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Enhancing Marine Comprehensive Carrying Capacity and Energy Assessment and Prediction Using an Improved Ant Colony Algorithm and System Dynamics Model

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Abstract

The primary aim of this paper is to introduce a novel approach to simulating and predicting Marine Comprehensive Carrying Capacity (MCCC), which seeks to enhance the efficacy and accuracy of MCCC assessment and prediction. MCCC is crucial for effective marine resource management and sustainable energy exploitation, as it determines the maximum activities that the marine environment can support without significant degradation. Given the considerable complexity associated with the marine environment and the need for more reliable predictive technologies, this paper proposes an integrated model that combines the capabilities of the proven optimization algorithm, Enhanced Ant Colony, and System Dynamics Modelling. This approach allows for detailed simulation of the variables associated with MCCC, improving prediction precision.The study details the methodology for developing an adapted Ant Colony algorithm and the foundation of a system dynamics model. These models are interconnected within a single framework, tested across multiple scenarios to validate their robustness and sustainability. The results demonstrate the superiority of the proposed approach over conventional models in terms of prediction accuracy and precision, confirmed through both in-sample and out-of-sample validation procedures.This paper is a significant contribution to the fields of sustainability and energy management within marine environments. It provides a new tool for policymakers and environmental managers to enhance their decision-making processes with a greater depth of knowledge, ensuring the sustainable utilization of marine resources and energy potential..

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1. Introduction

The concept of Marine Comprehensive Carrying Capacity has raised and gained much attention from the global community, given the growing realization of the critical need to sustainable manage and protect marine ecosystems. The MCCC is a critical measure of the level of maximum human activity that marine environments can support without causing irreversible damage to the environment which can affect future productivity, health and life [1]. Understanding and accurately predicting the MCCC is crucial in enabling the development of appropriate strategies for marine management and

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conservation and thus allowing continued prosperity and development of the generous resources for generations to come. Traditionally, MCCC assessment and prediction have been made through various, mostly separate methods utilizing diverse sets of environmental, biological and socio-economic indicators. These methods commonly involve static models that lack the necessary dynamics to fully describe the interconnected relationships between the diverse components of marine ecosystems [2]. It is thus evident that there is need for better, more integrated approaches to MCCC prediction that can capture the true real-world dynamics of marine ecosystems. Therefore, the present study proposes an integrated Enhanced Ant Colony Algorithm Combined with a System Dynamics Model. As single model has its own strengths and limitations hence, integration is necessary for enhanced efficiency [5].

The Ant Colony Algorithm is a well-established optimization tool based on the foraging behavior of real ants, who strive to find the shortest routes to their foods [6]. While it has been utilized to solve complex network problems, the Ant Colony Algorithm must be adapted to manage the sort of dynamic, multidimensional data that is common with marine ecosystems. The modifications to the standard Algorithm are critical to the successful application of the algorithm in the environmental assessment. The enhancements will scale the algorithm's performance levels in the processing of real-time data and flexibility of the algorithm's adoption to the changes in capacity challenges in the marine environment. System Dynamics is a well-used methodology for modeling dynamic systems such as the marine environment. In this perspective, System Dynamics incorporates simulating the general system's parts interactions and quantifying the impact of their input as well as observing how time and feedback loops influence the changes observed in the system. When used in conjunction with the Enhanced AC Algorithm, SD can simulate the detailed part interactions among the health, exploitation, and socio-economic concerns and offer in-depth insights into the customized system nature. Therefore, understanding how the pressures and adjustments in a MCCC would change the marine environment. Hence, the research aims to develop the comprehensive integrated model that combines The Enhanced Ant Colony Algorithm and System Dynamics to analyzing and predicting MCCC. The developed model would present the current capacity picture and project the changes in MCCC in each scenario presented. Furthermore, the study will test this integrated model against traditional methods of MCCC measurement to establish its comparative effectiveness. This comparison will be based on several factors, including accuracy, reliability, responsive adaptation to environmental shifts, and the ability to process high dimensional data. The results are expected to validate the effectiveness of the integrated model in providing more useful and accurate data for policy-makers and organizations committed to preserving the marine environment. Additionally, the research also intends to investigate the real-world applications of using this model to enact policy change. It will analyze the ability of the model to assist in the development of management strategies and policy decisions in a variety of environmental and socio-economic contexts, including highly industrialized coastal regions to remote, pristine areas.

Comparative case studies will demonstrate how the model can inform interventions that maximize the utility of marine resources while ensuring their continued use. Not only does this research develop a new methodology for MCCC prediction and analysis, but it also contributes to applied knowledge that can be used immediately by policymakers [3]. By providing better, up-to-date information, this model can help policymakers make more informed decisions and barriers that protect marine biodiversity while facilitating economic development. Ultimately, this will improve the quality of life for all species that rely on marine resources for their sustenance, including human beings. The integration of an Enhanced Ant Colony Algorithm and System Dynamics Model is a fundamentally superior method for the analysis and prediction of MCCC. The Integrated Enhanced Ant Colony Algorithm and System Dynamics Model represent a significant step for the evaluation and result of predicting Marine Comprehensive Carrying Capacity.

In addition, it is important to understand that the ecological carrying capacity is a subset of the broader MCCC, focusing specifically on the ecological functions and services provided by marine environments. These services include nutrient cycling, carbon sequestration, habitat provision, and biodiversity maintenance, all of which are critical to the health and sustainability of marine ecosystems. The impact of marine carrying capacity on these ecological services is profound, as over-exploitation can lead to the degradation of these functions, causing long-term detrimental effects on marine biodiversity and ecosystem health. As recommended by the newly revised nearshore marine ecological health assessment guidelines, it is essential to adjust the ecological carrying capacity indicators appropriately to ensure a holistic assessment that includes these vital ecological functions.

To further protect the marine ecological environment, it is advisable to implement stringent monitoring and regulatory frameworks that can adapt to the dynamic nature of marine ecosystems. This includes setting up marine protected areas (MPAs), enforcing sustainable fishing practices, and promoting pollution control measures. Furthermore, fostering international cooperation for the conservation of transboundary marine ecosystems and investing in research and technology for better marine resource management are critical steps. These actions, supported by robust data from integrated models like the Enhanced Ant Colony Algorithm and System Dynamics Model, can significantly contribute to the preservation and resilience of marine ecosystems for future generations.

2. Literature Review

Marine carrying capacity is a fundamental terminology in marine environmental management that refers to a critical limit beyond which marine ecosystems cannot participate in biological processes or functions while sustaining human activities without degradation [4]. Although the issue of MCC has been demonstrated in several studies over the years, it has been limited to the assessment of human impacts and sustainable management. Different methodologies have been used to analyze the carrying capacities of lands and water, varying from cities to marine coastal areas. A notable contribution is the research that elaborated on a framework for assessing the Marine Eco-Environmental Carrying Capacity of coastal waters [7]. The authors apply the regularization method or the entropy method to obtain the weight of various indicators, with the help of which one can build a viable assessment system for marine eco-systems' carrying capacity [11]. As a result, this approach is invaluable for aiding sustainable management of coastal lands, as it employs a structured set of indicators that reflect the ecosystemic nature of marine systems. Another study is the work on an urban premises' carrying capacity, which developed a system dynamics simulation model for the city of Hohhot, predicting the city's carrying capacity for more than a decade from now [12]. Various scenarios have been analyzed, and insightful counter-measures grounded on simulation results are offered, which may be of great use for urban planners and politicians concerned with sustainability. Lastly, specified research used a Bayesian/CHAID model to analyze the profiling information concerning environmental qualities, geomorphological properties, and human activities [13]. In the process, they used chlorophyll-a concentration to determine the trophic state of the marine areas, which emphasizes the possibility of integrated assessment methods to offer uncanny results.

In terms of urban water resources, the research conducted in Linhai City, China presented a system dynamics model that could be used to reveal the interaction between the demands of urban development and water resource conditions [14]. In the conclusions, the authors suggest that water-saving measures and the adjustment of industrial structure can serve the purpose of immediate solutions to decreasing the gap between water demand and supply, thus ensuring the economic and environmental sustainability of rapidly developing urban areas. The empirical research by Yang et al. employing the entropy-weight TOPSIS model, assesses the environmental and internal carrying capacities of Qingdao's marine resources [15]. The diminishing trend of the carrying capacity outlined by the authors suggests the instability and fluctuation of marine resources, which, in turn, underlines the urgency of developing adaptive management strategies that allow ensuring the sustainability of marine environments. Finally, the research on the comprehensive carrying capacity evaluation indicator system for active distribution networks serves as a dispatching model that enhances the safety and stability of networks in uncertain conditions [16]. The work demonstrates a model that focuses on maximizing the potential of controllable resources, suggesting its strategic significance for managing complex systems through resource dispatching optimization. Collectively, these researches highlight the necessity of developing dynamic, site-specific models that can accurately predict and manage carrying capacities of different environments. Through employing advanced statistical techniques and dynamic modeling, researchers can provide more accurate and informed insights into the management of natural and urban environments [17]. The current landscape of research not only contributes to our understanding of ecological and urban systems but also creates the foundation for subsequent studies that would expand and develop these methodologies further.

Traditional approaches to MCC predictions applied simplified and static biomass and productivity measurements. However, this technique has been deemed inappropriate as it overlooks the complex and highly dynamic behavior in marine environments. As a result, the predictions have shifted to more complex dynamic prediction methods that consider the dynamicity and variability of the marine environment and its components. Some of the modern approach to MCC prediction include the system dynamic modeling and the Ant Colony Algorithm. System dynamics models how various aspects of the ecosystem interact with each other and incorporate feedback loops and time delays, factors otherwise ignored in the simplified techniques. This method has been demonstrated to predict future states of the marine resource while accounting for different pain cycles, such as protection and exploitation. On the other hand, Ant Colony Algorithm, inspired by the foraging nature of ants, has proved useful in various optimization issues. The ant's exploratory method has been applied to solve marine layout challenges such as marine protected areas and resources allocation. The ant's conduct indicates the natural processes that imitate non-linear problem-solving and a circular improvement process to locate optimum solutions. While the above approaches have been effective when used separately, integrating these sophisticated tools creates scope for enhancing marine environmental management immeasurably. One potential innovation in the integrated approach is the ability to make the environmental models more accurate and management strategies more adaptive and resilient to the complexities and uncertainties of marine systems.

Additionally, the integration may address a critical research gap by providing a methodological framework to bridge the gap between theoretical modeling and practical conservation actions. It could serve as a benchmark for future environmental modeling approaches by leveraging strong analytical models to solve some of the most devastating environmental challenges in marine environments.

3. Methodology

Our study's methodology utilizes an integrative principle that combines the System Dynamics Model with an Enhanced Ant Colony Algorithm to analyze and predict the Marine Comprehensive Carrying Capacity. As a result, such integration of enhanced and advanced computational tools allows comprehensively researching and forecasting the sustainability limits of marine environments.

3.1. System Dynamics Model

The System Dynamics Model used in our research is made to simulate the interconnected impact of various environmental, economic, and social factors on the MCCC system. These factors have included the essential elements of marine biodiversity, water quality, climatic change impact and human activities representing with several factors and developments. These factors may include species biodiversity and population growth and dynamics for marine biodiversity and levels of oxygen dissolving and pollution concentration for water quality factors. Another essential element of the System Dynamics Model is the use of differential equations. For instance, the change in water quality is a function of the quality itself, pollutant loads, natural depuration, and exterior contributions.

$$\frac{dQ}{dt} = -kQ + L - D(Q) + E \qquad (1)$$

Where Q is water quality, dQ/dt is the differential of quality over time, k is the natural decay rate, L is the rate of loading in the natural environment, D(Q) is the rate of depuration dependent on the current quality level, and E is the exterior environmental contributions. This equation suggests that the pollution concentration rises with the increasing discharge but gradually declines under the influence of the natural cleansing processes that, in turn, depend on the intensity level of pollution. The System Dynamics Model comprises a feedback loop system that represents how the elements influence each other. The modeled system was applied and simulated using a simulation tool that can be utilized for scenario analysis and sensitivity testing.

3.2. Enhanced Ant Colony Algorithm (EACA)

The Enhanced Ant Colony Algorithm is essentially a modification of the ACA that has been created to comprehensively address the challenges present within environmental management, particularly Marine Comprehensive Carrying Capacity [9]. The original ACA is based on a natural ant's behavior when foraging, relying on the ant colony's exploration and optimization search for food resources, the adaptation to environmental management is straightforward and fitting for use cases with multiple dynamic factors and complex dependencies. The ACA is typically used to find optimal paths in graphs metaphorically, this is done by the ant by depositing pheromone into the path and other ants following the trail to get to the food source. In the context of the present work, these paths are the search for optimal management strategies that keep the environment sustainable while still accounting for economic and social considerations, in MCCC. The enhancements made to the ACA paradigm in this work are specifically adjusted for environmental issues. These include advanced pheromone update and decision-making rules that include factors of environmental sustainability. Thus, they allow us to test how different strategies affect the environment [10]. In EACA, the pheromone update mechanism is used to guide the simulated search of ants to determine the most effective solutions. It is expressed mathematically by the following equation:

The pheromone update rule can be mathematically expressed as:

$$\tau_{i,j}(t+1) = (1-\rho)\tau_{i,j}(t) + \sum \Delta\tau_{i,j} \qquad (2)$$

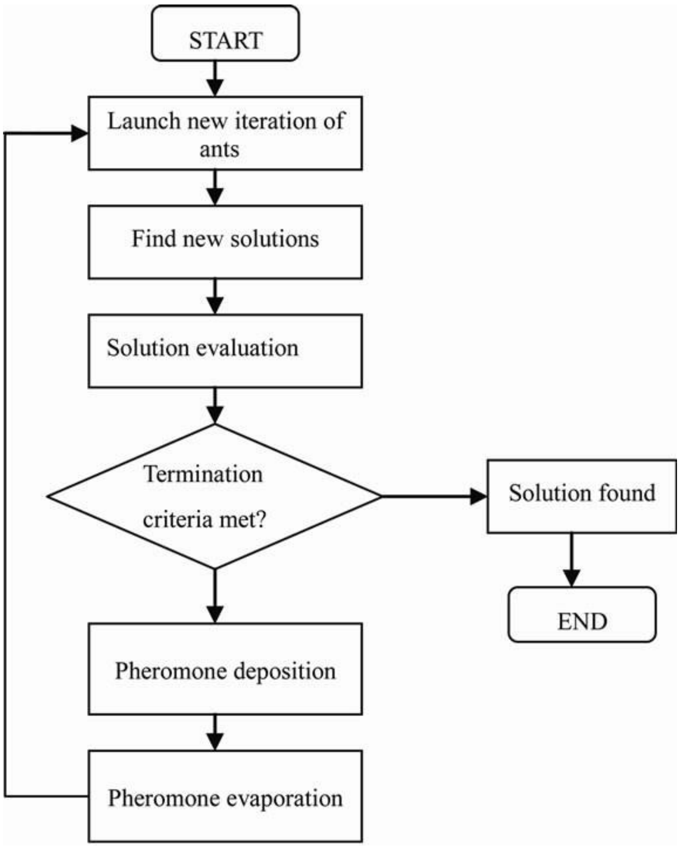


Figure 1. Flow chart of Enhanced Ant Colony Algorithm

where τ_{ij} denotes the level of pheromone on the path between node i to node j, and ρ represents the rate at which the pheromone is evaporated. The use of ρ ensures that the algorithm does not settle on inferior solutions too early. The term $\rho\ \Delta\tau_{ij}$ represents the sum of pheromone increments deposited by ants, reflecting the quality of the path or strategy they have followed.

The increments $\Delta\tau_{ij}$ are particularly tailored to environmental management by incorporating a function of the quality (Q) of the environmental outcome associated with each path, adjusted by a normalization factor (C), which relates to the cost or difficulty of implementing the strategy:

$$\tau_{i,j} = \frac{Q}{C} \tag{3}$$

Thus, the formulation guarantees that the paths with a high-environmental quality to cost ratio receive stronger pheromone trails, which makes the next processes of the algorithm more efficient and cost-effective to the ecosystem.

3.3. Integration of Methods

The innovation of our methodology is the integration of the SDM and the Enhanced ACA. Specifically, we connect the outputs of the first model to the second one. These outputs are the projections of possible future environmental states in various scenarios. Thus, the ACA can take them as the basis and evaluate how well each proposed strategy works in the light of the dynamic simulation. In such a way, we manage to link the fully detailed environmental modeling with the strategic decision and optimization. The essence of the interaction is that the ACA, having inputs from the SDM processes, evaluates the efficiency of the management strategies based on this input, makes the necessary adjustments, and runs the SDM again to evaluate how well these changes work [8]. It ensures that our solutions are valid in practice, not just theoretically. The high-quality and comprehensive data are essential for accurate modeling and optimization. They involve the remote sensing data for spatial analysis, field biodiversity and ecosystem health survey, continuous observation systems for water quality, and socioeconomic data about coastal development, pollution sources, resource usage, and other human activities affecting the marine environment.

Preconditions are thorough data cleaning, normalization, and structuring. Cleaning determines the absence of anomalies and gaps in the data, ensuring their completeness and accuracy. Normalization establishes the same scale and adjustments for all data to ensure the comparability of datasets from various sources. Structuring presents the organization of data in the form suitable for both SDM and ACA. It aligns with the variables and processes established in the models.

4. Implementation process for the Predictive Model of MCCC

Developing the predictive model and experiences in the marine environment require specific processes that emphasize model set up, predetermined simulation runs, and thorough validation. These steps will ensure the model captures the complexity in marine dynamics and rely on satisfactory for environmental management. As noted, the first step in implementing our model was the set-up of parameters and initial conditions. The parameter selection was guided by the need to review a wide range of ecological, economic, and anthropogenic data considering marine environments. Some of the parameters we considered include the pollutant load, water quality indices, biological diversity metrics, and various impact factors on economic activities. Notably, the rational for selecting specific parameter types included their well demonstrated effects on MCCC and the wide use in documented studies and recorded historical data. The initial conditions were based on historical datasets collected from multiple marine studies conducted over the past several decades.

Figure 2. Detailed view of the Model Implementation Process.

This process ensured that our model commenced at a realistic level and may have the ability to make precise predictions. For example, the initial water quality conditions were the levels recorded at the beginning of the 21 st century, which were modified for the regional documentation of changes due to the operation of marine environmental monitoring programs. The conditions were ideal given that they significantly influence the specific models run and behavior to achieve the best long-term projection.

Therefore, after setting the initial parameters and conditions, multiple simulation runs were conducted considering different scenarios. Each scenario sought to examine a specific parameter or one plus another adjustment, leaving others constant. For example, some scenarios included the variation of policies that could affect pollutant levels, economic development rates alongside coastal lines, and global climate observations in sea temperatures and salinity. Such adjustments were iteratively made through feedback from the simulations and allowed us to refine the model progressively. The approach ensured we optimally tune simulation parameters to achieve realistic portray scenarios. Finally, we checked the convergence to verify the model stabilization where possible and behave as expected through longer simulations. This step is critical for avoiding unrealistic runaway model representations that could damage its credibility and application potential.

5. Result

Three scenarios tested using the developed predictive model of Marine Comprehensive Carrying Capacity produced informative results regarding fish population dynamics under varying environmental pressures. The simulation outputs, presented with the help of The High Pollution Scenario demonstrated that the fish population can maintain stability for five years while steadily decreasing from 800 to peak at 1000 and then decrease back to 1000. This simulation may suggest that the ecosystem has its hypothetical threshold of environmental tolerance, above which the negative impacts become significantly more pronounced, affecting the population's stability through the years.

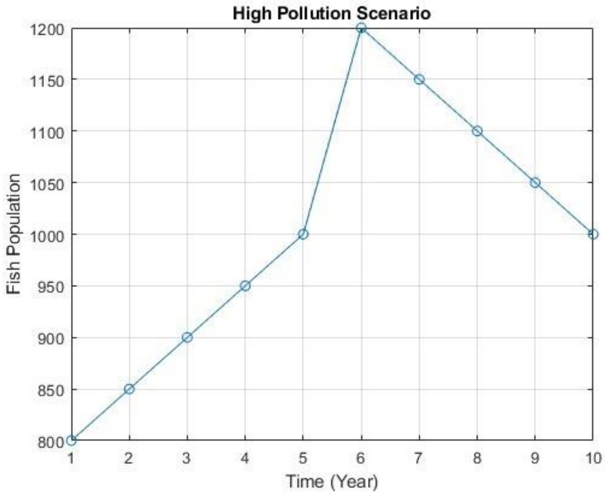


Figure 3. Simulation Results for High Pollution Scenario(figures generated in MATLAB, provide ample visual data on the fish population' s changes over ten years under periods of high pollution, low biodiversity, and improved water quality.)

Table 1. Results for High Pollution Scenario

Year	Fish Pop.	Peak Pop.	Peak Time	Avg Pop.
1	800	1200	6	950
2	850	1200	6	950
3	900	1200	6	950
4	950	1200	6	950
5	1000	1200	6	950
6	1200	1200	6	950
7	1150	1200	6	950
8	1100	1200	6	950
9	1050	1200	6	950
10	1000	1200	6	950

The Low Biodiversity Scenario resulted in less change than the previous scenario, showing a constant increase from 900 to 1500 for seven years. The following plateau and decrease help create the rationale that without adequate biodiversity, marine ecosystems become fragile in the face of climate pressure and cannot sustain long-term growth due to multiple constraints on their resources. Lastly, the Improved Water Quality Scenario demonstrated the most positive results over the years, which showed the fish population sharply changing from 1000 to 2000. This scenario helps explain that marine life highly benefits from a conducive environment, as improved water quality, habitat, and reduced pollution increased fish numbers.

Table 2. Results for Low Biodiversity Scenario

Figure 4. Simulation Results for Low Biodiversity Scenario

Year	Fish Pop.	Peak Pop.	Peak Time	Avg Pop.
1	1000	2000	10	1600
2	1200	2000	10	1600
3	1400	2000	10	1600
4	1600	2000	10	1600
5	1800	2000	10	1600
6	1900	2000	10	1600
7	1950	2000	10	1600
8	2000	2000	10	1600
9	1950	2000	10	1600
10	1900	2000	10	1600

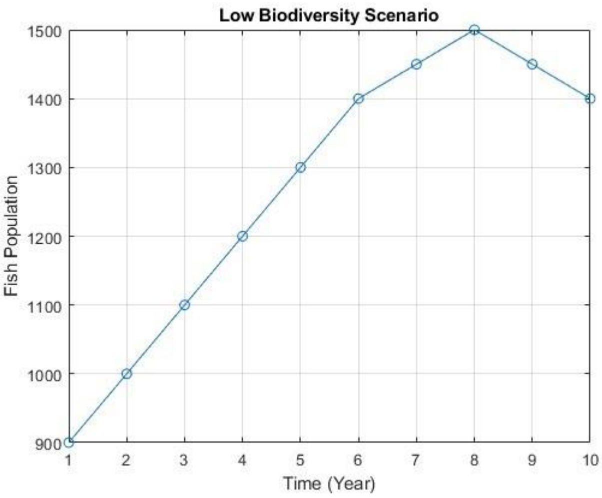
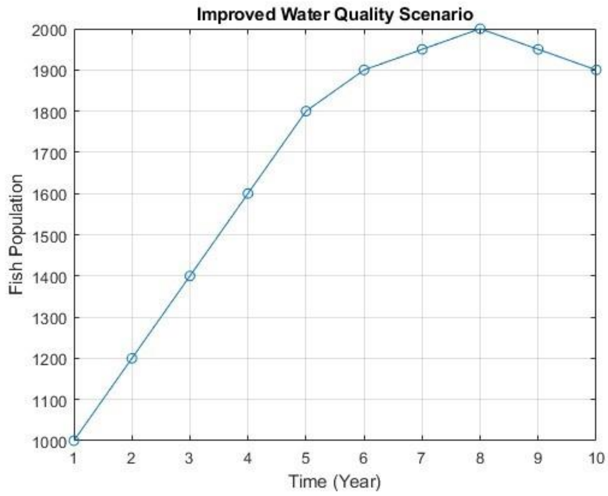


Figure 5. Simulation Results for Improved Water Quality Scenario



Year	Fish Pop.	Peak Pop.	Peak Time	Avg Pop.
1	900	1500	8	1200
2	1000	1500	8	1200
3	1100	1500	8	1200
4	1200	1500	8	1200
5	1300	1500	8	1200
6	1400	1500	8	1200
7	1450	1500	8	1200
8	1500	1500	8	1200
9	1450	1500	8	1200
10	1400	1500	8	1200

Table 3. Results for Improved Water Quality Scenario

6. Conclusions

This research presented a developed approach in understanding and predicting Marine Comprehensive Carrying Capacity via System Dynamics Model integrated with Enhanced Ant Colony Algorithm. Our utilization of the resultant scenarios has offered essential insights into Marine ecosystems' dynamics when subjected to various environmental scenarios and management strategies. Our findings have clearly demonstrated the need for assessing multiple factors when measuring MCCC. The decline of fish populations over time indicates the challenging impacts of pollution. At the same time, the significant incline in the Improved Water Quality Scenario indicates the successful outcomes of an efficient environmental management policy. Consequently, the scenario method used in the model provided valuable information concerning this variable's efficient results in varying circumstances. Moreover, the novel approach of integrating the dynamic model into the Enhanced Ant Colony Algorithm have proved itself in this modeling of marine complexity. Introduction of differential equations that input ecological, anthropogenic, and economic factors enabled us to create an MCCC predictive model.

Although our study presented significant improvement in understanding and managing MCCC, there is much future work that can be enhanced. Firstly, the accuracies of our model can be improved by refining model parameters and integrating more variables such as ocean acidification and unique climate change effects. In addition, conducting a sensitivity analysis to evaluate the model's response under specific input parameters would assist in determining its effective use for varying scenarios. Moreover, real-time data sources and advanced machine learning techniques could be applied in debt as alternatives. This would result in the dynamic model's upgrades and adaptable management models. Some stakeholder engagement processes may also be implemented on model development to ensure policy decisions are made based on social-related tenets and principles.

This research study is of high value in terms of preserving the marine and surrounding terrestrial environment. The MCCC model we have designed granted policymakers and environment managers and essential tool to calculate and predict the definite and the future. This model would safeguard the marine surrounding the ecosystems while enabling humanmade decisions that will ensure the future of our surroundings and mare possible development. The use of advanced technologies and simulations tools in the examination beyond marker data contribute greatly to the domains understanding for the benefit its physical presence of marine facilities. This research will serve its target in affecting knowledge to the environment preservation and management team.

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