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Feasibility analysis of the market-oriented construction management model of drainage project based on evolutionary game

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ABSTRACT

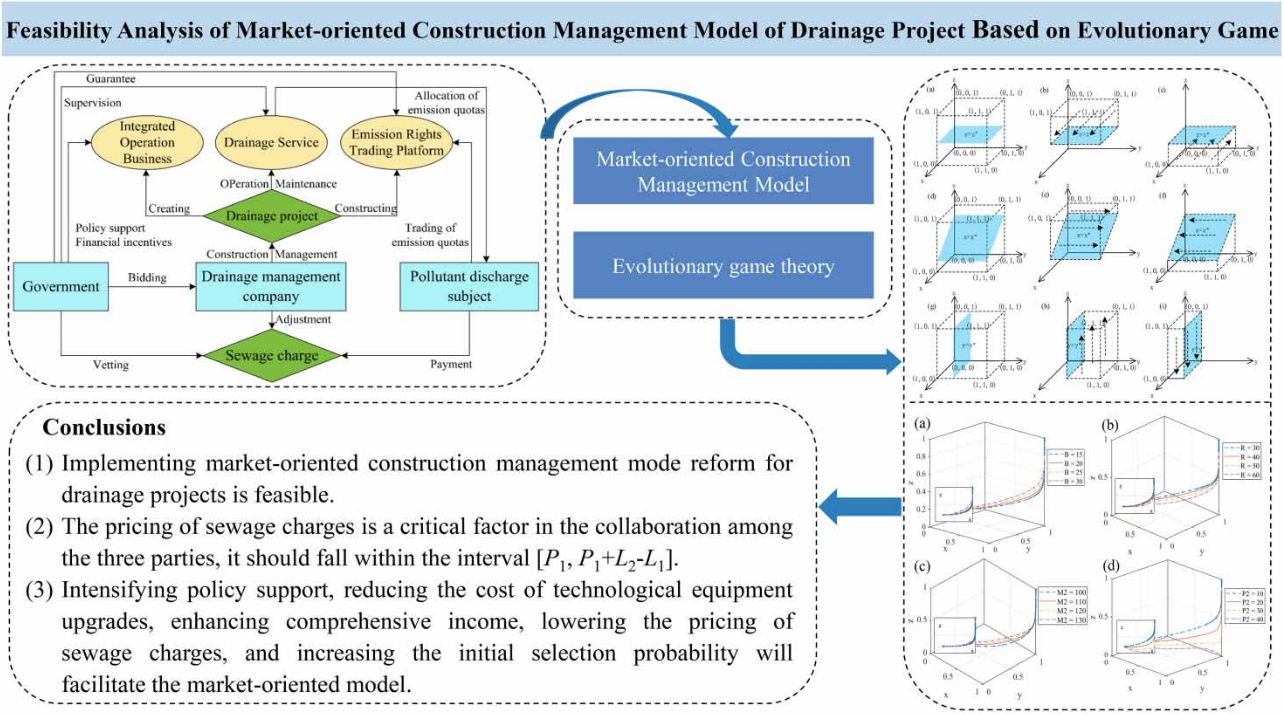
The construction and operational costs of drainage projects are high. Traditional construction management models impose significant financial pressure on the government and reduce stakeholder motivation. Within the market-oriented development context, reforming the construction management model is crucial for breaking the current predicament. This research establishes a framework for the market-oriented construction management model for drainage projects and constructs a behavioral strategy evolutionary game model involving government, drainage management companies, and pollution discharge subjects. Through theoretical analyses and simulations, this research presents recommendations for the implementation of the market-oriented model. The research findings indicate that: (1) the market-oriented model is feasible both theoretically and practically. Pollution rights trading aids pollution discharge subjects in adapting to the market-oriented model. (2) Ensuring sewage charges remain within the interval $[P_1, P_1 + L_2 - L_1]$ is crucial for trilateral cooperation. (3) Simulation analysis shows that intensifying policy support, reducing the cost of technological equipment upgrades, enhancing comprehensive income, lowering the pricing of sewage charges, and raising initial selection probability all promote a tendency towards ESS.

Key words: construction management model, drainage project, evolutionary game, market-oriented, pollution rights trading

HIGHLIGHTS

- To construct a market-oriented construction management model for drainage projects.
- To establish an evolutionary game model of three stakeholders involved in the model reforming.
- To analyze the feasibility of the market-oriented model.
- The promotion of the market-oriented model of drainage projects is to support significance to reduce government financial pressure and achieve sustainable development.

GRAPHICAL ABSTRACT



1. INTRODUCTION

1.1. Background

The drainage project is an engineering form that directs urban rainwater and domestic wastewater into natural water bodies, playing a crucial role in upholding urban hygiene and ecological environments. It typically encompasses municipal pipelines and wastewater treatment plants. The drainage system comprises separate and combined systems and stands as a pivotal infrastructure for the functioning of cities. With the expansion of urban areas, the scale of drainage projects is continuously increasing. The substantial construction and operational costs of these extensive projects are notably high. For instance, the investment in drainage pipelines in China ranges from 2 to 5 million CNY per kilometer (Cheng *et al.* 2022). In the '14th Five-Year Plan,' the projected length of these pipelines is 80,000 km. Considering the inadequacy of previous investments, the overall estimated funding shortfall is expected to reach 500 billion CNY (Cheng *et al.* 2022). Simultaneously, the total operating cost for urban sewage treatment in China exceeds the sewage treatment fee standards by approximately 0.45 CNY per cubic meter (Long *et al.* 2021a). With an annual sewage discharge volume surpassing 571.36 billion m^3, the annual funding gap exceeds 25.7 billion CNY, constituting approximately 0.1‰ of the general public budget expenditure in 2022. The funding gap will be supported through government fiscal revenue to ensure the proper development and operation of relevant infrastructure. It is evident that the government bears a significant fiscal burden in the construction and management of drainage projects. Addressing how to reduce the government's fiscal burden in this aspect becomes an important research topic.

Innovating the drainage project construction and management system is one of the vital approaches to address the current financial burden in drainage projects. The commonly seen approach is the public–private partnership (PPP) model. Due to the characteristic of involving private capital, the PPP model is believed to alleviate the pressure from government financial shortages (Gong *et al.* 2022). Moreover, it contributes to enhancing operational efficiency and improving services in drainage projects (Cheng *et al.* 2023). Most countries have attempted to adopt the PPP model in drainage projects (Wang *et al.* 2015). However, recent years have seen emerging issues globally in purely government-funded PPP projects, including premature termination, early changes in ownership, cost overruns, and time overruns (Musenero *et al.* 2023), drawing widespread attention from scholars both domestically and internationally. In the current environment, the state's more stringent and regulated management of PPP projects has limited the implementation scope of PPP projects in drainage engineering (Liu *et al.* 2021b).

PPP projects usually involve long-term contracts, unavoidably leading to incomplete dynamics, potentially allowing opportunities for opportunistic benefits for private capital and the government (Xiong *et al.* 2022). The implementation of PPP projects in drainage engineering involves numerous stakeholders, leading to difficulties in delineating responsibility boundaries and encountering issues with low management efficiency (Huang *et al.* 2018). Within all types of PPP arrangements, private capital aims for return on investment. However, drainage projects lack commercial attributes and rely on government payments, resulting in the government bearing higher financing costs (Jang *et al.* 2018). Additionally, due to private capital's lessened focus on operational efficiency during maintenance, the sewage treatment costs for drainage projects under the PPP model increased by 10.63% compared to those operated by the government (Liu *et al.* 2019a; Tang *et al.* 2021).

Resolving these issues essentially involves the strategic decision-making of the relevant stakeholders. The government aims to leverage the management and technical expertise of drainage management companies (DMCs) to enhance the efficiency of drainage projects while reducing their construction and management costs. The objective of these management companies is to maximize their profits. Urban residents and production companies hope to receive more efficient and stable drainage services within affordable cost ranges. The demands of these stakeholders might be addressed through market mechanisms. *Opinions on Standardizing the Implementation of the New Mechanism for Government and Social Capital Cooperation* (referred to as *Opinions*), released by the State Council on November 3, 2023, calls for further deepening the reform of infrastructure investment and financing mechanisms, aiming to leverage the role of market mechanisms fully (National Development and Reform Commission and Ministry of Finance 2023).

Therefore, the research proposes a market-oriented construction management model of drainage project, analyzes the decision-making behaviors of the stakeholders, and establishes an evolutionary game model to explore the feasibility and critical factors of the market-oriented model.

1.2. Literature review

At the early stages of systemic and large-scale construction of drainage projects, most countries adopt a government-led approach, wherein the government provides funding for both the construction and operation of drainage projects. Tax revenue serves as one of the sustainable financial resources in many countries, yet developing countries often lack adequate tax resources (Wu 2010). As environmental demands increase and the scale of drainage projects expands, local governments face mounting financial pressures. On the other hand, proficient sewage treatment demands high levels of expertise, making it challenging to rely solely on the government to ensure both effectiveness and efficiency (An *et al.* 2018).

Following the numerous issues encountered in drainage project PPPs, some scholars have proposed the implementation of an improved PPP model to enhance its applicability. This transition moves from the traditional PPP model to PPP + EOD (Government and Social Capital Cooperation + Environment-Oriented Development), and PPP + EOD + GSF (Government and Social Capital Cooperation + Environment-Oriented Development + Government Special Funds). These models aim to transform a portion of the increased land value and local fiscal revenue resulting from ecological environment enhancements towards drainage projects, achieving the monetization of ecological benefits (Weng *et al.* 2022). Additionally, by leveraging Real Estate Investment Trusts in the infrastructure sector, using drainage project PPPs as underlying assets, funds are raised from investors through securitization (Wang 2023), thereby alleviating the funding shortfall in drainage projects.

Scholars have proposed that the construction and management of drainage projects should adhere to a market-oriented model (Jia *et al.* 2022; Lu *et al.* 2022). This approach offers advantages such as efficient project implementation, technological innovation, and more diverse investment and financing channels (Bach *et al.* 2014; Bayliss 2014). Some of the least developed and developing countries have already begun adopting market-oriented models in drainage projects (Hilbig & Rudolph 2019; Anh *et al.* 2022). In developed countries, public funds often fall short of meeting the long-term demands for the operation and equipment upgrades of sewage treatment facilities. Government officials are typically unwilling to bear the political risk associated with raising taxes or fees. Hence, the market management model for drainage projects has long been one of the choices for many developed countries (Jacobs & Howe 2005).

In the context of pollution discharge rights, domestic and international scholars have primarily focused on four key aspects of research. First, there is research on the pollution discharge rights trading market. Yang Xia and others have proposed a framework for reforming the pollution discharge rights system, with the pollution discharge permit system at its core, allowing for compensated use and trading of these rights (Yang *et al.* 2023). Second, the allocation of pollution discharge rights is a significant study area. Gao Zhu and others researched the initial allocation of pollution discharge rights based on water functional zoning using a single-objective decision model (Gao & Li 2010). Betz and others have analyzed the issue from the perspectives of fairness principles and long-term development, suggesting that pollution discharge rights should not be allocated for free (Betz *et al.* 2010). Third, the pricing of pollution discharge rights is a subject of study. Sun Jinfeng and others have examined the optimization of enterprise production decisions and pollution emission strategy selection under uncertain pollution discharge trading prices (Sun *et al.* n.d.). Fourth, the impact of the pollution discharge trading market on enterprise production is investigated. Gong & Zhou (2013) have developed dynamic production models to study the influence of pollution discharge trading on production planning. Additionally, Cao & Liu (2023), based on panel data from 252 cities, used a difference-in-differences model to conclude that pollution discharge trading can promote urban economic development. Zhang & Xu (2013) introduced a profit maximization model for production decisions under pollution discharge trading.

The PPP improvement model primarily addresses the funding needs of drainage projects by augmenting fiscal revenue or establishing short-term financing channels. However, it falls short of resolving issues such as the lack of profit avenues, low operational efficiency, and dependency on government financial inputs in drainage projects. Consequently, this limitation restricts long-term development. Existing research on pollution discharge rights is predominantly based on the limited processing capacity of drainage projects. It focuses on exploring the impact of pollution discharge trading and allocation on pollution discharge subjects (PDSs). However, the current state of drainage projects significantly mismatches with the urbanization level in China. It overlooks the potential enhancement in production benefits for PDSs resulting from the improved efficiency of drainage projects.

In practice, the market-oriented construction management model effectively engages social DMCs, fosters drainage-related businesses, enhances the operational efficiency of drainage projects, reduces reliance on government subsidies, and promotes sustainable development. In theory, there is still a lack of comprehensive research on the implementation strategies and key factors of this model. This research addresses some of these gaps in the existing literature.

2. RESEARCH METHODS AND IDEAS

2.1. Evolutionary game theory

Evolutionarily stable strategy (ESS) and replicator dynamics are the two fundamental concepts in evolutionary game theory, representing the stable state of the evolutionary game and the dynamic convergence process towards this stable state (Smith & Price 1973; Taylor & Jonker 1978). In the game process, the players make strategic choices based on bounded rationality. ESS signifies the process in which a population tends towards a stable strategy after multiple rounds of the game, while replicator dynamics represents a set of dynamic differential equations describing the frequency at which a group adopts strategies – known as the replicator dynamic equation. The formula is as follows:

$$\frac{\mathrm{d}x_m}{dt} = x_m[U(m, s) - U(s, s)](m = 1, 2, \cdots, k) \tag{1}$$

where x_m represents the proportion or probability of adopting the pure strategy m in the population, $U(m,s)$ represents the fitness (expected payoff) of adopting strategy m, and $U(s,s)$ represents the average fitness (average expected payoff). To determine an ESS, it is necessary to compute the average fitness and the payoff for a specific strategy. These values are then used in the formula mentioned earlier to acquire the growth rate of the replicator dynamic equation for the given strategy. Last, the stability of the strategy is assessed by computing the eigenvalues using the Jacobian matrix. The steps for the evolutionary game methodology are outlined in Figure 1.

2.2. Research route

The framework of a market-oriented construction management model of drainage projects through background research and literature review is constructed. The interplay of interests among the government (GOV), DMCs, and PDSs is analyzed, and the necessary assumptions to establish the tripartite evolutionary game model are proposed. Based on evolution dynamics, the research analyzes the evolution trend of players, calculates the eigenvalues of each strategy combination, and analyzes the optimal strategy. The impact of key parameters on ESS is examined through simulation analysis. Finally, the research discusses the feasibility and critical factors of implementing the market-oriented construction management model, offering recommendations for sewage charges and relevant institutional safeguards. The research roadmap is depicted in Figure 2.

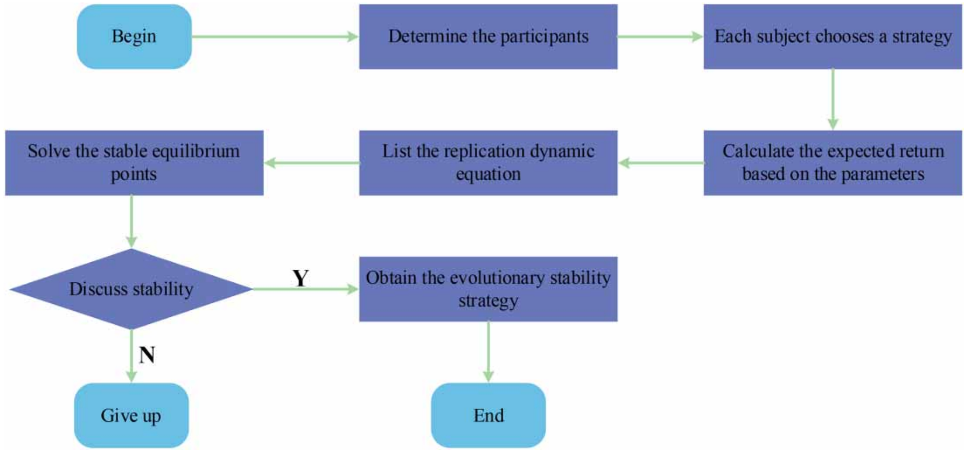


Figure 1 | Evolutionary game theory process.

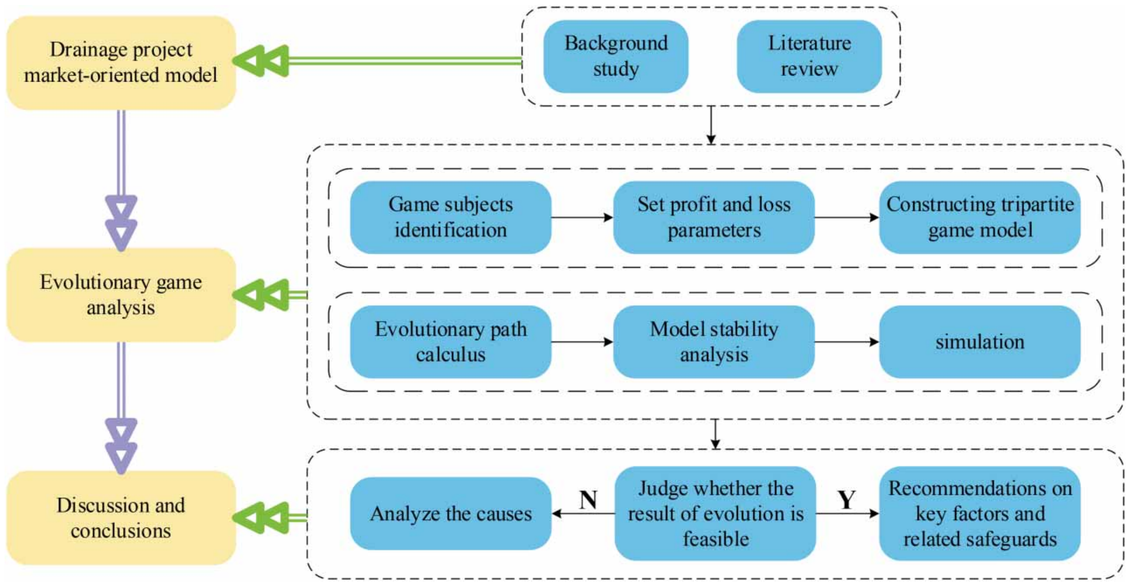


Figure 2 | Technology roadmap.

3. CONSTRUCTION OF THE TRIPARTITE EVOLUTIONARY GAME MODEL

3.1. Market-oriented construction management model

The market-oriented construction management model for drainage project involves open selection, targeting companies with qualifications related to drainage, to assume the responsibilities of constructing and managing urban drainage projects. It aims to achieve integrated governance of drainage pipelines and sewage treatment plants and to establish a platform for pollution discharge rights trading, as shown in Figure 3. GOV advocates selecting DMCs through bidding to establish cooperative relationships. It oversees the construction and management of the company, formulates related supportive policies, provides financial incentives, regulates the adjustment magnitude of sewage charge standards, and providing safeguards for trading pollution discharge rights. DMCs, either independently or as part of a consortium, are responsible for the upgrade, renovation, and operational maintenance of urban drainage projects. They expand into comprehensive drainage-related operational businesses, adjust and collect sewage charges, and establish platforms for trading pollution discharge rights. Urban production enterprises acting as PDSs are granted a certain quantity of sewage discharge quotas by DMC based on the

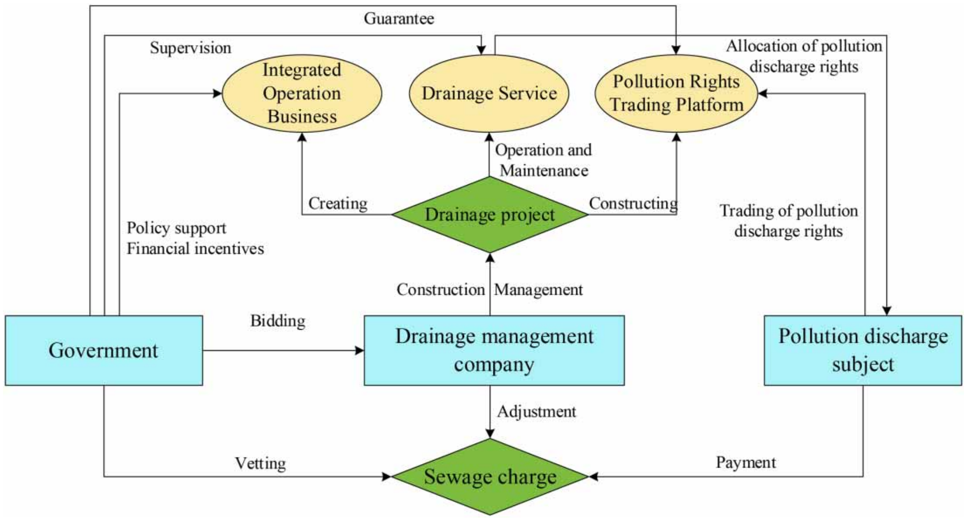


Figure 3 | Market-oriented construction management model of drainage project.

efficiency of the drainage projects. These quotas can be traded among PDSs, and PDSs pay sewage charges according to actual sewage discharge and sewage charge standards.

3.2. Analysis of stakeholders

The stakeholders in the market-oriented construction management model for drainage projects encompass the GOVs, DMCs, and PDSs. The GOVs need to balance fiscal expenditures, the effectiveness of drainage project, and the acceptance of PDSs, and decide whether to provide policies and economic incentives. The primary goal for DMCs is to secure higher profits. The incentives offered by the GOVs and the support willingness of PDSs significantly influence whether PDSs engage in the competition. As users of drainage projects, the support of PDSs for the market-oriented construction management model depends on sewage charge standards and the distribution of pollution discharge rights. Simultaneously, PDSs will evaluate the GOVs and DMCs based on the operational status of drainage projects and sewage charge standards. The interrelationships among stakeholders are shown in Figure 4.

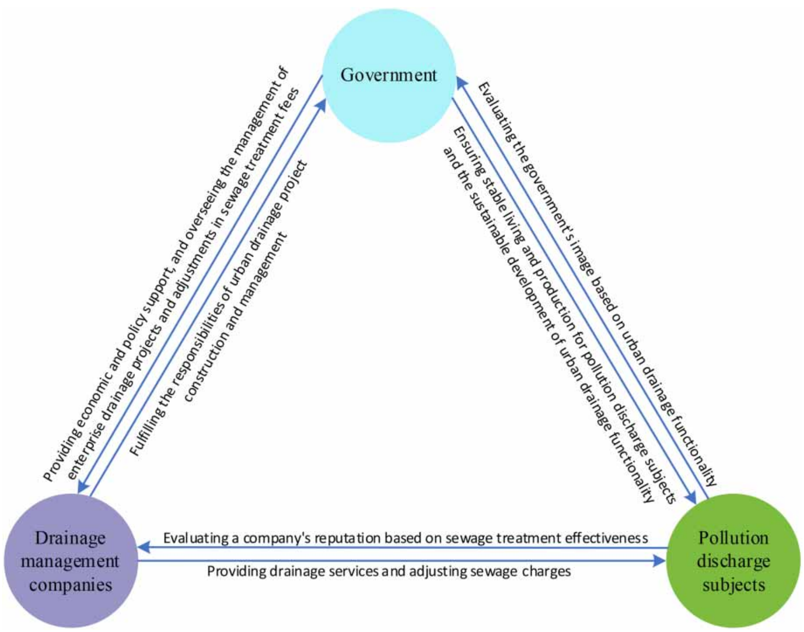


Figure 4 | Relationships between stakeholders.

3.3. Basic assumptions and parameters

Hypothesis 1: Assuming that tripartite players have bounded rationality, the pursuit of optimal strategies occurs through multiple gaming iterations. The GOV's strategy is whether to provide incentive measures, the strategy of DMCs is whether to participate in market-oriented reforms, and the strategy of PDSs is whether to support market-oriented reforms. The tripartite evolutionary game model has been established, as depicted in Figure 5. The probability of the GOVs choosing incentive is denoted as x, the probability of DMCs choosing to participate is denoted as y, and the probability of PDSs choosing to support is denoted as z.

Hypothesis 2: In the event that the GOVs choose Non-incentive, signifying its choice to delegate urban drainage project operation and management responsibilities to DMCs through the government procurement of services model, the regulatory cost borne by GOVs is denoted as S_1. The service fee, constituting sewage charges and financial subsidies, is contingent upon PDSs' level of support. When PDSs choose non-support, GOVs incur a service fee of O_1. Conversely, if PDSs choose support, GOVs must pay a service fee of O_2. Alternatively, if GOVs choose incentive, this indicates their willingness to pursue the market-oriented construction management model. This model involves formulating tailored support policies and performance incentives to stimulate competition among DMCs. The benefits derived from formulating policies are represented by B, while the financial rewards provided amount to W. The GOVs also bear a regulatory cost, indicated as S_2.

Hypothesis 3: In the context where DMCs choose non-participate, signifying their decision to abstain from competing for the qualification to manage urban drainage projects, the failure rate of the drainage system is denoted as α_1, with operational costs designated as C_1. Environmental benefits accrued by GOVs amount to β_1. Conversely, if DMCs choose Participate, it means that the companies compete for qualifications to manage urban drainage projects. DMCs incur costs associated with equipment upgrades and technological advancements, denoted as R. The failure rate of the drainage system is α_2, and the operational costs are C_2. GOVs realize the environmental benefits of β_2. The comprehensive revenue generated by DMCs in the market-oriented model is contingent upon its capabilities and the influence of government policy support. Under the non-market-oriented construction and management model, the comprehensive revenue is denoted as M_1. Conversely, it is represented by M_2. The failure rate of the drainage system influences the satisfaction benefits of PDSs $K(\alpha)$, the image benefits of GOVs $G(\alpha)$, and the maintenance and renovation costs of DMCs $F(\alpha)$.

Hypothesis 4: In the event that PDSs choose non-support, the subjects continue to remit sewage charges at the pre-reform standard, denoted as P_1. Conversely, the subjects pay sewage charges at the post-reform standard, denoted as P_2. At this juncture, PDSs wield influence over GOVs and DMCs, impacting public opinion. Should GOVs adopt an incentive strategy, it stands to gain image benefits denoted as V, while if DMCs adopt a participatory strategy, it stands to gain reputation benefits denoted as N. Otherwise, GOVs and DMCs will lose out on the corresponding benefits. Under the market-oriented model, the efficiency of urban drainage projects is enhanced, resulting in PDSs gaining additional pollution discharge rights. The

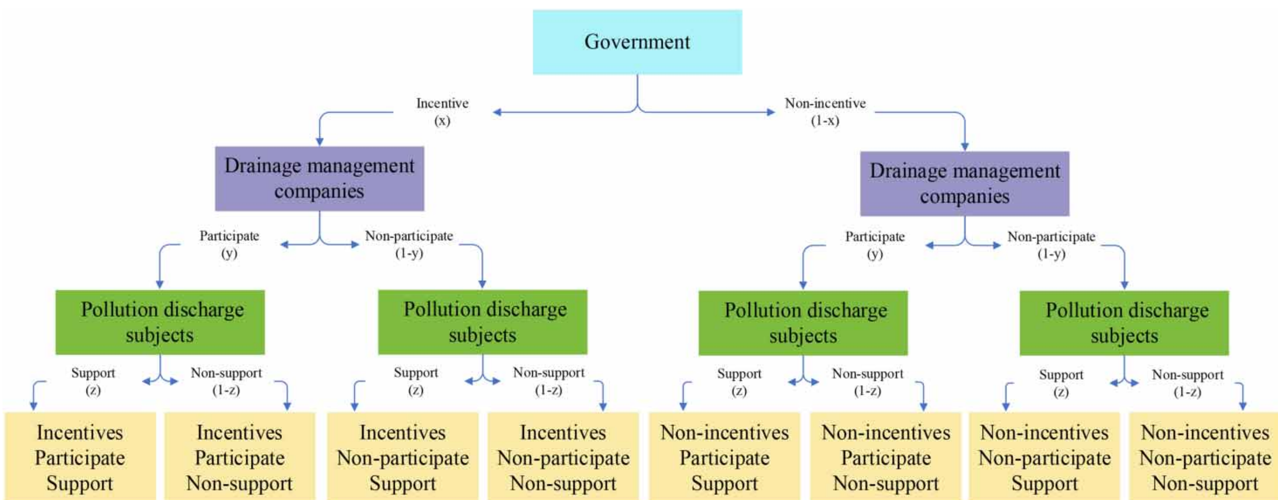


Figure 5 | The tripartite evolutionary game model.

increment in pollution discharge rights differs when PDSs choose non-support or support, leading to additional production benefits denoted as L_1 and L_2, respectively.

Table 1 presents the specific meanings of the parameters.

3.4. Payoff function of players

Based on the proposed strategies, eight interactive strategy combinations exist among GOVs, DMCs, and PDSs in the market-oriented model implemention. Table 2 presents the payoff matrix.

Table 1 | Description of the parameters

Parameter	Meaning
α_1	In the government procurement of services model, the failure rate of the drainage system in operation
α_2	In the market-oriented construction management model, the failure rate of the drainage system in operation
β_1	In the government procurement of services model, the environmental benefits obtained by GOVs
β_2	In the market-oriented construction management model, the environmental benefits obtained by GOVs
$F(\alpha)$	The maintenance and renovation costs for the DMCs
$G(\alpha)$	The image benefits for the GOVs
$K(\alpha)$	The satisfaction benefits for the PDSs
P_1	In the government procurement of services model, the sewage charges paid by PDSs
P_2	In the market-oriented construction management model, the sewage charges paid by PDSs
C_1	In the government procurement of services model, the operational costs of the drainage project
C_2	In the market-oriented construction management model, the operational costs of the drainage project
S_1	In the government procurement of services model, GOVs incur regulatory costs
S_2	In the market-oriented construction management model, GOVs incur regulatory costs
M_1	In the non-market-oriented construction management model, the comprehensive revenue benefits obtained by DMCs
M_2	In the market-oriented construction management model, the comprehensive revenue benefits obtained by DMCs
B	Benefits of policy support provided by the GOVs
W	Financial incentives provided by the GOVs
V	GOVs' image benefits from incentivizing the reform of the market-oriented construction and management model
N	DMCs' reputation benefits from participating in the reform of the market-oriented construction management model
L_1	The additional production benefits resulting from the increase in pollution discharge rights when PDSs choose Non-support
L_2	The additional production benefits resulting from the increase in pollution discharge rights when PDSs choose Support
O_1	The service fee paid by the government when PDSs choose Non-support
O_2	The service fee paid by the government when PDSs choose Support
R	Costs incurred for equipment upgrades and technological advancements

Table 2 | Payoff matrix of players

Strategy ranking	Government	DMC	PDS
(Incentive, Participate, Support)	$G(\alpha_2)+\beta_2+V-S_2-B-W$	$-F(\alpha_2)+P_2+B+W+M_2-C_2-R+N$	$K(\alpha_2)-P_2+L_2$
(Incentive, Participate, Non-support)	$G(\alpha_2)+\beta_2-S_2-B-W$	$-F(\alpha_2)+P_1+B+W+M_2-C_2-R$	$K(\alpha_2)-P_1+L_1$
(Incentive, Non-participate, Support)	$G(\alpha_1)+\beta_1+V-S_1-B-W$	$-F(\alpha_1)+P_2+B+W+M_1-C_1-N$	$K(\alpha_1)-P_2$
(Incentive, Non-participate, Non-support)	$G(\alpha_1)+\beta_1-S_1-B-W$	$-F(\alpha_1)+P_1+B+W+M_1-C_1$	$K(\alpha_1)-P_1$
(Non-incentive, Participate, Support)	$G(\alpha_2)+\beta_2-V-S_2-O_2$	$-F(\alpha_2)+P_2+O_2+M_1-C_2-R+N$	$K(\alpha_2)-P_2+L_2$
(Non-incentive, Participate, Non-support)	$G(\alpha_2)+\beta_2-S_2-O_1$	$-F(\alpha_2)+P_1+O_1+M_1-C_2-R$	$K(\alpha_2)-P_1+L_1$
(Non-incentive, Non-participate, Support)	$G(\alpha_1)+\beta_1-V-S_1-O_2$	$-F(\alpha_1)+P_2+O_2+M_1-C_1-N$	$K(\alpha_1)-P_2$
(Non-incentive, Non-participate, Non-support)	$G(\alpha_1)+\beta_1-S_1-O_1$	$-F(\alpha_1)+P_1+O_1+M_1-C_1$	$K(\alpha_1)-P_1$

4. OPTIMAL STRATEGY FOR TRIPARTITE BENEFIT EQUILIBRIUM

4.1. Theoretical calculations

The expected payoffs of GOV choosing incentive and non-incentive are calculated and denoted as $E(x_1)$ and $E(x_2)$, respectively, as follows:

$$\begin{cases} \mathrm{E(x_1)} = yz[G(\alpha_2) + \beta_2 + Q + V - S_2 - B - W] \\ \quad + y(1-z)[G(\alpha_2) + \beta_2 + Q - S_2 - B - W] \\ \quad + (1-y)z[G(\alpha_1) + \beta_1 + V - S_1 - B - W] \\ \quad + (1-y)(1-z)[G(\alpha_1) + \beta_1 - S_1 - B - W] \\ E(\mathrm{x_2}) = yz[G(\alpha_2) + \beta_2 + Q - V - S_2 - O_2] \\ \quad + y(1-z)[G(\alpha_2) + \beta_2 + Q - S_2 - O_1] \\ \quad + (1-y)z[G(\alpha_1) + \beta_1 - V - S_1 - O_2] \\ \quad + (1-y)(1-z)[G(\alpha_1) + \beta_1 - S_1 - O_1] \end{cases} \tag{2}$$

The expected payoffs of DMC choosing participate and non-participate are calculated and denoted as $E(y_1)$ and $E(y_2)$, respectively, as follows:

$$\begin{cases} E(y_1) = xz[-F(\alpha_2) + P_2 + B + W + M_2 - C_2 - R + N] \\ \quad +x(1-z)[-F(\alpha_2) + P_1 + B + W + M_2 - C_2 - R] \\ \quad +(1-x)z[-F(\alpha_2) + P_2 + O_2 + M_1 - C_2 - R + N] \\ \quad +(1-x)(1-z)[-F(\alpha_2) + P_1 + O_1 + M_1 - C_2 - R] \\ E(y_2) = xz[-F(\alpha_1) + P_2 + B + W + M_1 - C_1 - N] \\ \quad +x(1-z)[-F(\alpha_1) + P_1 + B + W + M_1 - C_1] \\ \quad +(1-x)z[-F(\alpha_1) + P_2 + O_2 + M_1 - C_1 - N] \\ \quad +(1-x)(1-z)[-F(\alpha_1) + P_1 + O_1 + M_1 - C_1] \end{cases} \tag{3}$$

Finally, the expected payoffs of PDS choosing support and non-support are calculated and denoted as $E(z_1)$ and $E(z_2)$, respectively, as follows:

$$\begin{cases} E(z_1) = xy[K(\alpha_2) - P_2 + L_2] + x(1-y)[K(\alpha_1) - P_2] \\ \quad + (1-x)y[K(\alpha_2) - P_2 + L_2] + (1-x)(1-y)[K(\alpha_1) - P_2] \\ E(z_1) = xy[K(\alpha_2) - P_1 + L_1] + x(1-y)[K(\alpha_1) - P_1] \\ \quad + (1-x)y[K(\alpha_2) - P_1 + L_1] + (1-x)(1-y)[K(\alpha_1) - P_1] \end{cases} \tag{4}$$

The replicator dynamic equations for each player can be obtained from Equations (2)–(4).

$$\begin{aligned} F(x) &= x(1-x)[E(x_1) - E(x_2)] \\ &= x(1-x)[z(2V - O_1 + O_2) - W - B + O_1] \end{aligned} \tag{5}$$

$$\begin{aligned} F(y) &= y(1-y)[E(y_1) - E(y_2)] \\ &= y(1-y)[C_1 - C_2 + F(\alpha_1) - F(\alpha_2) - R + x(M_2 - M_2) + 2zN] \end{aligned} \tag{6}$$

$$\begin{aligned} F(z) &= z(1-z)[E(z_1) - E(z_2)] \\ &= z(1-z)[P_1 - P_2 - y(L_1 - L_2)] \end{aligned} \tag{7}$$

Equations (5)–(7) constitute a dynamic system for the evolution of the tripartite strategy in the market-oriented construction management model reforming. To facilitate the subsequent analysis of evolutionary dynamics, the first-order derivatives of

$F(x)$, $F(y)$, and $F(z)$ are calculated as follows:

$$F'(x) = (1 - 2x)[z(2V - O_1 + O_2) - W - B + O_1] \tag{8}$$

$$F'(y) = (1 - 2y)[C_1 - C_2 + F(\alpha_1) - F(\alpha_2) - R + x(M_2 - M_1) + 2zN] \tag{9}$$

$$F'(z) = (1 - 2z)[P_1 - P_2 - y(L_1 - L_2)] \tag{10}$$

4.2. Tripartite evolutionary dynamics

In the evolutionary dynamic system, every point represents a tripartite strategy. A point is an ESS if it remains constant and is robust to arbitrarily small disturbances. Consequently, when a point $X = (x, y, z)$ is an ESS, then x must simultaneously satisfy $F(x) = 0$ and $F'(x) < 0$ to reach asymptotic stability conditions (Jiang *et al.* 2019), and y and z also need to meet similar requirements.

For GOVs, when $z = z^* = \dfrac{W + B - O_1}{2V - O_1 + O_2}$ (Figure 6(a)), then $F(x) \equiv 0$, and $F'(x) \equiv 0$. Thus, x will not change over time, and no ESS will exist in the system. When $z > z^*$ (Figure 6(b)), then $F(x)|_{x=0} = F(x)|_{x=1} = 0$, $F'(x)|_{x=0} > 0$, and $F'(x)|_{x=1} < 0$. Thus, $x = 1$ is asymptotically stable; that is, GOVs will eventually select incentive over time. When $z < z^*$ (Figure 6(c)), then $F(x)|_{x=0} = F(x)|_{x=1} = 0$, $F'(x)|_{x=0} < 0$, and $F'(x)|_{x=1} > 0$. Thus, $x = 0$ is asymptotically stable, which denotes that GOVs will eventually select non-incentive.

For DMCs, when $x = x^* = \dfrac{2zN + C_1 - C_2 + F(\alpha_1) - F(\alpha_2) - R}{M_1 - M_2}$ (Figure 6(d)), then $F(y) \equiv 0$, and $F'(y) \equiv 0$. Thus, y will not change over time, and no ESS will exist in the system. When $x > x^*$ (Figure 6(e)), then $F(y)|_{y=0} = F(y)|_{y=1} = 0$, $F'(y)|_{y=0} > 0$, and $F'(y)|_{y=1} < 0$. Thus, $y = 1$ is asymptotically stable, which denotes that DMCs will eventually select participate. When $x < x^*$ (Figure 6(f)), then $F(y)|_{y=0} = F(y)|_{y=1} = 0$, $F'(y)|_{y=0} < 0$, and $F'(y)|_{y=1} > 0$. Thus $y = 0$ is asymptotically stable; that is, DMCs will eventually select non-participate over time.

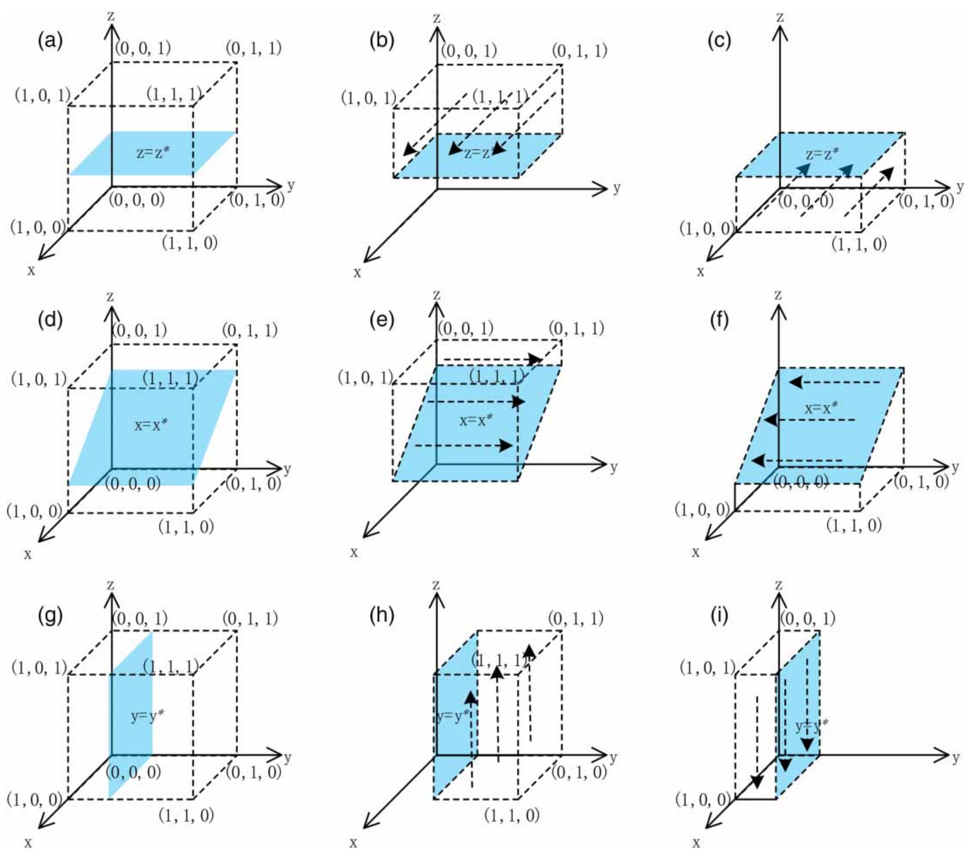


Figure 6 | Phase diagram of evolutionary dynamics.

For PDSs, when $y = y^* = \dfrac{P_1 - P_2}{L_1 - L_2}$ (Figure 6(g)), then $F(z) \equiv 0$, and $F'(z) \equiv 0$. Thus, z will not change over time, and no ESS will exist in the system. When $y > y^*$ (Figure 6(h)), then $F(z)|_{z=0} = F(z)|_{z=1} = 0$, $F'(z)|_{z=0}>0$, and $F'(z)|_{z=1}<0$. Thus $z = 1$ is asymptotically stable; that is, PDSs will eventually select support. When $y<y^*$ (Figure 6(i)), Thus, $z = 0$ is asymptotically stable, which denotes that PDSs will eventually select non-participate over time.

The phase diagram of the evolutionary dynamics of the tripartite strategies is shown in Figure 6.

4.3. Stability analysis of equilibrium points

To ensure the evolutionary stability of each player in the game, the replicator dynamics equations must simultaneously satisfy the following conditions:

$$\begin{cases} \mathrm{F}(x) = dx/dt = 0 \\ \mathrm{F}(y) = dy/dt = 0 \\ \mathrm{F}(z) = dz/dt = 0 \end{cases} \tag{11}$$

Solving Equations (11) yields 13 local solutions, including 8 pure strategy equilibrium points, namely $E_1[1,1,1]$, $E_2[1,1,0]$, $E_3[1,0,1]$, $E_4[1,0,0]$, $E_5[0,1,1]$, $E_6[0,1,0]$, $E_7[0,0,1]$, and $E_8[0,0,0]$. ESSs in a multi-subject game must constitute a strict Nash equilibrium and a pure strategy combination. Therefore, analyzing conditions for the emergence of ESSs requires examining only eight pure strategy equilibrium points. The Jacobian matrix is obtained as follows:

$$J = \begin{bmatrix} \dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y} & \dfrac{\partial F(x)}{\partial z} \\ \dfrac{\partial F(y)}{\partial x} & \dfrac{\partial F(y)}{\partial y} & \dfrac{\partial F(y)}{\partial z} \\ \dfrac{\partial F(z)}{\partial x} & \dfrac{\partial F(z)}{\partial y} & \dfrac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{12}$$

where $a_{11} = (2x - 1)[B - O_1 + z(O_1 - O_2 - 2V) + W]$, $a_{12} = 0$, $a_{13} = x(1 - x)(O_2 - O_1 + 2V)$, $a_{21} = y(y - 1)(M_1 - M_2)$, $a_{22} = (1 - 2y)[C_1 - C_2 + F(\alpha_1) - F(\alpha_2) - R + x(M_2 - M_1) + 2zN]$, $a_{23} = 2y(1 - y)N$, $a_{31} = 0$, $a_{32} = z(z - 1)(L_1 - L_2)$, $a_{33} = (1 - 2z)[P_1 - P_2 + y(L_2 - L_1)]$.

According to the Lyapunov indirect method for analyzing the asymptotic stability of equilibrium points, an equilibrium point is asymptotically stable if all eigenvalues of the Jacobian matrix have negative real parts. If at least one eigenvalue of the Jacobian matrix has a positive real part, the equilibrium point is unstable. When all eigenvalues of the Jacobian matrix, except those with real parts equal to zero, have negative real parts, the equilibrium point is in a critical state, and stability cannot be determined solely by the signs of the eigenvalues (Liu & Chen 2023). The eigenvalues for each equilibrium point are presented in Table 3.

In the current charge structure for sewage in China, the charges are far below the unit cost of sewage treatment and operational costs (Liu *et al.* 2021a). Therefore, under the market-oriented construction management model, sewage charges should be increased, so $P_2 > P_1$. At this point, the eigenvalue $\lambda_1 > 0$ of the equilibrium points E_3 and E_7. The cost borne by the GOV under the market-oriented construction management model is less than that under the government procurement of services model. Consequently, $O_1 > O_2 > B + W - 2V > B + W$, resulting in $\lambda_2 > 0$ of E_5, E_6, E_7, and E_8. Market competition can lead to lower operating costs and failure rates. Under government support policies, necessary upgrades in technical equipment will help DMC explore new markets, gaining more comprehensive revenue benefits. It can be inferred that $M_2 + 2N - C_2 - F(\alpha_2) - R > M_2 - C_2 - F(\alpha_2) - R > M_1 - C_1 - F(\alpha_1)$, resulting in $\lambda_3 > 0$ of E_3, and E_4. The cost of upgrading technical equipment is greater than the reduced operating costs under the market-oriented construction management model. Thus, $C_2 + F(\alpha_2) + R > C_2 + F(\alpha_2) + R - 2N > C_1 + F(\alpha_1)$, the eigenvalue $\lambda_3 > 0$ of the equilibrium points E_5 and E_6.

In summary, equilibrium points E_3, E_4, E_5, E_6, E_7, and E_8 are all unstable. When the algebraic expressions for eigenvalues satisfy certain inequality conditions, equilibrium points E_1 and E_2 may evolve into evolutionarily stable strategies.

4.4. Optimal strategy analysis

E_1 and E_2 are mutually exclusive, Condition ① and Condition ②, respectively, correspond to the requirements for E_1 and E_2 to become ESS. The distinction between the two strategy combinations lies in the behavior of PDS. From a practical perspective,

Table 3 | The eigenvalues for each equilibrium point

Equilibrium point	Eigenvalue				Asymptotic stability	Condition
	λ_1	λ_2	λ_3	Sign		
$E_1[1,1,1]$	$-P_1+P_2+L_1-L_2$	$-O_2+B-2V+W$	$-C_1+C_2-F(\alpha_1)+F(\alpha_2)+M_1-M_2-2N+R$	(×,–,–)	Uncertain	①
$E_2[1,1,0]$	$P_1-P_2-L_1+L_2$	$-O_1+B+W$	$-C_1+C_2-F(\alpha_1)+F(\alpha_2)+M_1-M_2+R$	(×,–,–)	Uncertain	②
$E_3[1,0,1]$	$-P_1+P_2$	$-O_2+B-2V+W$	$C_1-C_2+F(\alpha_1)-F(\alpha_2)-M_1+M_2+2N-R$	(+,–,+)	Unstable	\
$E_4[1,0,0]$	P_1-P_2	$-O_1+B+W$	$C_1-C_2+F(\alpha_1)-F(\alpha_2)-M_1+M_2-R$	(–,–,+)	Unstable	\
$E_5[0,1,1]$	$-P_1+P_2+L_1-L_2$	$O_2-B+2V-W$	$-C_1+C_2-F(\alpha_1)+F(\alpha_2)-2N+R$	(×,+,+)	Unstable	\
$E_6[0,1,0]$	$P_1-P_2-L_1+L_2$	O_1-B-W	$-C_1+C_2-F(\alpha_1)+F(\alpha_2)+R$	(×,+,+)	Unstable	\
$E_7[0,0,1]$	$-P_1+P_2$	$O_2-B+2V-W$	$C_1-C_2+F(\alpha_1)-F(\alpha_2)+2N-R$	(+,+,–)	Unstable	\
$E_8[0,0,0]$	P_1-P_2	O_1-B-W	$C_1-C_2+F(\alpha_1)-F(\alpha_2)-R$	(–,+,–)	Unstable	\

Note: × indicates uncertain sign.
①: $-P_1+P_2+L_1-L_2<0$; ②: $P_1-P_2-L_1+L_2<0$.

the lower sewage charge standard cannot cover the normal operational costs of drainage projects, resulting in the unsustainable development of drainage projects. Therefore, this strategy is merely a theoretically potential ESS, rather than the optimal solution to the challenges faced by drainage projects.

From Table 2, it can be observed that under the stable strategy $E_1[1,1,1]$ (incentive, participation, support), when the adjusted sewage charges $P_2 \in [P_1, P_1+L_2-L_1]$, PDS can obtain additional production benefits, enhancing its willingness to support the market-oriented construction management mode. DMC will receive compensation for operational costs and improve its reputation, leading to an increased willingness to participate. The GOV benefits by reducing financial burdens and achieving higher environmental efficiency, strengthening its incentive to promote the strategy. This approach contributes to improving the operational efficiency of drainage projects, establishing a pollution discharge rights trading market, and realizing the sustainable development of drainage projects. It represents the optimal and stable strategy under the reform of the market-oriented construction management mode for drainage projects.

5. SIMULATION ANALYSIS

To enhance the visual representation of the evolutionary game process, the research employs a simulation method to investigate the impact and sensitivity of relevant parameters. After analysis, it has been established that the initial probability of strategy selection for each player is set uniformly at 0.2. The initial simulation parameters are determined as follows: $F(\alpha_1)=100$, $F(\alpha_2)=80$, $G(\alpha_1)=60$, $G(\alpha_2)=110$, $K(\alpha_1)=40$, $K(\alpha_2)=60$, $P_1=10$, $P_2=16$, $C_1=40$, $C_2=30$, $S_1=30$, $S_2=24$, $M_1=80$, $M_2=160$, $O_1=40$, $O_2=30$, $B=20$, $W=10$, $R=40$, $N=50$, $V=60$, $L_1=30$, $L_2=55$.

5.1. Impact analysis of strategic probability

Let x vary at values of 0.2, 0.4, 0.6, and 0.8 to explore the impact of changing x on the evolutionary path of the game model. Similarly, set $y=z=0.2$, 0.4, 0.6, 0.8, and the simulation results are shown in Figure 7. From Figure 7, it is observed that: ① regardless of how the initial probabilities for the three players' choices (incentive, participation, support) change, all players will evolve in the same direction, ultimately converging to the optimal evolutionary stable strategy $E_1[1,1,1]$. ② The more extensive the initial probability choices for each player, the shorter the time needed for the game model to stabilize, indicating a faster evolution speed. ③ The increase in initial probability choices for different players has varying effects on the improvement of evolution speed, with the highest impact on PDSs, followed by GOVs, and the lowest on DMCs.

5.2. Impact analysis of the policy support

The parameter B represents the benefits of GOVs' supportive policies, with B taking values of 15, 20, 25, and 30. The evolutionary paths are illustrated in Figure 8(a). The larger the scale of supportive policies provided by GOVs, the slower GOVs' evolution towards stability, while DMCs exhibit the opposite trend. This indicates that a larger scale of supportive policies from GOVs increases the enthusiasm of DMCs to participate. However, this also means more tremendous pressure on the GOVs. Moreover, the early stages of the evolutionary process in the game model are relatively slow, while the speed accelerates in the middle and later stages. The reason for this phenomenon may be that in the early stages of the market-oriented

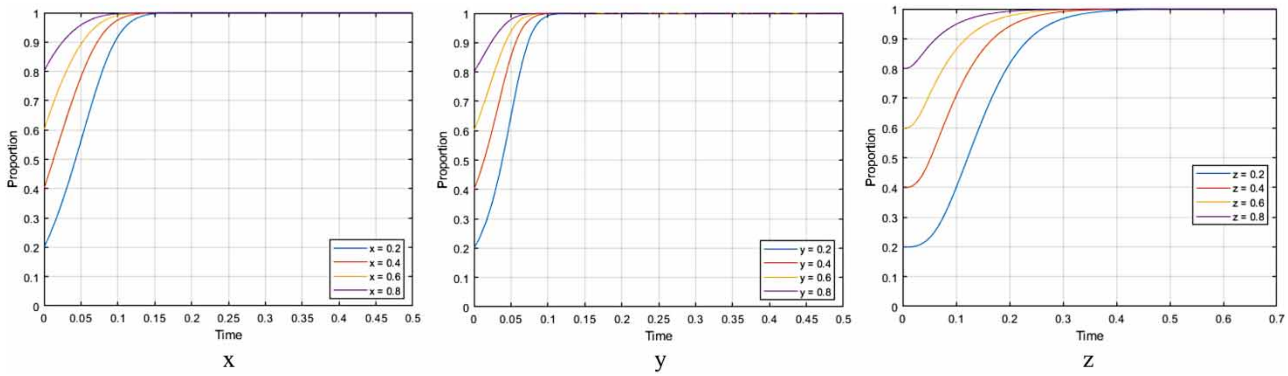


Figure 7 | *x*, *y*, *z* evolution curves with different values.

construction management model, DMCs are in a growth phase of creating comprehensive business operations, generating limited economic income, and still requiring economic subsidies from the government. Therefore, the early process is relatively slow. As comprehensive business operations mature, with the help of supportive policies, they gradually generate sufficient revenue, achieve profitability, and reduce dependence on the GOVs' economic support. Consequently, the convergence speed towards stability increases in the middle and later stages.

5.3. Impact analysis of the costs of technology and equipment upgrades

The parameter *R* represents the cost incurred by DMCs for technical equipment upgrades during its participation in the reform, with *R* taking values of 30, 40, 50, and 60. The evolutionary trajectories are depicted in Figure 8(b). As the cost for technical equipment upgrades increases, the convergence speed of the game model towards stability decreases. This

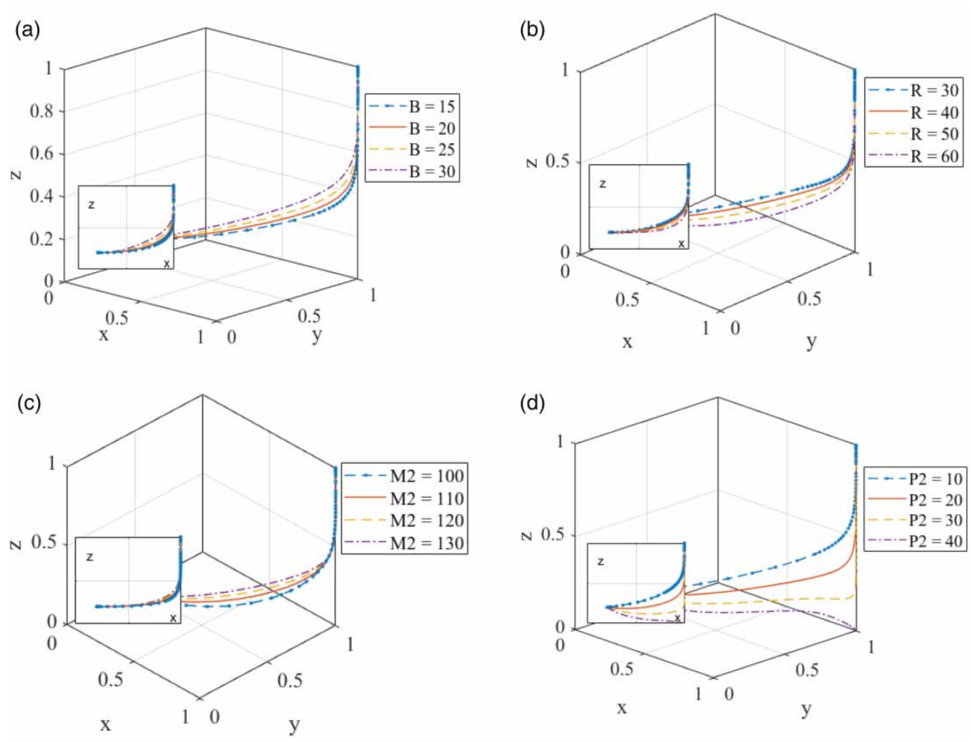


Figure 8 | Model evolution trajectory for different values of parameters.

indicates that if DMCs invest excessively in the early stages, they face higher risks. The early stages of the evolutionary process in the game model are relatively slow, while the speed accelerates in the middle and later stages. The reason for this phenomenon is that the cost of upgrading technical equipment exists in the early stages of project implementation. After the upgrades are completed, DMCs can enjoy lower operating costs and maintenance expenses, generating more comprehensive revenue. Since DMCs bear the costs of implementing technical equipment upgrades. A well-planned and efficient upgrade can reduce or eliminate the need for secondary investments.

5.4. Impact analysis of the comprehensive revenue benefits

The parameter M_2 represents the comprehensive revenue benefits for DMCs under the market-oriented construction management model, with M_2 taking values of 100, 110, 120, and 130. The evolutionary trajectories are illustrated in Figure 8(c). As the comprehensive revenue benefits increase, the speed at which GOVs and DMCs converge towards stability accelerates. Under the same policy support, the higher the comprehensive revenue benefits that DMCs can obtain, the faster their probability of choosing to participate increases. Moreover, the reliance on government financial rewards decreases, alleviating the financial pressure on GOVs, the probability of GOVs choosing incentives also increases. The comprehensive revenue benefits are directly related to the capabilities of DMCs. Therefore, selecting more capable DMCs is helpful in accelerating the convergence towards stable strategies.

5.5. Impact analysis of the sewage treatment fee

The parameter P_2 represents the adjusted sewage charges that PDSs need to pay, with P_2 taking values of 10, 20, 30, and 40. The evolutionary trajectories are illustrated in Figure 8(d). As the adjusted sewage charge increases, the speed at which the game model converges towards stability significantly decreases. This means that PDSs are sensitive to changes in sewage charges, and the acceptance of the adjusted sewage charges depends on the production benefits brought about by the increase in sewage discharge. Excessively high sewage charges may lead to dissatisfaction among PDSs, potentially fostering unfavorable public opinion towards GOVs. Therefore, GOVs' probability of choosing incentive strategies increases slowly. However, if GOVs choose Non-incentive, the long-term funding gap in drainage projects will remain unresolved, ultimately impacting the regular operation of urban drainage projects, and causing significant risks to the urban infrastructure and the natural environment. Consequently, GOVs are still inclined to choose Incentive, promoting comprehensive business support for DMCs to generate additional revenue. This approach satisfies the profit requirements of DMCs, thereby reducing sewage charge standards.

6. DISCUSSION

6.1. Feasibility analysis of a market-oriented construction management model

In the context of the government procurement of services model, where the government bears a heavy financial burden and the management level is lagging, the market-oriented construction management model is considered a crucial approach to address numerous current issues (Jia *et al.* 2022; Lu *et al.* 2022). From the perspective of evolutionary game theory, the players will eventually tend to (incentive, participate, support) evolve stable strategy combinations based on the principle of maximizing benefits, theoretically demonstrating feasibility. From a practical standpoint, the *Opinions* explicitly require that the proportion of equity held by private enterprises in drainage projects should not be less than 35%. Additional income obtained through strengthened management, cost reduction, efficiency improvement, and proactive innovation primarily belongs to the franchise operator (National Development and Reform Commission and Ministry of Finance 2023). This support encourages private DMCs to enter the drainage project industry through market competition and ensures that they gain revenue by creating comprehensive operational business. In an environment of sufficient competition, selecting a DMC with more excellent capabilities for urban drainage projects can lead to reduced operational and management costs, increased self-revenue capabilities, and a decreased reliance on government finances (Hilbig & Rudolph 2019; Tan & Zhao 2019; Sinha *et al.* 2021; Almeile *et al.* 2022). With rising national income and the production benefits of PDSs being constrained by the efficiency of drainage projects (Sun *et al.* n.d.), the acceptance of an increase in sewage charges becomes feasible (Long *et al.* 2021b). Moreover, the sewage and sludge generated in drainage projects contain substantial resources and energy. However, their value-added transformation and efficient utilization have historically been relatively low, partly due to insufficient policy support from GOVs for recycling and reusing resources (Ross 2017; Herr *et al.* 2020). If GOVs increase support for relevant policies, they will facilitate DMCs in creating comprehensive revenue through the utilization of recyclable resources, thereby generating economic value. In summary, the real-world conditions support the feasibility of advancing the market-oriented construction management model.

6.2. Sewage charge pricing strategy

From the simulation results, it is observed that PDSs are sensitive to price adjustments. Therefore, sewage charge is a key factor affecting the stability of the strategy. Through the discovery of evolutionary stable strategies, it is observed that when the sewage charges $P_2 \in [P_1, P_1 + L_2 - L_1]$, signifying that the increase in sewage charges is less than the augmentation in production benefits ($P_2 - P_1 < L_2 - L_1$), the PDSs tend to support. Existing studies advocate a phased adjustment strategy, gradually aligning sewage charges with the 'covering costs and reasonable profit' threshold as PDSs' capacity incrementally expands (Saz-Salazar *et al.* 2009; Liu *et al.* 2019b; Li & Zhang 2021), offering a plausible solution for the conditions mentioned above. It is suggested that DMCs collaborate with government bodies such as the tax bureau and the National Development and Reform Commission. This collaboration, coupled with evaluating pollution discharge rights trading market trends, should involve a periodic assessment of PDSs' production scale and pollution discharge rights demand. Adjustments to the sewage charges can then be made when the PDSs experience an expansion in production scale or an increase in pollution discharge rights demand, ensuring the implementation of sewage charge pricing policies at each stage within the PDSs' financial capacity.

6.3. Pollution discharge rights trading provides support

The pollution discharge rights trading market allows polluting entities to freely trade pollution discharge rights within certain legal limits. Explored since the late 1980s and essentially established by the end of 2017 in China (Niu & Jin 2023), the compensatory use and trading market for pollution discharge rights has been implemented in 28 provinces (regions, municipalities) as pilot projects (Sun *et al.* n.d.). Additionally, the *Opinions* require the establishment of a normalized information disclosure mechanism (National Development and Reform Commission and Ministry of Finance 2023). The pollution discharge rights trading market, accompanied by the registration and supervision system for pollution discharge rights, enhances the reliability of emission data. It also aids DMCs in understanding the demand in the pollution discharge rights trading market, enabling more accurate adjustments to sewage charges. On the other hand, the pollution discharge rights trading market is one of the ways to allocate resources using market-oriented means, reducing the rigidity of pollution control, alleviating to some extent the short-term inadequacies in the efficiency of drainage projects (Betz *et al.* 2010; Gong & Zhou 2013; Yang *et al.* 2023). This encourages an increase in the parameter L_2, thereby expanding the upper limit of the parameter P_2, essentially enhancing the capacity of PDSs to accept sewage charges. Consequently, this assists PDSs in better adapting to a market-oriented model and encourages a positive inclination towards the market-oriented model among all players.

6.4. Recommendations for institutional safeguards

This study proposes a comprehensive market-oriented construction management model for drainage projects and demonstrates its feasibility. Given the involvement of tripartite players, it is essential to establish relevant institutional frameworks to ensure the smooth operation of the market-oriented construction management model (Bel *et al.* 2010; García-Rubio *et al.* 2016; Bel 2020). This involves legally defining the rights and obligations of the involved parties to safeguard the interests of DMCs and PDSs. Additionally, clear punitive measures for any violations should be specified. The establishment of regulatory mechanisms is crucial to guarantee the operational efficiency of drainage projects and compliance with sewage charge standards. Preserving channels for market competition is recommended to encourage competitive DMCs, ultimately contributing to efficiency improvement and cost reduction.

7. CONCLUSIONS

To enhance the efficiency and profitability of drainage projects while reducing the financial burden on the government, the research establishes a tripartite evolutionary game model involving the GOV, DMC, and PDS within the market-oriented construction management model. The model reveals the evolutionary trends of the tripartite stakeholders, and considering practical circumstances, identifies the optimal strategy combination, namely (incentive, participation, support). Simulation is employed to analyze the sensitivity of key factors. The major conclusions are as follows:

(1) Implementing market-oriented construction management mode reform for drainage projects is feasible. In theory, the evolutionary game model tends to (incentive, participation, support). The existing environmental conditions support the advancement of the market-oriented construction management model. Furthermore, the pollution discharge trading market aids PDSs in adapting to the market-oriented model.
(2) The pricing of sewage charges is a critical factor in the collaboration among the three parties. Based on pollution discharge rights trading data, GOVs should collaborate with DMCs to regularly assess the production scale and pollution discharge demand of PDSs. Ensuring that sewage charges within the range of $[P_1, P_1 + L_2 - L_1]$.
(3) The impact analysis through simulation reveals that increasing the strategy selection probabilities of PDSs is the most noticeable way to enhance the evolutionary speed. Intensifying policy support, reducing technical equipment upgrade costs, enhancing comprehensive revenue benefits, and lowering sewage charge pricing all contribute to promoting the model towards ESS. The pricing of pollution discharge fees involves a critical threshold at $P_1 + L_2 - L_1$, which determines the direction of the evolutionary game model.

This study is primarily based on the common situations in drainage projects across various regions. However, due to differences in regional conditions, the relationships among the players are more complex in reality. The applicability of this model may be constrained by related assumptions and simplifications. Nevertheless, the conclusions drawn from addressing common issues provide broader applicability and utility. Future research could broaden the scope of investigations to analyze the applicability of market-oriented models. And exploring how to incentivize DMCs to participate in market competition with lower policy costs will also be a key focus.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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