Economic and Environmental Effects Assessment of Water Transport Infrastructure Based on MRIO Modeling and System Dynamics Simulation: A Case Study of the Jinghan Canal of China

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Abstract : The Jinghan Canal, aimed at resolving the “middle blockage” problem of the Yangtze River's golden waterway and addressing the comprehensive challenges of navigation safety and ecological protection, as well as enhancing the water security capabilities of the four water systems in the Jianghan Plain's four lakes area and Dongting Lake, is located in Hubei Province. With a total length of 246 km (including 93.5 km of new canal) and seven 10,000-ton-class port areas along its route, this paper systematically evaluates its strategic value and economic-environmental effects using a combined short- and long-term analytical framework. A Multi-Regional Input-Output (MRIO) model estimates the short-term stimulus of the 77.93-billion-yuan investment during construction. Results show an investment multiplier of approximately 2.76, driving over 215 billion yuan in total output and generating more than 84.9 billion yuan in value added across the Yangtze River Economic Belt. Hubei Province benefits most significantly, with cross-regional synergies in metal smelting, transportation, and finance. A System Dynamics (SD) model simulates the medium- to long-term evolution of Hubei, Hunan, and other provinces. The findings indicate that canal operation, by reducing logistics costs and optimizing transport structure, continuously promotes regional economic growth and industrial upgrading. Carbon emissions exhibit a green transition pattern characterized by an "overall decline with gradually slowing reduction rate," though significant spatial heterogeneity exists across provinces. The study concludes that the Jinghan Canal is not only a key project for optimizing the national waterway network but also a systemic strategic project fostering regional coordination and green growth, offering policy references for major infrastructure planning in other regions.

1. Introduction

The Jinghan Canal, aims to connect Songzikou in Jingzhou with Paizhouwan in Wuhan. By detouring the winding Jingjiang reach—known as “nine bends and a winding intestine”—it will significantly shorten navigation distance, remove shipping bottlenecks, and improve transport efficiency in the middle reaches of the Yangtze River. Strategically, this project forms a“golden dual-channel”with the main river of the Yangtze River, strengthening the country's comprehensive transportation network, enhancing factor mobility and industrial integration. It also promotes coordinated regional development by improving transport links across the Yangtze River Economic Belt, helping the central region integrate into the national market. In the context of China's dual carbon goals, the canal offers notable environmental advantages as a low-carbon transport mode that can replace higher-emission road and rail freight.

The existing literature on transportation infrastructure and economic growth, beginning with Gibbons et al. [1], establishes that public capital enhances productivity, while subsequent research confirms transport infrastructure boosts economic activity by reducing costs, expanding markets, and facilitating factor flows [2,3]. Different transport modes exhibit distinct mechanisms: roads affect urban specialization, while waterways are more critical for bulk cargo and manufacturing spatial organization. However, compared to extensive studies on highways and ports, systematic research on modern canals remains scarce. Historical studies show canals contributed to market integration, and recent research has begun exploring their role in regional connectivity, though most work remains case-based.

Methodologically, input-output analysis (IO/MRIO) is well-established for assessing sectoral transmission of investment shocks and quantifying direct and indirect effects[4,5], particularly for construction-phase impacts. System dynamics (SD) models nonlinear feedback and long-term evolution, such as industrial adjustment and environment-economy linkages[6,7]. Under China's dual carbon goals, canals offer low-carbon value through modal substitution effects, though increased traffic may bring ecological risks [7,8].

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The literature reveals significant gaps: limited empirical research on modern canals like the Jinghan Canal, lack of unified frameworks linking short- and long-term effects, and underutilized integration of MRIO and SD. Addressing these, this study adopts a mixed "MRIO→SD" approach, supplemented by uncertainty quantification and model validation to ensure robustness, to analyze the economic implications of the Jinghan Canal. This research not only fills academic voids but also informs key decisions along the Yangtze River Economic Belt, helping assess investment efficiency, guide industrial agglomeration, and support policy design that balances economic growth with environmental constraints.

2. Theoretical Framework and Mechanisms

2.1. Short-term Effect Mechanism

In recent years, under the situation of pressure on boosting domestic consumption and slowing export growth, the pulling effect of major infrastructure investment on economic growth has become increasingly prominent, becoming a key starting point for ensuring the sustained and stable development of regional economy. For the managers of the areas along and radiated by the Jinghan Canal, scientifically controlling the investment scale and rhythm during the canal construction period has become one of the core economic measures of governance at this stage. Therefore, accurately evaluating the economic effects induced by the investment during the construction period of the Jinghan Canal has important reference value for optimizing the project investment planning and formulating supporting economic policies.

Specifically, the spatial spillover of the economic pull of the investment during the canal construction period, that is, the linkage drive of the investment to the associated areas around Jingzhou, Wuhan and the surrounding areas along the route, is the core uncertain factor for evaluating its effects. The industrial chain links involved in canal construction, such as engineering construction, building material supply, and logistics transportation, will not only directly drive the industrial growth and employment improvement in the project location, but also further drive the development of energy supply, engineering consulting, operation and maintenance services and other fields through the multi-regional industrial chain transmission, forming a cross-regional industrial synergy chain.

At the same time, this pulling effect will radiate to surrounding cities through the transmission effect of the inter-regional supply chain, showing a clear regional spillover pattern. Upstream provinces provide raw materials such as steel and sand and gravel relying on resource endowments, midstream provinces undertake building material processing, engineering equipment manufacturing and other links by virtue of industrial foundation, and downstream riverine areas undertake the demand for logistics distribution and supporting services with the advantages of ports and location, forming a gradient linkage development trend. In addition, the investment in supporting industries in surrounding areas will also provide support for canal construction in return.

It can be seen that the systematic evaluation of the spatial spillover of the economic pull of the investment during the construction period of the Jinghan Canal is a necessary prerequisite for scientifically formulating project investment policies, and this study attempts to construct a set of targeted quantitative evaluation methods.

2.2. Medium and Long-term Effect Mechanism (System Evolution)

After the operation and navigation of the Jinghan Canal, its impact will gradually shift from the initial investment pull to the medium and long-term structural adjustment and systematic evolution. The effect mechanism at this stage is more complex, involving multiple feedbacks and dynamic coupling between the economic subsystem, shipping subsystem, energy subsystem and environmental subsystem.

The medium and long-term effects brought by the canal construction are not only reflected in the economic benefits directly brought by the reduction of shipping costs, but also in the profound changes of the regional economic system through reconfiguring factors, upgrading industrial structure, optimizing spatial pattern and green low-carbon transformation.

The reduction of shipping costs and market expansion will significantly improve shipping competitiveness, attract bulk cargo to transfer to water transport, promote the formation of specialized clusters in the industrial belt along the river, and strengthen the synergy of regional industrial chains through the multimodal transport system; structural restructuring drives the cross-regional flow of factors, the upstream strengthens energy and raw material supply relying on resource endowments, the midstream undertakes high value-added industries, and the downstream enhances service industry radiation, gradually optimizing the development gradient of "strong east and weak west";

Under the green transformation mechanism, the reduction of carbon emissions per unit of freight directly replaces high-energy-consuming land transportation, but the growth of shipping volume simultaneously causes ecological disturbance, which requires policy intervention to balance environmental constraints and economic growth, and ultimately form a dynamic balance of "economy-shipping-energy-environment".

This study uses the System Dynamics (SD) model to capture this multi-dimensional, nonlinear and time-lagged evolution process, thus revealing the sustained impact of the Jinghan Canal on the middle reaches of the Yangtze River and a wider range of regions.

3. Model Assumptions and Research Methods

3.1Basic Model Assumptions

This study builds separate models for short term and medium to long term analyses, with the following basic assumptions.

Short term (construction period) MRIO model assumptions: (1) The time horizon covers the construction period of the Jinghan Canal (approximately 4 5 years); input structures are fixed, i.e., direct input coefficients remain unchanged. (2) Excess capacity exists in each sector to meet the additional demand generated by canal construction. (3) There is a linear relationship between total output and final demand, disregarding returns to scale. (4) The influence of relative price changes on input output coefficients is ignored.

Medium to long term (operation period) SD model assumptions: (1) The time horizon is 2028 2048 (20 years after canal opening) with a one year time step; the system boundary is limited to the four core subsystems of economy, shipping, energy, and environment. (2) No extreme external shocks (e.g., major economic crisis or sudden environmental disaster) occur during this period. (3) Decision makers follow adaptive expectations and bounded rationality, adjusting their decisions through feedback loops. (4) Policy variables (e.g., environmental investment ratio) are set under a baseline scenario with continuation of current trends.

3.2 Short-term Analysis: Multi-Regional Input-Output Model (MRIO)

For the short-term analysis, this study employs the Multi-Regional Input-Output (MRIO) model to evaluate the economic effects of investment during the construction phase of the Jinghan Canal. The MRIO model is particularly suited for this purpose as it captures inter-regional and inter-sectoral economic linkages, enabling the quantification of direct, indirect, and induced impacts across supply chains. The data are sourced from the CEADS 2017 Interregional Input-Output Table covering 31 provinces and 42 sectors. To align with the canal's radiation scope, the analysis focuses on the Yangtze River Economic Belt, aggregating the remaining 20 provinces into a single external region. Using value-added coefficient vectors derived from the input-output table, the model traces how construction investment propagates through regional industrial chains and generates spatial spillover effects. According to the multi-regional input-output table(see Table 1), define the vector V as the value-added coefficient vector, that is, the share of value-added (Va) in total output (X), and the expression is as Eq(1):

$$V = Va * (\widehat{X})^{-1} \tag{1}$$

The total investment of 77.932 billion yuan is allocated across regions and sectors using coefficients αr and βs to construct the impact vector $\Delta Yr,s$, based on project data and analogous canal constructions, as shown in Eq(2).

$$\Delta Y_{r,s} = I_{total} * \alpha_r * \beta_s \tag{2}$$

According to the classic input-output model, the row-wise balance relationship (output vector) can be expressed as in Eq(3):

$$X = AX + Y = (I - A)^{-1}Y = BY \tag{3}$$

Where A is the direct consumption coefficient matrix, B is the Leontief inverse matrix, and Y is the final demand column vector. At this time, the value-added vector Va can be expressed as Eq(4):

$$\Delta Va = \widehat{V} * B * \Delta Y \tag{4}$$

Among them, Va is a 1×m row vector, and V is a diagonal matrix with V as the diagonal element. VBY represents the value creation matrix induced by the final demand, and its specific expansion formula is shown in Eq(5).

$$\widehat{V}B\Delta\widehat{Y} = \begin{bmatrix} V^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & V^m \end{bmatrix} \begin{bmatrix} B^{11} & \cdots & B^{1m} \\ \vdots & \ddots & \vdots \\ B^{m1} & \cdots & B^{mm} \end{bmatrix} \begin{bmatrix} \Delta Y^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \Delta Y^m \end{bmatrix}$$

$$= \begin{bmatrix} V^1B^{11}Y^1 & \cdots & V^1B^{1m}\Delta Y^m \\ \vdots & \ddots & \vdots \\ V^mB^{m1}Y^1 & \cdots & V^mB^{mm}\Delta Y^m \end{bmatrix} \tag{5}$$

ΔX denotes the total output effect, measuring the increase in provincial gross output following investment; ΔVa denotes the value-added effect, reflecting the corresponding rise in provincial GDP.

Table 1: Multi-regional Input-Output Table

		Intermediate goods				Final goods				Gross Output
		1	2	…	m	1	2	…	m	
Intermediate Input	1	Z^{11}	Z^{12}	…	Z^{1m}	Y^{11}	Y^{12}	…	Y^{1m}	X^1
	2	Z^{21}	Z^{22}	…	Z^{2m}	Y^{21}	Y^{22}	…	Y^{2m}	X^2
	..	…	…	…	…	…	…	…	…	…
	m	Z^{m1}	Z^{m2}	…	Z^{mm}	Y^{m1}	Y^{m2}	…	Y^{mn}	X^m
Value Added		Va^1	Va^2	…	Va^n					
Total Input		X^1	X^2	…	X^m					

The total output multiplier m_out = ΔX / I_total and value-added multiplier m_va = ΔVa / I_total can be decomposed by expanding the Leontief inverse matrix into a power series:

$$B=I+A+A2+A3+ \tag{6}$$

which converges if the spectral radius $\rho(A) < 1$. For the 2017 inter-regional input-output table used in this study, $\rho(A) = 0.68$, confirming convergence. The first term I represents the direct effect of the initial investment; A captures the first-round indirect effects (suppliers' responses); and Ak (for k≥2) captures higher-order ripple effects. The ratio of indirect to direct effects is (m_out-1)/1 = 1.76, indicating that inter-industry spillovers amplify the initial investment by 176%.

3.3 Medium and Long-term Analysis: System Dynamics (SD)

3.3.1. Research Area

Hubei Province and Hunan Province are important economic and transportation hubs in the central region of China. In 2024, the gross domestic product (GDP) of Hubei Province exceeded 6 trillion yuan, and the regional

GDP of Hunan Province reached 5.32 trillion yuan. Relying on the unique advantages of the golden waterway of the Yangtze River, the two provinces have a significant proportion of water transport in the comprehensive transportation system.

The port cargo throughput of Hubei Province reached 753 million tons, a year-on-year increase of 8.6%; the total cargo transportation turnover of Hunan Province in the whole year was 3116.0 billion ton-kilometers, in which water transport played an important role. In terms of energy consumption, water transport is an important development direction of green transportation due to its characteristics of large transport capacity, low energy consumption and low pollution.

Improving the shipping capacity in the middle reaches of the Yangtze River and promoting the green development of shipping have become key measures for Hubei and Hunan to implement the "carbon peaking and carbon neutrality" strategy. This paper intends to take Hubei Province, Hunan Province and the Yangtze River Economic Belt as the research objects, and use the system dynamics model to simulate and analyze the complex relationship between regional economy, shipping, energy and environment[9].

3.3.2. System Boundary

To scientifically quantify the comprehensive impact of the Jinghan Canal on the middle reaches of the Yangtze River, this study establishes four core subsystems of economy, shipping, energy and environment as the core boundary, and the four subsystems form a coupling effect analysis framework as shown in Figure 1.

Among them, the economic subsystem is the driving core, covering variables such as regional GDP, industrial structure, environmental protection investment, and environmental pollution losses; the shipping subsystem is the carrier of action, including indicators such as waterway cargo turnover, port throughput, shipping industry investment ratio, and transportation industry input coefficient; the energy subsystem is the metabolic context, focusing on the total energy consumption and energy consumption generation coefficient; the environmental subsystem is the constraint feedback[10,12], quantifying pollutant emissions, the impact of water ecological sensitive areas, and low-carbon emission reduction benefits.

Each subsystem realizes the dynamic balance of the green shipping system in the middle reaches of the Yangtze River through multiple feedback mechanisms. Economic growth drives the expansion of transportation demand and directly promotes the development of inland water transport; the shipping industry feeds back to the regional economy by reducing logistics costs and strengthening hub functions, forming a positive reinforcement loop of "economy-shipping".

On the one hand, it will bring a policy regulation mechanism: the governments of the two provinces increase environmental protection investment, optimize the energy structure, improve the utilization efficiency, and ultimately realize the system-level green low-carbon transformation.

This mechanism reveals that through policy intervention and technological innovation, Jinghan Canal can be transformed into the core driving force that promote the development of green shipping in the middle reaches of the Yangtze River, and ultimately realize the coordinated optimization of the "economy-energy-environment" system[11,13].

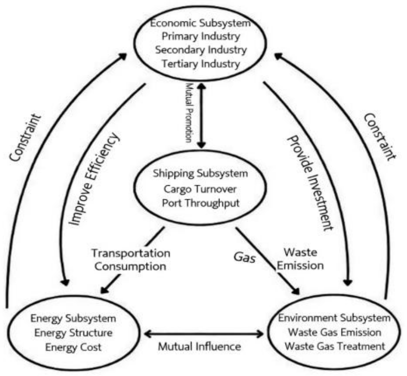

Figure 1 Analysis Framework of Coupling Effect

3.3.3 Parameter estimation and calibration

In the parameter estimation of system dynamics models, this paper adopts a strategy that combines the fourth-order Runge-Kutta method (RK4) with the Levenberg-Marquardt (LM) algorithm. Specifically, for a given parameter vector $\theta \in Rn$, the RK4 is used to numerically integrate the system of ordinary differential equations. Assuming the system state equation is x = f(t, x, θ), with a step size of h ,the iterative format of RK4 is:

$$\text{RK4 is:}\begin{cases}\mathbf{k}_1 = \mathbf{f}(t_k, \mathbf{x}_k, \theta)\\ \mathbf{k}_2 = \mathbf{f}\left(t_k + \frac{h}{2}, \mathbf{x}_k + \frac{h}{2}\mathbf{k}_1, \theta\right)\\ \mathbf{k}_3 = \mathbf{f}\left(t_k + \frac{h}{2}, \mathbf{x}_k + \frac{h}{2}\mathbf{k}_2, \theta\right)\\ \mathbf{k}_4 = \mathbf{f}(t_k + h, \mathbf{x}_k + h\mathbf{k}_3, \theta)\\ \mathbf{x}_{k+1} = \mathbf{x}_k + \frac{h}{6}(\mathbf{k}_1 + 2\mathbf{k}_2 + 2\mathbf{k}_3 + \mathbf{k}_4)\end{cases} \tag{7}$$

The model output at each observation time is thereby obtained as ymodel (θ), based on which the residual vector is constructed as r(θ)= ymodel(θ)− yobs. The objective function is defined as the sum of squared residuals: S(θ)= ½ r(θ)^T r(θ). The Levenberg-Marquardt algorithm utilizes this residual vector to compute parameter updates by means of an adaptive damping mechanism. In each iteration, the following regularized linear system of equations is solved:

$$(\mathbf{J}^T\mathbf{J} + \mu\mathbf{I})\Delta\theta = -\mathbf{J}^T\mathbf{r} \tag{8}$$

Here, J = $\partial r/\partial \theta$ represents the Jacobian matrix of the residuals, μ is the damping factor, and I is the identity matrix. This method combines the rapid local convergence of the Gauss-Newton method (as μ approaches 0) with the global search characteristics of the gradient descent method (as μ approaches infinity). During the iteration process, at each step, the RK4 method needs to be recalculated to obtain the model output under the current parameters, and the finite difference method is used to approximate the Jacobian matrix. The component calculation formula is:

$$\mathbf{J}_{ij} \approx \frac{\mathbf{r}_i(\theta+\delta_j\mathbf{e}_j)-\mathbf{r}_i(\theta)}{\delta_j} \tag{9}$$

Here, δ_j represents a small perturbation to the j-th parameter, and ej is a unit vector. By dynamically adjusting the damping factor μ, this method combines global convergence and local rapid convergence, enabling stable and efficient estimation of the unknown parameters of the model.

3.4 Methodological comparison

The SD model was chosen over the CGE model for the following reasons: CGE models rely on assumptions of perfect competition and market clearing, making them ill-suited for capturing the long-term, non-linear feedback and multi-subsystem coupling induced by the canal. In contrast, SD explicitly models stock-flow structures, feedback loops, and time delays, making it more appropriate for simulating post-operation dynamics such as reduced logistics costs, industrial upgrading, and carbon emission trajectories. Moreover, the canal involves irreversible investment and path dependence, which CGE's comparative static framework cannot easily handle.

Compared to a single model, the MRIO-SD framework has clear advantages: a standalone MRIO can accurately calculate the spatial multiplier effects of construction investment but cannot simulate post-operation dynamics; a standalone SD can simulate long-term evolution but lacks fine-grained quantification of cross-regional industrial chain transmission. This study adopts a two-stage "MRIO → SD" framework: first using MRIO to estimate the short-term investment effects, then introducing dynamic variables (e.g., reduced logistics costs, increased water-transport share) into the SD model to simulate medium- long term economic-environmental coupling. This achieves an organic integration of "short-term precise accounting" and "long-term mechanism simulation".

4. Results and Discussion

4.1. Short-term Results

The MRIO model yields a total output multiplier m_out = 2.76 and a value-added multiplier m_va = 1.09. Using the power-series expansion $B = I + A + A^2 + A^3 + \ldots$, the direct effect (first term I) accounts for 1.00 unit of output per unit investment; the sum of indirect effects $(A + A^2 + A^3 + \ldots)$ contributes 1.76 units. The spectral radius $\rho(A) = 0.68$ (computed from the 2017 input-output matrix) ensures convergence and indicates moderate inter-sectoral connectivity.The 77.932-billion-yuan construction investment of the Jinghan Canal has a significant economic pulling effect on the Yangtze River Economic Belt, and its core pulling capacity is reflected by the multiplier effect with a total output multiplier of 2.76, that is, 1 yuan of investment can drive 2.76 yuan of total output. The value-added multiplier is 1.09, that is, 1 yuan of investment can create 1.09 yuan of value-added.

Based on this calculation, full implementation of the project investment will drive the Yangtze River Economic Belt's total output to exceed 215.1 billion yuan and create over 84.945 billion yuan in value-added, directly supporting regional GDP growth. This value-added effect penetrates all provinces' industrial systems, becoming a key short-term growth driver.

Provincial benefits show an obvious "gradient difference" as described in **Figure 2**. As the core construction province, Hubei benefits most, with total output effect of 89.938 billion yuan (42% of basin total) and value-added of 36.130 billion yuan (0.97% of provincial GDP), highlighting deep linkage with construction and building material industries. Hunan, as a direct radiation area, has output of 31.027 billion yuan and 0.35% contribution. Upstream, Sichuan and Chongqing form a core benefit pole, driving growth through petroleum and coal resource supply, focusing on resource export and industrial supporting, complementing the midstream's construction participation. Downstream provinces see relatively higher growth in transport and finance, reflecting that the canal will expand downstream shipping advantages and enhance high-value-added industry competitiveness.

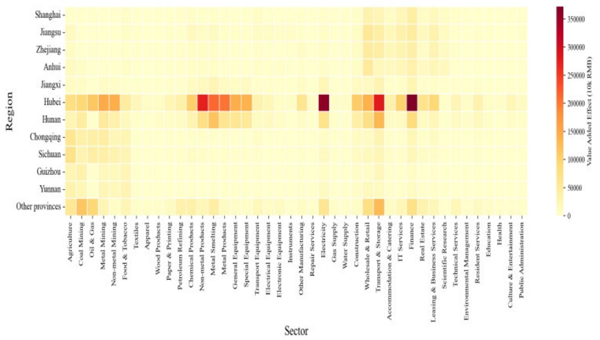

Figure 2 Value-Added Effects of the Jinghan Canal Investment on Various Provinces and Sectors

Table 2 Economic Effects of the Jinghan Canal Investment on Provinces (Unit: 100 million yuan)

Region	Total Output Effect	Value-Added Effect
Shanghai	63.03	21.31
Jiangsu	102.21	39.07
Zhejiang	76.24	31.70
Anhui	82.23	29.29
Jiangxi	83.79	26.40
Hubei	899.38	361.30
Hunan	310.27	116.94
Chongqing	84.33	37.25
Sichuan	93.19	40.01
Guizhou	41.91	19.36
Yunnan	46.58	21.27
Other Provinces	270.70	103.35

The Jinghan Canal's investment has driven a diversified industrial pattern through industrial chain correlation, promoting midstream construction and downstream services while strengthening upstream resource supply, forming cross-regional, whole-chain coordinated development in Table 2. The three most significant pulling sectors are metal smelting and rolling, transportation/warehousing/postal services, and finance, highlighting dependence on basic materials, logistics, and capital services. Metal smelting has the highest total output effect, with value-added of 4.349 billion yuan, driving upstream mining and energy support via cross-regional procurement. Transportation/warehousing/postal services has value-added of 7.872 billion yuan (ranking first), ensuring efficient circulation of materials and promoting regional network integration. The financial industry has total output effect of 13.582 billion yuan and value-added of 7.787 billion yuan, covering project financing, credit, and settlement, enhancing liquidity and risk resistance. Additionally, electricity and heat production improved significantly, reflecting high energy demand, relying on cross-regional grid dispatching and clean energy to optimize the energy structure. In summary, the canal's pulling effect extends beyond traditional infrastructure to energy, materials, logistics, and finance, forming a cross-regional, multi-level synergy network that demonstrates major infrastructure's role in resource allocation and regional division of labor.

.4.2. Medium and Long-term Effect Results

4.2.1. Scenario Simulation and Analysis Based on Hubei and Hunan

To assess the impact of the canal's opening on industrial structure, economic growth, and carbon emissions in Hubei and Hunan, relevant parameters were imported into the system model to simulate medium-to-long-term development trends, as shown in Figures 3 and 4.

First, the impact of the canal on economic growth and industrial structure is significant. The canal's opening significantly reduces logistics costs and improves transportation efficiency, injecting new momentum into high-quality economic development in Hubei and Hunan. In the short term, it stimulates investment in infrastructure and boosts secondary industries such as construction and manufacturing. Enhanced shipping conditions also promote industrial agglomeration and optimized division of labor along the rivers, supporting industrial upgrading and regional coordinated development.

Comparative analysis shows that the economic development trajectories of the two provinces show similar characteristics, but there are certain differences in specific performance due to the differences in regional industrial structure and location conditions. Both Hunan Province and Hubei Province have benefited from the improvement of shipping conditions. Advantageous industries in the secondary industry such as equipment manufacturing and non-ferrous metals have received stronger support, and the development of modern logistics and regional commerce and trade in the tertiary industry has accelerated.

Second. the impact of the canal on carbon emissions of the two provinces in medium and long-term is also important.

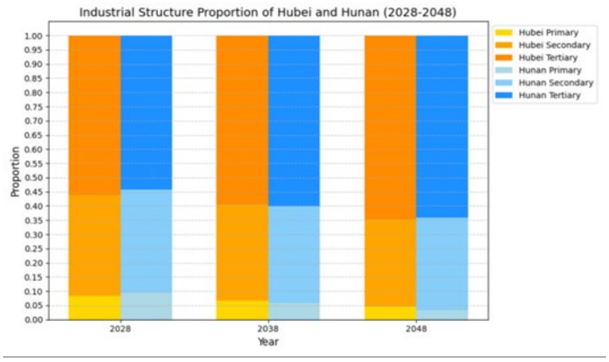

Figure 3 The Changing Trend of The Industrial Structure

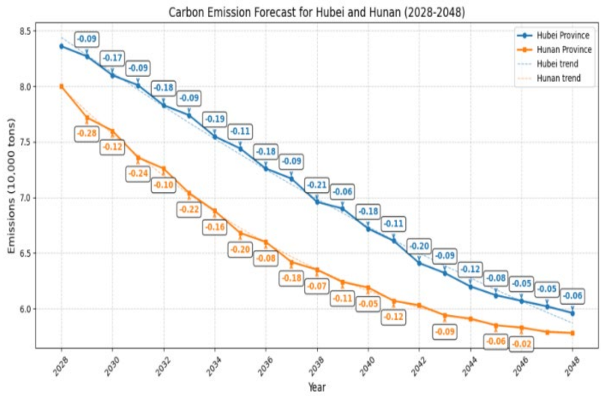

Figure 4 Forecast of Carbon Emission Trends in the Two Provinces (Unit: 10,000 tons)

In the medium and long term, the enhancement of the canal's navigation capacity and the improvement of the multimodal transport system have effectively supported the development of the export-oriented economy of the two provinces, promoted trade facilitation and supply chain efficiency improvement, and created favorable conditions for the rapid development of the tertiary industry, especially modern logistics, commercial and trade services and other industries.

In addition, the environmental benefits brought by the canal have gradually emerged. By promoting the development of "water-rail-road-air" multimodal transport, part of the traditional high-energy-consuming and high-emission land transportation has gradually shifted to more green and low-carbon water transportation, which not only reduces the energy consumption and carbon emissions per unit of freight volume, but also helps the two provinces achieve the goals of green low-carbon transformation.

4.2.2. Scenario Simulation and Analysis Based on Various Provinces and Cities in the Yangtze River Economic Belt

In this study, Hubei Province and Hunan Province are taken as typical cases to deeply reveal the typical mechanisms and differentiated performances of the impact of canal opening on regional economic development and carbon emissions. Based on the above analysis framework and research methods of the two provinces, this paper further expands the research scope to the whole Yangtze River Economic Belt, and systematically investigates the economic and environmental performance of each city under the background of the improvement of the canal network, as reported in Table 3 and Table 4.

Through the empirical analysis of the panel data of major cities in the Yangtze River Economic Belt, this study quantifies the economic growth contribution rate and carbon emission trend of each city brought by the improvement of shipping conditions.

The research shows that although each city has differences in industrial structure, location conditions and development stage, the construction of canal infrastructure has significantly promoted the local GDP growth, among which the economic growth contribution rate of riverine hub cities is generally higher than that of inland node cities.

At the same time, the carbon emission trajectory of each city shows a typical characteristic of "overall decline, but the decline rate gradually slows down", but the emission reduction intensity shows an obvious gradient difference due to the different urban endowments and policy regulation efforts.

This comprehensive analysis not only verifies the positive significance of canal infrastructure for regional coordinated development, but also provides city-level policy basis based on empirical evidence for promoting the high-quality development of the Yangtze River Economic Belt. The research results show that it is necessary to formulate differentiated development and emission reduction strategies according to local conditions to realize the coordinated optimization of economy and environment.

Table 3 Economic Growth Impact and Contribution of Each Province and Municipality in the Yangtze River Economic Belt

Province	Contribution rate in the fifth year (%)	Contribution Rate in the tenth year (%)	Contribution rate in the twentieth year (%)
Shanghai	1.91	5.44	8.56
Jiangsu	2.12	7.95	8.58
Zhejiang	3.54	7.87	11.77
Anhui	2.82	5.30	8.91
Jiangxi	2.97	6.72	7.23
Hubei	7.54	11.66	15.58
Hunan	4.77	6.43	12.09
Chongqing	1.32	6.98	7.2
Sichuan	4.55	6.98	11.07
Guizhou	2.17	5.81	5.80
Yunan	3.57	6.50	9.00

Table 4 Carbon Emissions of Each Province and Municipality in the Yangtze River Economic Belt (Unit: 10,000 Tons)

Province	2028	2033	2043	2048
Shanghai	1.05	0.72	0.69	0.53
Jiangsu	6.02	4.98	3.8	3.12
Zhejiang	5.11	3.89	3.01	2.65
Anhui	6.99	6.01	5.33	4.62
Jiangxi	6.71	4.83	3.99	3.09
Hubei	9.73	7.38	6.27	5.26
Hunan	7.83	6.92	6.11	5.34
Chongqing	3.58	2.05	1.5	1.02
Sichuan	8.67	6.64	5.54	4.72
Guizhou	4.81	3.06	2.67	2.09
Yunan	4.5	3.77	2.97	2.13

The operation of the Jinghan Canal primarily influences regional growth and emissions through two distinct pathways:

On the one hand, the canal directly reduces unit transportation costs by shortening the navigation distance and accommodating 10,000-ton vessels. This reduction lowers the generalized cost of trade for industries along the route. As logistics costs decrease, the market access for local manufacturers expands, encouraging economies of scale and specialization. This mechanism explains why Hubei's contribution rate increases from 7.54% in year five to 15.58% in year twenty—the compound effect of reduced costs allows local industries to reinvest savings into expansion and innovation.

On the other hand, the canal induces a substitution away from road and rail freight. Since water transport has a significantly lower carbon footprint per ton-kilometer, this shift directly contributes to the decoupling of economic growth from carbon emissions. The data in Table 4 shows a steady decline in absolute emissions for most provinces. This "overall decline" is not merely a byproduct of efficiency; it is a direct structural result of replacing high-emission transport modes with low-emission water transport. However, the "gradually slowing reduction rate" suggests that once the easily substitutable freight has shifted, further reductions require deeper technological investments in green shipping and port electrification.

5. Conclusions and Policy Implications

5.1. Main Conclusions

The main research conclusions of this paper are as follows: First, in the short term, the 77.932 billion yuan construction investment of the Jinghan Canal has a significant pulling effect, with a multiplier of about 2.76, driving total output of over 215 billion yuan and value-added of over 84.9 billion yuan. Hubei benefits the most, while Hunan, Sichuan, and others gain through industrial chain synergy, mainly pulling key sectors such as metallurgy, building materials, and transportation. Second, in the medium and long term, the canal reduces transportation costs, promotes industrial structure optimization, increases the proportion of the tertiary industry, shifts the industrial chain toward green, high-end, and intensive transformation, and enhances the linkage and factor flow efficiency in the middle reaches of the Yangtze River. Third, in terms of environmental effects, the increase in the share of water transport and technological progress gradually reduce carbon intensity, achieving a long-term green emission reduction trajectory. Fourth, the overall conclusion: The Jinghan Canal is a systematic project for promoting regional coordination and green growth. In the short term, it relies on investment pull; in the medium term, it shows structural upgrading; and in the long term, it realizes ecological feedback, providing a replicable experience for other regions.

5.2. Policy Recommendations

Based on the above conclusions, this paper proposes: (1) Improve investment efficiency and regional synergy via whole-chain optimization (raw materials, equipment, logistics, finance); establish inter-provincial co-construction and benefit-sharing to amplify the multiplier. (2) Enhance multimodal integration by connecting canal with rail, road, ports and aviation; build a water-rail-road-air system in the middle Yangtze; raise digital shipping levels to cut carbon and boost efficiency. (3) Address the "strong middle, weak upper/lower reaches" imbalance through industrial transfer and factor compensation; support downstream services and upstream resource conservation. (4) Promote green transport: set up shipping carbon accounting, clean-energy ships and shore power; use carbon trading and green credit to reduce transport emissions. (5) Build a system dynamics-based "transport-economy-energy-environment" platform for real-time monitoring and policy adjustment, ensuring scientific governance and sustainable development.

This study has limitations. First, the MRIO analysis is based on the 2017 input-output table, which involves a time lag and does not fully capture recent industrial structural changes. Second, policy variables (e.g., environmental investment ratio) are treated as exogenous scenarios, without considering local governments' endogenous policy adjustments in response to real-time environmental feedback. To address these limitations, future research can be carried out in two directions. First, update the input-output table and explore coupling dynamic IO with the SD model to achieve longer-horizon rolling projections. Second, endogenise "race-to-the-bottom" or "collaborative emission reduction" behaviours among local governments, and construct a multi-regional SD-game hybrid model to analyse economic and environmental performance under different cooperation mechanisms.

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