taking into account economic and social functions. In recent years, the zoning of aquatic ecological regions has received attention, with studies on aquatic ecological zoning and watershed water environmental functional zoning being conducted.²² These studies have accumulated experience for the scientific management of China's aquatic systems. However, the technology for functional zoning of lake fisheries still needs to be based on and complemented by research on watershed aquatic ecological functional zoning and other related work, in order to advance the regional planning and coordinated management of lake fisheries.

AUTHORS' CONTRIBUTION

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INFORMED CONSENT STATEMENT

All authors and institutions have confirmed this manuscript for publication.

DATA AVAILABILITY STATEMENT

All are available upon reasonable request.

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