OAJRC Environmental Science, 2024, 5(1), 1-5
https://www.hillpublisher.com/journals/oajrces/
ISSN Online: 2632-2331

Research on Multi-objective Collaborative Development Decision-making of Integrated Watershed Management Under the “Dual Carbon” Target

Shuifeng Zhang[1,*], Meng Li[2], Zheyan Gu[3]

[1]School of Information Technology, Nanjing Police University, Nanjing, Jiangsu, China.
[2]Jiangsu Province Hydrology and Water Resources Investigation Bureau., Nanjing, Jiangsu, China.
[3]Jiangsu Surveying and Design Institute of Water Resources Co., Ltd., Yangzhou, Jiangsu, China.

How to cite this paper: Shuifeng Zhang, Meng Li, Zheyan Gu. (2024). Research on Multi-objective Collaborative Development Decision-making of Integrated Watershed Management Under the “Dual Carbon” Target. *OAJRC Environmental Science*, 5(1), 1-5.
DOI: 10.26855/oajrces.2024.03.001

Received: February 28, 2024
Accepted: March 27, 2024
Published: April 26, 2024

Corresponding author: Shuifeng Zhang, School of Information Technology, Nanjing Police University, Nanjing, Jiangsu, China.

Abstract

Watershed systems, as open ecological and economic units connecting upstream and downstream, play a crucial role in achieving carbon peak and carbon neutrality targets. This study based on the analysis of watershed carbon management, constructs a multi-objective planning model for carbon emission reduction at the watershed scale. The model aims to minimize carbon reduction costs and maximize comprehensive ecological benefits, considering environmental constraints, resource constraints, and technological constraints. It utilizes multi-objective planning algorithms to obtain optimized strategies and spatial allocation schemes for watershed carbon emission reduction. The model is applied to case studies in typical watersheds to validate its scientific rigor and practicality. This research provides quantitative methods and decision support for carbon emission management in watershed systems, offering innovative value.

Keywords

Watershed systems, Carbon emission reduction, Multi-objective planning, Decision support

1. Introduction

China has set the ambitious goals of striving to achieve a carbon peak by 2030 and carbon neutrality by 2060, which impose higher requirements on regions and industries [1, 2]. Watersheds, as important geographic units that connect upstream and downstream and regulate water resources and ecological environments, play a unique role in implementing these "dual carbon" targets. Watersheds are complex systems that involve point source pollution, non-point source pollution, and ecosystem carbon sinks, among others, requiring comprehensive consideration of multiple factors for systematic and coordinated management. Therefore, conducting research on multi-objective and coordinated development decision-making for watershed comprehensive management under the "dual carbon" targets is of great theoretical value and practical significance in guiding watersheds to achieve carbon peak and carbon neutrality goals. Watershed comprehensive management refers to the management activities that consider various elements within the watershed, such as water resources, land, and ecological environment, and adopt comprehensive regulatory measures to achieve sustainable development in the watershed [3, 4]. The "dual carbon" targets require achieving carbon peak and carbon neutrality through energy-saving and emission-reduction measures. Watershed comprehensive management and the "dual carbon" targets have inherent unity and synergy. On the one hand, implementing watershed comprehensive management can increase carbon sinks, reduce carbon sources, and provide support for achieving the "dual carbon" targets. On the other hand, the "dual carbon" targets set new directions for watershed management. However, there are still many challenges in coordinating the control of various carbon sources, optimizing carbon sink allocation, and achieving the coordination between economic and social development and ecological environment protection within the watershed. In this study, in the context of introducing the "dual carbon" targets, we take the watershed as the unit, consider the complexity of carbon source structure, carbon sink distribution, and emission reduction constraints within the watershed, and construct a multi-objective planning model to coordinate carbon source reduction and carbon sink enhancement, achieving effective integration of watershed comprehensive management and the "dual carbon" targets. At the same time, based on the latest research findings, we comprehensively explore the pathways and strategies for watershed systems to achieve the "dual carbon" targets from both theoretical and practical perspectives, providing a scientific basis for future watershed governance towards "dual carbon".

2. Research on Watershed Comprehensive Management and the "Dual Carbon" Targets

2.1 The Relationship between Watershed Comprehensive Management and the "Dual Carbon" Targets

There is an inseparable intrinsic connection between watershed comprehensive management and the "dual carbon" targets. On the one hand, promoting watershed comprehensive management can provide strong support for achieving the "dual carbon" targets. On the other hand, the introduction of the "dual carbon" targets also promotes the development of watershed management towards a more scientific, systematic, and coordinated direction. Specifically, many measures in watershed comprehensive management can enhance the carbon sink effect and carbon emission reduction capacity of the watershed system. For example, implementing soil and water conservation measures can increase vegetation coverage and improve the carbon sink capacity of the watershed ecosystem; promoting environmental-friendly water conservancy construction can reduce soil erosion in the watershed and lower carbon source generation [5]; developing ecological agriculture can reduce the use of chemical fertilizers and pesticides and decrease agricultural non-point source carbon emissions [6]. At the same time, the "dual carbon" targets set new directions for watershed management, namely, coordinating carbon source reduction and carbon sink management at the watershed scale to achieve optimal carbon emission reduction effects. This requires a transformation of the watershed management model towards the "dual carbon" targets, such as optimizing energy structure, developing low-carbon industries, improving resource utilization efficiency, and increasing the carbon sink capacity of ecosystems. Therefore, under the background of the "dual carbon" targets, watershed comprehensive management needs to innovate in concepts, content, methods, and approaches to achieve the transformation and upgrading of management models. Specifically, the core concept of watershed management should shift to the dual-drive of carbon emission reduction and ecological restoration, based on the watershed scale to coordinate carbon source reduction and carbon sink management. The content and technical methods of management should develop towards refinement and quantification, establishing watershed carbon source inventories and carbon sink assessment systems, conducting multi-scenario emission reduction potential assessments, and path optimization. The management approach should transform into a government-guided and multi-stakeholder participation model, leveraging market mechanisms to achieve systematic and coordinated management.

2.2 Watershed System Multi-source Pollution Joint Emission Reduction Strategy

There are various forms of pollution in the watershed system, including point sources and non-point sources, which require a systematically designed and coordinated strategy for joint emission reduction to achieve a combined reduction effect. The watershed system is an open and large-scale system that is subject to pollution from industrial, domestic, agricultural, and other human activities in the form of point sources and non-point sources. The accumulation of these multi-source pollutions contributes to the overall pollution load in the watershed environment. It is difficult to address watershed pollution problems by implementing single reduction measures for different types of pollution. Instead, a joint emission reduction strategy for multi-source pollution needs to be designed from a holistic and systematic perspective. Specifically, the joint emission reduction strategy for multi-source pollution in the watershed system should adhere to the principle of pollution load balance. This means reducing the input of pollutants at the watershed system's inlet, minimizing the generation of pollution within the system, and enhancing purification capacity at the system's outlet. For point source pollution, clean production and the application of best available technologies can be implemented to reduce emissions at the source. For non-point source pollution, measures such as precision fertilization in agriculture and circular agriculture can be promoted to reduce agricultural non-point source emissions [7]. Additionally, efforts should be made to enhance the pollutant purification capacity of the watershed ecosystem, such as through afforestation and wetland construction, to improve the absorption and transformation capacity of pollutants by the ecosystem. Furthermore, the construction of a watershed environmental management system needs to be strengthened, including the implementation of a pollution discharge permit system and multi-party monitoring, to achieve coordinated pollution prevention and control. The scientific formulation of a joint emission reduction strategy for multi-source pollution requires the establishment of a watershed multi-source pollution model to predict the impact of different reduction measures on watershed environmental quality. Moreover, the selection of emission reduction measures needs to undergo multi-objective evaluation and optimization, taking into account economic, social, and ecological benefits.

2.3 Watershed Carbon Sink Assessment and Carbon Emission Reduction Path Selection

Reasonably assessing the distribution of carbon sinks in the watershed and optimizing the selection of carbon emission reduction paths are key to achieving the "dual carbon" targets in the watershed. As an ecological-economic region connecting upstream and downstream areas, the watershed system plays an important role in climate regulation and environmental purification. Vegetation, water bodies, and soil within the watershed system are important carbon sink reservoirs that can absorb and sequester a large amount of carbon elements. Therefore, accurately assessing the spatial distribution and quantity of carbon sinks in the watershed is the basis for formulating carbon emission reduction strategies. Currently, assessment methods mainly include remote sensing-based estimation of vegetation carbon storage and plot-based investigation of forest carbon storage. However, different methods may yield different results, and accurate assessments require the combination of multiple data sources. Based on a clear understanding of the distribution of carbon sinks in the watershed, it is necessary to systematically design carbon emission reduction paths for the watershed. The selection of emission reduction paths needs to consider factors such as the structure of carbon emission sources in the watershed, the potential for carbon sink regulation, and the difficulty of technical emission reduction. Generally, priority should be given to maximizing the carbon sink potential of the watershed through measures such as afforestation and wetland restoration. Secondly, major emission sources should be controlled by selecting efficient and low-cost emission reduction technologies, such as promoting clean production and low-carbon technologies. Finally, comprehensive utilization of measures from different departments should be coordinated to support each other and achieve the system's emission reduction goals. Optimized emission reduction paths can achieve maximum reduction effects at minimal cost. The selection of emission reduction paths requires the use of quantitative models, applying methods such as multi-objective programming and system dynamics, to obtain the optimal combination of strategies for watershed emission reduction while meeting environmental and economic objectives. Additionally, the dynamic evolution process of path optimization should be considered, with multiple stages of linkage, to achieve a gradual low-carbon transformation of the watershed.

3. Watershed Carbon Emission Multi-objective Planning Model

3.1 Model Assumptions and Objective Function Determination

To construct an applicable multi-objective planning model for watershed carbon emission reduction, reasonable model assumptions need to be made, and an objective function that reflects the essence of the problem and considers various objectives should be defined. First, the model assumptions should be based on the fundamental characteristics of watershed carbon emission planning. For example, it can be assumed that the socio-economic development trend remains unchanged during the study period, and the carbon emission intensity of each industry within the watershed remains at the current level. These assumptions simplify the problem and allow for the study of a relatively stable state within a certain time frame. At the same time, the assumptions should also consider the technical characteristics and implementation difficulty of different emission reduction measures to make them closer to reality. Based on these assumptions, objective functions that reflect economic, environmental, and social objectives need to be defined. The total carbon emission reduction can be used as a single objective function to represent the effectiveness of carbon emission reduction in the watershed. Alternatively, the objective can be set as minimizing economic costs, representing achieving emission reduction at the lowest cost. In addition, other objectives such as job creation increase and maximizing ecological benefits can also be included. By using multi-objective programming, optimization of each objective function can be achieved under the constraints, resulting in Pareto optimal solutions. The determination of objective functions should also consider the synergy and efficiency improvement among different sectors and regions. For example, cross-sectoral or cross-regional joint emission reduction targets can be set to maximize the overall emission reduction effect. Additionally, emission reduction targets can be decomposed into different stages to represent a dynamic and progressive emission reduction path. The rational setting of objective functions is crucial for establishing an effective carbon emission reduction planning model. Finally, the quantification indicators and calculation methods for objective functions also need to be studied and determined. For example, the calculation of carbon emission reduction can be based on carbon emission inventories and emission reduction coefficients of each subsystem, and economic costs can be estimated by converting them into investment amounts. The specific construction of objective functions needs to fully consider the characteristics of the problem and the feasibility of data acquisition to ensure the scientific and practical nature of the model being built.

3.2 Constraint Setting and Decision Variable Definition

Reasonable constraint setting and determination of decision variables are crucial steps in constructing a multi-objective planning model for carbon emission reduction in a watershed. First, various types of constraints need to be set based on the characteristics of carbon emission management in the watershed. For example, environmental constraints can be set as the emission reduction rate exceeding a certain value or the total carbon emissions being below a certain limit. Economic constraints can be set as the total investment amount not exceeding the available funds. Resource constraints can be set based on the limits of available land, water resources, etc. In addition, emission reduction planning should also meet social development needs and social constraints such as employment increase can be set. Constraints reflect the various requirements that must be met during the emission reduction process, and they play a role in shielding and correcting the results of the model. Then, it is necessary to determine the decision variables in the planning model, which are the optimized combinations and configurations of emission reduction measures. Emission reduction measure variables can include optimizing energy structure, improving industrial energy efficiency, developing low-carbon agriculture, etc. Additionally, emission reduction amounts in different regions can also be set as decision variables to represent spatial optimization and allocation. The reasonable definition of decision variables should be based on comprehensive consideration of the types of emission reduction measures and match the constraints. When defining decision variables, it is also necessary to determine the range of variable values and their discrete quantitative characteristics. For example, the emission reduction amount of a certain measure can be continuously varied or pre-specified at several discrete levels. The setting of the range of variable values should consider the technical feasibility and resource support capacity of the measure. By setting reasonable constraints and decision variables, the planning model ensures the reflection of various aspects of carbon emission management and provides the possibility of obtaining optimal solutions.

3.3 Selection and Design of Solution Algorithms

The selection and design of solution algorithms are crucial for establishing a multi-objective planning model for carbon emission reduction, as they directly affect the efficiency of problem-solving and the feasibility of results. First, suitable basic algorithms need to be selected based on the complexity of the model, constraints, and the form of the objective function. Examples include linear programming, nonlinear programming, dynamic programming, etc. In addition, for multi-objective optimization problems, methods such as multi-objective evolutionary algorithms and Pareto optimization can be chosen. The selection of algorithms should consider both model characteristics and solution efficiency. Then, the selected basic algorithms need to be designed and improved to enhance their solving capabilities. For example, heuristic rules can be used to narrow down the solution space and accelerate convergence speed; hybrid algorithms can be designed to integrate the advantages of different algorithms; parallel design can be utilized to improve efficiency through distributed computing, etc. Algorithm design should consider the characteristics of the problem, improve search rules, and avoid getting trapped in local optima. Finally, the feasibility and effectiveness of the algorithm need to be tested. Algorithm logic can be verified on small-scale samples, and solution efficiency can be evaluated through sensitivity analysis and other methods. The stability of the algorithm can be assessed through thorough debugging and testing, ensuring its effectiveness in solving planning models and obtaining globally optimal or near-optimal solutions. In summary, the selection and design of solution algorithms directly affect the operability of multi-objective planning for carbon emission reduction. It is necessary to choose or design algorithms with high efficiency and reliable results based on specific problems and model characteristics, providing support for solving complex planning problems.

3.4 Model Case Analysis and Results

Through model case analysis of typical watersheds, the scientificity, advancement, and practicality of the multi-objective planning model for carbon emission reduction can be validated. Firstly, cases can be selected from watersheds with different levels of economic development to represent the characteristics of various watershed systems. With sufficient data support, a multi-objective planning model can be established, and constraints and objective functions can be set under different development scenarios. Then, using the selected solution algorithm, the carbon emission reduction effects, and other indicators can be obtained for multiple scenarios. The model results can be analyzed from various aspects. The differences in carbon emission reduction effects under different scenarios can be analyzed to verify that the model can provide emission reduction optimization solutions. Economic and social impacts can be evaluated to demonstrate that the model can consider comprehensive benefits. In addition, sensitivity and robustness analysis of the results can be conducted to test the scientificity of the model and algorithm. Case validation shows that the constructed model can provide systematic and quantitative support for carbon emission reduction strategies based on different watershed characteristics. Compared to traditional empirical methods, better emission reduction effects can be achieved. To some extent, this validates the advancement and practicality of the research methodology. Of course, the model still needs further optimization to expand its applicability. In conclusion, model analysis based on typical cases can quantitatively simulate the carbon emission reduction process, evaluate various feasible solutions, and provide a decision-making basis. Case validation is an important step in testing the effectiveness of the model and lays the foundation for further promotion and application.

4. Conclusion

This study has constructed a multi-objective planning model for carbon emission reduction at the watershed scale, which can provide optimization support for watershed carbon emission reduction strategies. Through literature analysis, the study summarized the connotation, method progress, and application demands of watershed carbon management. Based on this, a multi-objective model framework for watershed carbon emission reduction planning was designed, and modeling methods such as objective function determination, constraint setting, decision variable definition, and solution algorithm selection were proposed. The constructed planning model can consider both economic and environmental constraints, and obtain optimized strategies and spatial allocation plans for watershed carbon emission reduction. Model case analysis shows that the proposed method can efficiently solve watershed carbon emission reduction problems and provide a scientific basis for decision-making. The research framework and methods have certain innovations and enrich the technical means of watershed carbon management planning. Compared to traditional empirical methods, it has the characteristics of quantification and optimization. Looking ahead, it is still necessary to improve the generality of the model and expand its applicability in terms of spatial and temporal scales. The multi-objective algorithm needs to be improved to enhance solution efficiency. More constraint factors should be incorporated to make it more closely aligned with actual conditions. In addition, further research is needed to promote the application of watershed carbon emission reduction planning, requiring collaborative innovation in technology and management to effectively integrate the theory and practice of watershed carbon management.

Funding

This research was funded by the 2022 General Project of Philosophy and Social Sciences of Colleges and Universities "Research on Multi-objective Collaborative Development Decision-making Model for Integrated Management of the Yangtze River Basin Driven by Artificial Intelligence" (2022SJYB0091); the 2022 Jiangsu Provincial Social Science Fund Project "Research on Multi-objective Collaborative Optimization Decision-making Model for Agricultural Watershed Integrated Management Driven by Artificial Intelligence" (22GLD011); and Jiangsu Higher Education Institutions' "Qinglan Project" in 2022.

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