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Sustainable Water Supply Chain Management Through Corporate-Oriented Water Rights Trading: An Application of an Evolutionary Game Model Under Imbalanced Water Quotas

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Abstract

Freshwater scarcity is emerging as a critical constraint on industrial clusters, production networks, and urban service systems, where water functions simultaneously as an essential production input and a shared regional resource. This study investigates how post-allocation water-quota imbalances in large inter-basin diversion systems can be addressed through adaptive secondary water rights trading. Focusing on China's South-to-North Water Diversion Project (SNWDP), the research aims to explain under what institutional and efficiency conditions water rights trading can enhance corporate social responsibility, environmental management, and sustainable supply chain resilience. The study's main innovation lies in the development of a corporate-oriented evolutionary game model that links water governance with corporate production, urban–industrial demand, and responsible supply chain management. Unlike conventional models, it incorporates bounded rationality, heterogeneous water-use efficiency, information asymmetry, transaction costs, primary allocation water pricing, and the risk of unrecovered basic water fees. Using a case inspired by the Zhengzhou–Nanyang transaction along the Middle Route of the SNWDP, the model simulates the strategic interaction between a water-rich node with surplus quota and a water-scarce node facing deficit demand. The findings show that a socially desirable Trade–Trade equilibrium emerges only when efficiency expectations and institutional conditions are favorable. Lower transaction costs and basic water prices, higher sunk-fee risk, and clearer efficiency differentials significantly increase trading willingness. The study demonstrates the practical value of transparent secondary water markets in improving allocative flexibility, reducing governance rigidity, and promoting more responsible and environmentally efficient regional water management.

Keywords: corporate social responsibility; environmental management; water rights trading; sustainable supply chain management; water stewardship; evolutionary game theory

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1. Introduction

Water has emerged as a critical resource in advancing corporate sustainability. However, the use of freshwater to meet industrial demand cannot be regarded as an inherently

viable or sustainable long-term solution. Although freshwater remains indispensable for many industrial activities, including processing, cooling, cleaning, steam generation, sanitation, waste treatment, product quality control, operational reliability, and environmental compliance [1], its continued use must be evaluated within broader ecological and social limits. Freshwater resources cannot be expanded rapidly enough to match the combined pressures of industrialization, urbanization, and rising consumption. At the same time, climate change, ecological degradation, and population growth have transformed water scarcity from a localized concern into a systemic challenge affecting supply chains, regional development, and wider socio-economic stability [2–4]. Consequently, corporate water stewardship has moved from the margins of environmental management to the center of Environmental, Social, and Governance (ESG) discourse. This shift is especially evident in water-intensive sectors such as energy, food processing, textiles, chemicals, metallurgy, construction materials, semiconductors, logistics, and public utilities [5]. In this context, water allocation should be understood not as a means of legitimizing greater industrial freshwater use, but as a governance challenge that must remain subordinate to conservation, efficiency improvement, ecological protection, and long-term sustainability goals [6,7].

Contemporary shifts in water management have significantly reshaped the focus and scope of research in this field. Earlier scholarship largely approached water as a technical and managerial issue, emphasizing regulatory compliance, engineering efficiency, and cost control within organizational and infrastructural systems [8]. In this view, water was primarily treated as a resource to be managed for operational performance. More recent research, however, adopts broader governance and sustainability perspectives that recognize water's intertwined social, ecological, and economic dimensions. This expanded framing highlights stakeholder accountability, social equity, ecosystem integrity, and the externalities transmitted across supply chains [9]. Consequently, water management is now understood not merely as an operational concern but as a strategic and sustainability-critical issue. From a stakeholder theory perspective, water-related decisions affect diverse actors beyond the firm, including local communities, agricultural users, regulators, downstream and upstream populations, and ecosystems [10]. Likewise, the natural-resource-based view suggests that environmental constraints influence firm competitiveness, making stewardship, resource efficiency, and pollution prevention central to long-term value creation. The shared value perspective further argues that firms can create economic benefits by addressing social and environmental externalities [11]. Nevertheless, a major governance challenge remains: firm-level efficiency gains do not necessarily ensure equitable or efficient water allocation across regions, sectors, or interconnected systems [12–14].

Governance challenges are especially pronounced in large inter-basin water transfer systems, where the successful movement of water does not necessarily result in efficient or adaptive allocation after delivery. China's South-to-North Water Diversion Project (SNWDP) exemplifies this problem [15]. Designed to address the longstanding imbalance between water-rich southern basins and water-scarce northern regions, the SNWDP has become vital to urban water supply, industrial continuity, ecological restoration, and regional development. Nevertheless, its quota-based allocation system often fails to keep pace with changing demand shaped by demographic shifts, industrial restructuring, conservation efforts, and infrastructure expansion [16]. Consequently, some recipient regions face temporary or persistent surpluses, while others continue to experience scarcity, producing a water-quota imbalance that reduces allocation efficiency and weakens the project's overall benefits [17]. Research on the SNWDP and comparable systems has evolved along two related but insufficiently connected lines of inquiry. One focuses on allocation design, emphasizing administrative arrangements, optimization models, and distributive trade-offs [18]. The other examines water rights trading as a market-oriented mechanism for

reallocating water toward higher-value uses under appropriate institutional conditions [19]. Integrating these perspectives is essential because regional allocation systems, corporate water use, and sustainable supply chain governance are deeply interdependent [20,21].

Much of the existing literature on water rights trading assumes fully rational actors and frictionless exchange, thereby understating the institutional and behavioral complexity of real-world transactions. In practice, trading decisions are shaped by uncertainty, information asymmetry, and regulatory constraints [22]. Potential sellers may retain unused quotas because future economic expansion or policy change could increase their own water demand. Potential buyers may likewise hesitate because of transaction costs, procedural burdens, doubts about contractual reliability, and exposure to political risk. These difficulties are intensified by incomplete information about counterparties' water-use efficiency, environmental performance, and long-term regulatory exposure. Under such conditions, actors do not optimize once in a static setting; rather, they adapt incrementally, learn through repeated interactions, imitate successful strategies, and respond to changing incentives. Evolutionary game theory therefore offers an appropriate analytical framework for examining water rights trading [23]. Although prior studies have applied this approach to water governance [24,25], corporate-oriented sustainable water supply chain management and related CSR concerns remain insufficiently explored.

This research addresses an important gap by advancing the concept of corporate-oriented water rights trading. Crucially, this concept does not advocate the privatization of public water governance or the prioritization of private gain over collective welfare. Rather, it refers to a governance arrangement in which secondary water trading is assessed by its capacity to support socially responsible production, environmentally efficient water use, and the resilience of sustainable supply chains. Within this framework, the value of a water rights transaction lies not simply in transferring water to the highest bidder, but in reallocating it to users who can generate greater economic value per unit of water, reduce environmental inefficiency, strengthen accountability, and contribute more effectively to regional development and social welfare. The supply chain perspective adopted here extends beyond inter-firm logistics to encompass the wider socio-economic and ecological system through which transferred water is converted into industrial output, service provision, employment, community well-being, and ecological stewardship. Accordingly, institutional factors such as property rights definition, information asymmetry, transaction costs, water pricing, and unrecovered fees are reinterpreted through the lenses of corporate social responsibility and environmental management, as determinants of transparency, trust, stewardship, and adaptive resource allocation.

This research is situated within the South-to-North Water Diversion Project (SNWDP), with particular attention to the quota-adjustment dynamics illustrated by Zhengzhou and Nanyang along the Middle Route. The case exposes a persistent governance dilemma: a rapidly expanding urban–industrial center faces rising water demand despite relatively efficient use, while another region underuses its allocated quota yet hesitates to release it because of uncertainty about future development needs. This tension between short-term surplus and long-term strategic reservation provides a useful setting for examining whether adaptive, efficiency-oriented water rights trading can complement administrative allocation mechanisms. Against this background, the study addresses four questions: how water-quota imbalance can be interpreted through the lenses of corporate social responsibility, environmental management, and sustainable supply chains; the conditions under which secondary water rights trading reaches equilibrium; the influence of information asymmetry, transaction costs, pricing, and loss risk on agreement formation; and the implications for firms, utilities, regulators, and basin managers seeking more sustainable water governance.

2. Conceptual Research Framework

Figure 1 shows that intensifying macro-structural pressures (such as climate change, ecological decline, population growth, industrialization, urban expansion, and rising consumption) have transformed water scarcity into a strategic issue at the heart of corporate sustainability and ESG agendas.

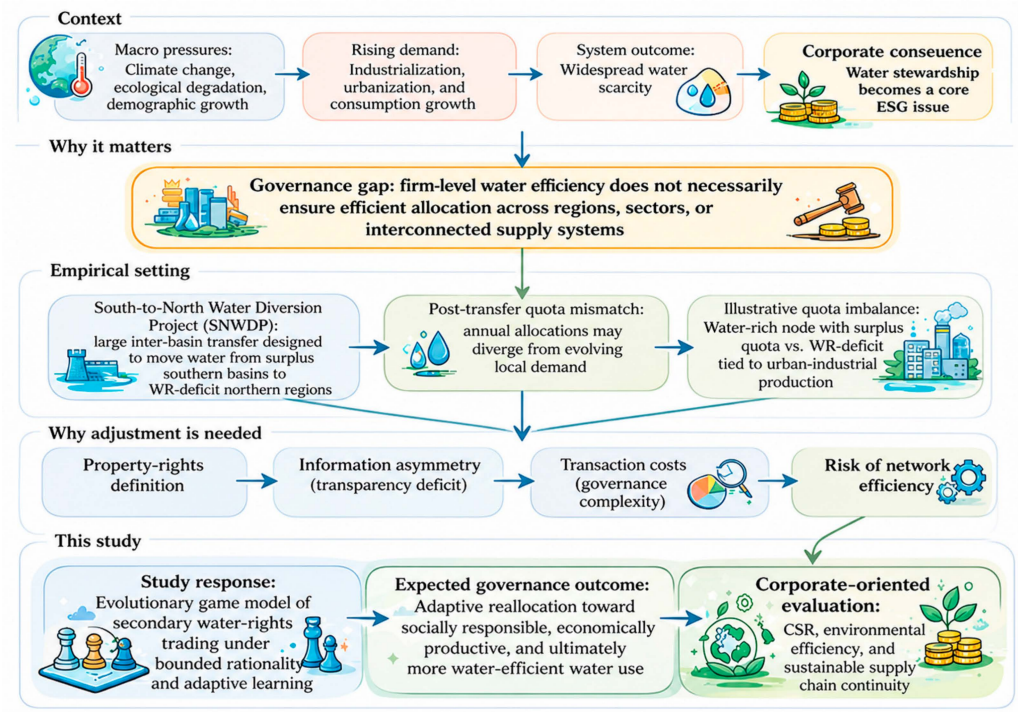


Figure 1. Conceptual framework linking water scarcity, corporate sustainability, and adaptive water rights trading in inter-basin transfer systems.

In doing so, it underscores the exposure of water-dependent sectors and reflects a broader transition in scholarship from compliance-driven and efficiency-centered approaches toward more expansive concerns with governance, stakeholder accountability, ecosystem integrity, and shared value creation. The framework also reveals a fundamental governance gap: enhanced water efficiency at the firm level does not, in itself, ensure that water is allocated effectively across regions, sectors, or supply networks. Using the South-to-North Water Diversion Project (SNWDP) as an empirical reference point, the figure demonstrates how misaligned post-transfer quotas can produce both surplus and deficit conditions, thereby creating the basis for secondary water rights trading. At the same time, it identifies several institutional constraints on adaptive reallocation, including property rights definition, information asymmetry, transaction costs, baseline water pricing, and the risk of unrecovered fees. Within this conceptual structure, the study's evolutionary game framework is introduced as a means of analyzing how boundedly rational actors adapt over time and how such adaptation may support forms of water governance that are CSR-aligned, environmentally efficient, and resilient across supply chains.

3. Literature Review and Existing Research Gap

3.1. Corporate Social Responsibility, Stakeholder Governance, and Water Stewardship

Water governance has emerged as a crucial test of whether CSR has evolved beyond simply managing reputation to encompass genuine accountability for shared natural resources. Earlier CSR research often differentiated between philanthropic activities and a firm's core economic purpose. However, more recent studies have called this separation into

question. Lu Yali et al. examined the stakeholders of a water diversion project through the lens of sustainable supply chain theory and demonstrated that effective project governance depends on understanding the behavior and interdependence of multiple stakeholder groups [26]. Achyar's natural-resource-based view builds on this argument, asserting that the natural environment can influence both the constraints and opportunities of competitive strategy [27]. The triple-bottom-line framework by Narassima et al. [28] and Shekhar's shared value concept [29] further emphasize that companies should generate economic returns in ways that also provide environmental and social benefits. Water stewardship exemplifies where these theoretical perspectives align clearly. Water is locally situated, ecologically limited, socially contested, and essential for operations [30]. Unlike some environmental impacts that can be managed through different times or locations, water risk is often specific to a particular basin and immediately apparent to local communities [31]. This characteristic makes water governance a domain where responsibility, legitimacy, and tangible performance are closely interconnected.

The current agenda for corporate water stewardship reflects a significant evolution in how companies view water use. The CEO Water Mandate, developed by the United Nations Global Compact in collaboration with the Pacific Institute, emphasizes water stewardship through several key areas: direct operations, supply chain and watershed management, collective action, public policy, community engagement, and transparency [32]. This comprehensive approach is crucial because it recognizes water as a shared resource, rather than just a private commodity with effects limited to individual companies. Corporate reporting practices have also adapted to this perspective. Carbon Disclosure Projects (CDP's) water disclosure framework indicates that organizations are increasingly aware of water-related risks in areas such as procurement, supplier continuity, product quality, regulatory compliance, and their social license to operate [33]. A growing number of companies now include assessments of supplier water practices, wastewater standards, contextual water targets, and basin-focused partnerships in their sustainability initiatives [34]. These developments are important as they show that corporate responsibility regarding water management extends beyond internal efficiency; it increasingly requires coordination among organizations and collaborative governance.

Stewardship commitments alone do not address the problem of resource allocation. A company might enhance its internal water efficiency but still face challenges if regional allocation remains inflexible or if neighboring entities hold unused entitlements [35]. Similarly, an industrial cluster can invest significantly in recycling, reducing leakage, and adopting cleaner production methods, yet still experience unreliable access to water if it is restricted by a rigid quota system [36]. This highlights the need for a joint examination of corporate stewardship and public allocation design. The existing literature on corporate social responsibility (CSR) has traditionally focused on targets [37], reporting [38], and stakeholder engagement [39] rather than on mechanisms for reallocating secondary resources. However, once water scarcity is acknowledged as a systemic issue, the capability to reallocate water toward uses that provide greater social and environmental value becomes essential for responsible management. Therefore, the relevant research question is not whether CSR can substitute for public governance, but how governance instruments can be structured so that responsible firms, utilities, and regions are not disadvantaged by institutional rigidity.

3.2. Sustainable Water Supply Chain Management and Environmental Performance

Sustainable supply chain management (SSCM) forms a key foundation for this article. Carter and Rogers defined SSCM as the strategic integration of social, environmental, and economic goals across inter-organizational business processes [40]. Gonçalves et al. also highlighted the importance of managing the flow of materials, information, and capital

while achieving sustainability objectives throughout the supply chain [41]. Subsequent research has expanded this framework to include concepts such as circularity, resilience, and risk governance. Within this extensive body of literature, water has emerged as a critical yet often under-theorized aspect. Studies on water footprints have shown that water use can be embedded in products and transmitted across regions through trade [42]. Barbosa et al. synthesized the water footprint literature in the context of supply chain management, revealing that freshwater preservation has become a significant corporate challenge, particularly in the agri-food sector and water-intensive manufacturing industries [43]. Additionally, Silva noted that companies are increasingly integrating water management initiatives into their social responsibility agendas, as consumers, investors, and regulators are closely examining the water intensity and environmental performance of production systems [44].

Research on water-related supply chain management (SSCM) has provided several important insights:

1. Uneven Distribution of Water Risk: Water risk is not evenly distributed throughout the supply chain. A focal company may have relatively low direct water withdrawals, but it can still have significant indirect exposure through its suppliers located in water-stressed areas [45].
2. Need for Comprehensive Water Governance: Effective water governance goes beyond simply measuring direct water consumption. It requires engaging with suppliers, forecasting demand, setting contractual standards, making joint investments, transferring technology, and monitoring the conditions of water basins [46].
3. Importance of Collaborative Governance Structures: Improvements in environmental performance often hinge on governance structures that coordinate multiple stakeholders, rather than relying solely on isolated improvements at individual plants. For instance, a buyer that mandates suppliers to lower water intensity may need access to reliable data, financial support, or shared infrastructure to achieve these goals [47].
4. Connection to Broader Sustainability Goals: Supply chain water management is increasingly linked to broader objectives such as climate resilience, waste reduction, and circular economy principles. This includes practices like industrial symbiosis, wastewater reuse, and closed-loop production [48].

Despite recent advances in SSCM, there remains a significant gap in the literature that this study aims to address. Most research focuses on operational practices within or between firms, such as cleaner production, supplier standards, green procurement, inventory design, reverse logistics, and product stewardship. However, there has been far less attention given to the institutional frameworks that influence the transfer of water between regions, utilities, industrial clusters, or quota holders when supply and demand conditions fluctuate. In practical terms, the continuity of supply chains often depends on these institutional factors. For instance, a semiconductor plant, food processing facility, industrial park, or logistics hub cannot solely rely on supplier engagement if regional water quotas are depleted while neighboring areas have temporary surpluses. What is needed is a connection between the reallocation of institutional water rights and corporate-oriented supply chain sustainability. This article proposes the concept of corporate-oriented water rights trading, which addresses this gap by treating secondary water allocation as a crucial enabling condition for responsible production.

3.3. Property Rights, Water Markets, and the Governance of Diverted Water

The economic literature on property rights and water markets provides valuable insights into the relevant issues. According to Coasean logic, when rights are clearly defined and transaction costs are low, market exchanges can help rectify inefficient initial alloca-

tions [49]. Water economists have long discussed the applicability of this logic to water systems, as water possesses unique characteristics that complicate its commodification: it is essential for life, varies spatially and temporally, is ecologically embedded, and is politically sensitive [50]. Nonetheless, a substantial body of research indicates that well-designed water rights trading mechanisms can enhance allocative efficiency during periods of scarcity, given that appropriate environmental safeguards, monitoring capabilities, and legal certainty are in place. International water market research from Australia, Chile, and the western United States contributes valuable but differentiated perspectives on water governance and water markets. Australian research maps the evolving literature on water security, governance, and trading [51], Chilean evidence underscores the institutional importance of local water user associations [52], and work from the western United States examines key trends and opportunities in water markets under conditions of scarcity [53]. Taken together, these studies suggest that the effectiveness of water trading depends not only on market design, but also on broader governance structures and institutional context. Milhorance et al. highlighted that water markets can provide flexibility, but this is contingent upon institutions that reduce uncertainty and ensure enforceability [54]. Zhang et al. examined water right financing and found that environmental disruption and intangible risk play an important role in shaping financing performance, suggesting that imperfect information and transaction-related uncertainties may weaken the efficiency of water rights market mechanisms [55]. Subsequent research by Wang et al., along with studies of China's Yellow River Basin and pilot water markets, further supports the idea that trading can lead to improved outcomes when static allocation causes persistent mismatches [56].

Research on water rights reform in China has documented a gradual shift from a purely centralized allocation system to a hybrid model that incorporates both administrative allocation and emerging market mechanisms. Li et al. emphasized the significance of a two-tier market structure, where the primary market allocates initial water rights, and the secondary market facilitates the reallocation of these rights among users [57]. In the context of the South–North Water Diversion Project (SNWDP), several studies have identified a persistent mismatch between the quotas allocated and the actual water usage. Yang et al. analyzed the impact of the South-to-North Water Diversion Project on meteorological parameters in the Middle Route area, thereby extending discussion of the project beyond allocation issues to its potential environmental and climatic implications [58], while Yang et al. proposed frameworks for priority-based allocation [59]. Yuan et al. investigated the conflicts and uncertainties in regional water allocation [60]. Xu et al. discussed the pilot practices of water rights trading along the central route of the project [61]. Peng et al. analyzed the governance dilemma of enterprise water-audit systems through a three-party evolutionary game framework, emphasizing the role of information asymmetry in shaping institutional effectiveness [62]. Meanwhile, Chang et al. examined surface-water recovery in the water-receiving area of the Middle Route of the South-to-North Water Diversion Project, thereby drawing attention to the broader hydrological outcomes of large-scale diversion systems [63]. Together, these studies reveal that the imbalance in water quotas is not merely an incidental issue, but a recurring governance challenge that requires institutions capable of dynamic correction.

The literature highlights several important limitations. First, many studies focus primarily on intergovernmental allocation or macro-level optimization, neglecting the downstream effects on industrial ecosystems and corporate users. Second, having a formal trading mechanism does not automatically address issues such as information asymmetry, trust deficits, or political reluctance to share rights. Third, studies that call for stronger administrative rebalancing often overlook the social resistance and coordination costs associated with repeated top-down reallocation. Fourth, few analyses explicitly connect

water rights trading to CSR objectives, including transparency, responsible efficiency, equitable access, and environmental legitimacy. As demonstrated by Sheng and colleagues, market-based approaches can influence inequality and should, therefore, be integrated into broader governance frameworks. For diversion projects aimed at domestic, industrial, and ecological purposes, the design challenge is not only to maximize private gains but also to create an exchange that enhances welfare, respects environmental boundaries, and is socially credible.

3.4. Evolutionary Game Theory in Environmental and Water Governance

Evolutionary game theory offers a valuable methodological framework for addressing design challenges in various fields. Unlike classical game theory, which often relies on the assumption of perfect rationality and focuses on one-time equilibrium calculations, evolutionary games examine how strategies evolve over time [64]. These strategies can spread, stabilize, or fade away through repeated interactions, imitation, and adaptive learning. This perspective is particularly advantageous for environmental governance, where actors often deal with uncertainty, incomplete information, and ongoing institutional changes. Mariano et al. highlighted the importance of evolutionary games in economics by formalizing replicator dynamics [65]. Since then, this framework has been applied to a range of issues, including emissions reduction, pollution rights, green technology diffusion, ecological compensation, common-pool resource management, and multi-enterprise sustainability challenges.

In water research, evolutionary games have been utilized to analyze various aspects such as irrigation trading, basin conflicts, ecological compensation, and cooperative behavior among governments, users, and regulators [66]. For example, Cao et al. investigated user cooperation in the Hanjiang Basin [67]. Mooren et al. examined transboundary water management within the context of the water–energy–food–ecosystem nexus [68]. Additionally, Ma et al. delved into ecological compensation in cross-regional transfer projects [69], while Zhang et al. evaluated the effectiveness of water rights trading policies concerning water poverty [70]. Wang et al. explored irrigation water rights trading behavior using evolutionary game theory [71]. These studies indicate that adaptive behavior, bounded rationality, and policy parameters often play a more significant role than mere theoretical efficiency achieved in one-off situations. Furthermore, they demonstrate that stable equilibria rely not only on direct benefits but also on factors such as trust, the quality of governance, and the cost structure involved.

Most existing models focus primarily on government intervention as the main factor, giving less attention to the implications for corporations or supply chains. Typically, players in these models are categorized as governments, farmers, or generic regional users, with the outcomes evaluated mainly in terms of cooperation or non-cooperation. While this focus is understandable, it creates a significant blind spot. In water-stressed industrializing regions, corporate users and production systems increasingly influence the social value derived from each unit of water. For instance, water allocated to a low-productivity or poorly accountable user does not have the same value (regarding CSR and environmental management) as water allocated to a user that generates higher economic value with less waste, employs better reuse practices, implements effective wastewater treatment, and demonstrates greater social accountability. If evolutionary game models overlook these distinctions, they risk underestimating the importance of transparency and efficiency benchmarking in sustainable water governance.

4. Research Innovation

This study makes following important contributions to the literature:

1. This research makes a conceptual contribution by reframing water rights trading as a problem of sustainable water supply chain governance rather than viewing it narrowly as an issue of administrative allocation or interregional coordination. In the context of the South-to-North Water Diversion Project (SNWDP), water-quota imbalance is not merely a technical mismatch between supply and demand; it is a governance challenge with far-reaching implications for production continuity, environmental stewardship, and social welfare. By introducing the concept of corporate-oriented water rights trading, the study shifts attention from the simple transfer of water quotas to the broader question of how transferred water is ultimately used across downstream production systems, utilities, services, and communities. In doing so, it argues that the value of water reallocation should be judged not only by whether exchange occurs, but by whether it supports more productive, environmentally efficient, accountable, and socially beneficial outcomes.
2. The research brings together property rights theory, stakeholder-oriented corporate social responsibility, sustainable supply chain management, and evolutionary game theory to explain how water rights trading unfolds under real-world institutional constraints. Building on this interdisciplinary foundation, it constructs a two-node evolutionary game model between a water-rich surplus node and a water-scarce deficit node, explicitly incorporating water-use efficiency, information asymmetry, transaction costs, basic water pricing, and sunk-fee loss risk into the payoff structure. This modeling strategy moves beyond conventional water market analyses that often assume frictionless exchange or purely price-driven behavior. Instead, it demonstrates that mutually beneficial trade emerges through bounded rationality, adaptive learning, and institutional credibility, thereby offering a more realistic and policy-relevant account of how socially desirable water reallocation can occur.
3. Anchored in the Zhengzhou–Nanyang case along the SNWDP Middle Route, the analysis shows that secondary water rights trading should not be understood as a self-executing market mechanism, but as a conditionally viable governance instrument whose success depends on institutional design. The findings underline the importance of transparent efficiency certification, lower procedural frictions, appropriate basic pricing rules, and clear safeguards for ecological security, domestic needs, and equity. These conditions are essential not only for making trade feasible, but also for making it socially legitimate. In this respect, the paper advances a more compelling governance vision: water should not flow automatically to the highest bidder, but to the most responsible and efficient user within a framework of explicit public-interest protections. That insight gives the study both practical significance and wider normative appeal for scholars and policymakers concerned with balancing efficiency, sustainability, and justice in water governance.

Overall, these innovations enable the study to contribute to both theory and practice. Theoretically, it enhances the understanding of water rights trading by placing it within the larger framework of sustainable supply chain governance. Practically, it provides a framework for designing secondary water markets that can uphold corporate responsibility goals while still maintaining public-interest safeguards. The next section outlines the research method and the evolutionary game model used to analyze these dynamics.

5. Research Method

5.1. Analytical Perspective and Game Participant

The analytical framework begins from a simple but substantively rich observation as shown in Figure 2: after the initial allocation of transferred water, the core governance problem is no longer whether water can be physically conveyed, but whether it can be

institutionally redirected toward higher-value and more responsible uses as conditions change. To capture this problem, the study defines two strategic actors. The first actor is a water-rich supply chain node, denoted by R, which possesses transferable quota surplus. This node may represent a receiving region, municipal utility, or regional supply platform whose current realization of demand is below its administratively allocated quota. The second actor is a water-scarce demand node, denoted by S, which requires additional water to support corporate production, urban–industrial services, or other socially valuable activities. In a literal SNWDP interpretation, these actors correspond to receiving regions such as Nanyang and Zhengzhou. In the corporate-oriented interpretation advanced here, they can also be understood as linked water governance nodes through which water enters production networks and urban systems.



Figure 2. Analytical framework of inter-nodal water rights trading under adaptive governance.

Each actor chooses between two strategies: Trade (T) and No Trade (N). Strategy adoption is not assumed to be perfectly rational or instantaneous. Instead, each actor adjusts over time according to bounded rationality and adaptive learning. Let x in [0,1] denote the probability that the water-rich node adopts Trade, and y in [0,1] denote the probability that the water-scarce node adopts Trade. These probabilities evolve through replicator dynamics. A Trade–Trade equilibrium corresponds to a stable state in which both nodes find participation preferable to non-participation. A No Trade equilibrium corresponds to a state in which both nodes retreat from exchange. The evolutionary interpretation is appropriate because water rights trading under large diversion projects typically involves repeated negotiation, policy learning, procedural experimentation, and revision of expectations rather than one-time optimization.

5.2. Define Game Variables and Parameters

The study incorporates five independent variables that are central to its analytical design, as they collectively capture the physical, economic, institutional, behavioral, and informational conditions under which water rights trading may emerge and reach a stable equilibrium. Considered together, these variables substantially enhance the explanatory power of the model by enabling the analysis to address not only whether trade is possible, but also whether it is economically rational, institutionally feasible, behaviorally credible, and socially desirable within a water governance framework oriented toward corporate social responsibility and sustainable supply chain management.

Variable 1 (Tradable volume and scope of transfer): *The potential volume of water available for transfer is denoted by Q. Consistent with the Zhengzhou–Nanyang case, the baseline simulation sets Q = 200 million cubic meters. For simplicity, the model measures Q in units of million cubic meters. Therefore, when Q is multiplied by a price or value expressed in yuan per cubic meter, the resulting monetary amount is expressed in million yuan. The model considers only conventional quota transfers and excludes emergency reallocations for domestic water security or ecological emergency response.*

Variable 2. (Price parameters): *The secondary-market trading price of water is denoted by p, whereas the basic water price paid in the primary allocation system is denoted by b. In the baseline simulation, $p = 0.87$ yuan/m^3 and $b = 0.09$ yuan/m^3. The parameter b reflects the basic charge associated with the initial administrative allocation, including debt repayment, operation, and maintenance obligations, while p represents the benchmark transaction price used in the secondary reallocation stage.*

Variable 3. (Transaction costs): *The water-rich and water-scarce nodes incur transaction costs denoted by C_R and C_S, respectively, whenever they engage in trade. These costs represent search, verification, negotiation, legal processing, contract management, and platform expenses. In the baseline scenario, $C_R = 6$ million yuan and $C_S = 8$ million yuan. This asymmetry reflects the possibility that deficit nodes face higher due-diligence and implementation costs when securing additional water under institutional uncertainty.*

Variable 4. (*Loss-risk coefficient for sunk basic fees): A surplus holder that cannot recover value from unused quota faces the risk that part of the sunk basic water fee becomes an economic loss. This effect is represented by $\lambda \in [0, 1]$, where a higher value indicates stronger perceived loss pressure associated with holding unused quota. The baseline case sets $\lambda = 0.70$. Behaviorally, λ captures the extent to which sunk charges create an incentive to sell rather than hoard unused quota.*

Variable 5. *(Heterogeneous water-use efficiency and information asymmetry): The value of allocating additional water to a deficit node increases when that node can generate greater economic and environmental returns per unit of water. Conversely, the opportunity cost to a surplus node of releasing part of its quota is higher when that water could be used more productively within the node itself. To represent these differences, the model assumes that both actors may operate under high- and low-efficiency states of water use. Specifically, η_R^H and η_R^L denote the high and low marginal value of water in the surplus node, respectively, while η_S^H and η_S^L denote the corresponding values in the deficit node. Following the case logic developed in the current research, the baseline simulation sets $\eta_R^H = 0.65$ yuan/m^3 and $\eta_R^L = 0.20$ yuan/m^3, and $\eta_S^H = 1.10$ yuan/m^3 and $\eta_S^L = 0.35$ yuan/m^3. These parameter values reflect the expectation that, on average, the deficit node exhibits higher marginal water productivity because water is allocated to more intensive industrial, service-sector, or urban uses.*

Because neither actor can directly observe the other's true water-use efficiency, the model incorporates subjective beliefs to represent information asymmetry. Let ρ denote the probability assigned by the deficit node that the surplus node is in the high-efficiency state, and let σ denote the probability assigned by the surplus node that the deficit node is in the high-efficiency state. Accordingly, the expected marginal value of water for the surplus and deficit nodes is defined as:

$$\overline{\eta}_R = \rho\eta_R^H + (1-\rho)\eta_R^L, \tag{1}$$

$$\overline{\eta}_S = \sigma\eta_S^H + (1-\sigma)\eta_S^L. \tag{2}$$

In this notation, $\overline{\eta}_R$ and $\overline{\eta}_S$ represent the belief-weighted expected marginal value of water for the surplus and deficit nodes, respectively; η^H and η^L denote the high- and low-efficiency states; ρ captures the deficit node's belief about the likelihood that the surplus node has high water-use efficiency; and σ captures the surplus node's belief about the likelihood that the deficit node has high water-use efficiency. A lower value of ρ implies that the deficit node perceives the surplus node's opportunity cost of releasing water to be relatively low, thereby increasing the perceived attractiveness of trade. By contrast, a higher value of σ indicates that the surplus node views the deficit node as a more efficient and socially valuable user of water, which strengthens the incentive to transfer quota.

This formulation has an important analytical advantage. By expressing information asymmetry through probabilistic beliefs, the model remains both parsimonious and behaviorally interpretable, while capturing how imperfect information shapes trading decisions. In practical terms, ρ and σ provide a transparent mechanism for examining how credibility, signaling, and perceived efficiency influence willingness to trade, making the framework especially useful for corporate social responsibility and environmental management analyses of interjurisdictional water transactions.

5.3. Game Model of Payoff Structure

The payoff structure follows the institutional logic while being reformulated for corporate-oriented sustainability analysis. For the surplus node, the decision to trade involves a trade-off between earning net revenue from water transfer and retaining water for potential internal use. When both nodes choose to trade, the surplus node receives the transaction price p for water volume Q, but it has already paid the basic water charge b for that quota. In addition, it forgoes the expected value of self-use, $\overline{\eta}_R Q$, and incurs a transaction cost C_R. The resulting payoff is therefore given by:

$$\Pi_R^{(T,T)} = (p-b)Q - \overline{\eta}_R Q - C_R. \tag{3}$$

If the surplus node is willing to trade but the deficit node does not complete the transaction, the surplus node retains the water, still incurs the transaction cost associated with the failed attempt, and continues to face pressure from the sunk basic fee. Its payoff in this case is:

$$\Pi_R^{(T,N)} = \overline{\eta}_R Q - C_R - \lambda bQ \tag{4}$$

If the surplus node chooses not to trade, it retains the water and its expected self-use value, but still bears the loss pressure associated with unused quota:

$$\Pi_R^{(N,T)} = \Pi_R^{(N,N)} = \overline{\eta}_R Q - \lambda bQ \tag{5}$$

For the deficit node, successful trade provides access to additional water that yields an expected benefit of $\bar{\eta}_S Q$, but this benefit is reduced by the purchase payment pQ and the transaction cost C_S. Accordingly, its payoff under successful trade is:

$$\Pi_S^{(T,T)} = \bar{\eta}_S Q - pQ - C_S \tag{6}$$

If the deficit node attempts to trade but the surplus node refuses, the deficit node still suffers the opportunity loss associated with water shortage and also incurs the transaction cost. To preserve analytical tractability while capturing the logic of unsuccessful search and negotiation, the payoff under failed trade is specified as:

$$\Pi_S^{(N,T)} = -\bar{\eta}_S Q - C_S \tag{7}$$

If the deficit node chooses not to trade, the shortage-related opportunity loss remains, but no transaction cost is incurred:

$$\Pi_S^{(T,N)} = \Pi_S^{(N,N)} = -\bar{\eta}_S Q \tag{8}$$

In this notation, Π denotes the payoff of an actor, with subscripts R and S referring to the surplus and deficit nodes, respectively. The superscripts (T,T), (T,N), (N,T), and (N,N) indicate the strategy combinations of the two nodes, where T denotes Trade and N denotes No Trade. The parameter p represents the transaction price per unit of water, b the basic water charge, and Q the quantity of water involved in the transaction. The terms $\bar{\eta}_R$ and $\bar{\eta}_S$ are the expected marginal values of water for the surplus and deficit nodes, respectively, reflecting belief-weighted water-use efficiency under information asymmetry. The parameters C_R and C_S denote transaction costs borne by the surplus and deficit nodes, while λ captures the intensity of loss pressure associated with unused quota or sunk basic charges.

This formulation offers several analytical advantages. First, it links institutional water-allocation logic with a corporate sustainability perspective by explicitly incorporating opportunity cost, transaction cost, and perceived productive value into the payoff structure. Second, the notation provides a transparent basis for simulation and comparative statics, allowing researchers to identify the conditions under which trade becomes individually rational for each actor. For the surplus node, trade is attractive when the net return from selling water exceeds the value of retaining it for internal use after accounting for costs. For the deficit node, trade is attractive when the expected value generated by additional water outweighs the purchase price and transaction costs. Third, the framework is especially useful for CSR and environmental management applications because $\bar{\eta}_S$ can be interpreted not only as private marginal benefit, but also as the broader social and environmental value associated with responsible and productive water use. In this sense, the model captures both economic incentives and sustainability considerations within a unified strategic framework.

5.4. Game Model of Replicator Dynamics

Let $x \in [0,1]$ denote the probability that the surplus node chooses Trade, and $y \in [0,1]$ denote the probability that the deficit node chooses Trade. Given these mixed strategies, the expected payoff to the surplus node from choosing Trade is:

$$E_R(T) = y\Pi_R^{(T,T)} + (1-y)\Pi_R^{(T,N)}. \tag{9}$$

whereas the expected payoff from choosing No Trade is:

$$E_R(N) = y\Pi_R^{(N,T)} + (1-y)\Pi_R^{(N,N)}. \tag{10}$$

Substituting the payoff expressions and simplifying yields the strategy-difference term for the surplus node:

$$\Delta_R = E_R(T) - E_R(N) = y[(p-(1-\lambda)b-2\overline{\eta}_R)Q] - C_R. \tag{11}$$

The corresponding replicator dynamic equation is:

$$\frac{dx}{dt} = x(1-x)\Delta_R. \tag{12}$$

Similarly, for the deficit node, the expected payoff from choosing Trade is:

$$E_S(T) = x\Pi_S^{(T,T)} + (1-x)\Pi_S^{(N,T)}. \tag{13}$$

and the expected payoff from choosing No Trade is:

$$E_S(N) = x\Pi_S^{(T,N)} + (1-x)\Pi_S^{(N,N)}. \tag{14}$$

After simplification, the strategy-difference term for the deficit node becomes:

$$\Delta_S = E_S(T) - E_S(N) = x[(2\overline{\eta}_S - p)Q] - C_S. \tag{15}$$

Accordingly, the replicator dynamic equation for the deficit node is:

$$\frac{dy}{dt} = y(1-y)\Delta_S. \tag{16}$$

In this notation, $E_R(T)$ and $E_R(N)$ denote the expected payoffs to the surplus node under the strategies Trade and No Trade, respectively, while $E_S(T)$ and $E_S(N)$ denote the corresponding expected payoffs for the deficit node. The terms Δ_R and Δ_S represent the net payoff advantage of choosing Trade over No Trade for the surplus and deficit nodes, respectively. The variables x and y are the dynamic strategy proportions, and $\frac{dx}{dt}$ and $\frac{dy}{dt}$ measure how these proportions evolve over time through adaptive learning or strategic imitation. A positive value of Δ implies that Trade performs better than No Trade and therefore becomes more prevalent, whereas a negative value implies the opposite.

This formulation offers several analytical advantages. First, it provides a compact and rigorous representation of boundedly rational strategic adjustment, allowing the model to capture how trading behavior evolves over time rather than assuming full rationality from the outset. Second, the notation is directly interpretable: the surplus node's willingness to trade increases when the deficit node is more likely to participate (y is higher), when the effective transaction return is more favorable, when the perceived opportunity cost of releasing water is lower, and when the pressure associated with unused quota is stronger. Likewise, the deficit node's willingness to trade increases when the surplus node is more likely to participate (x is higher), when the expected productivity of additional water is greater, and when transaction costs are lower. Third, the replicator dynamics framework is especially useful for sustainability and environmental management applications because it makes it possible to examine path dependence, strategic stability, and policy sensitivity in water rights transactions under conditions of uncertainty and information asymmetry.

5.5. Game Model of Equilibrium Trade Logic and Qualitative Stability Conditions

The dynamic system admits the four corner equilibria, (0,0), (0,1), (1,0), and (1,1) as well as potential interior threshold points. Because the present study is primarily concerned with managerial and policy interpretation rather than exhaustive formal proof, the analysis focuses on the conditions under which the socially desirable Trade–Trade equilibrium can emerge and remain locally stable. Two threshold expressions are central to this assessment:

$$A_R = (p - (1-\lambda)b - 2\overline{\eta}_R)Q, \tag{17}$$

$$A_S = (2\overline{\eta}_S - p)Q. \tag{18}$$

Here, A_R represents the surplus node's net strategic incentive to trade, while A_S represents the deficit node's net strategic incentive to trade. More specifically, p denotes the transaction price per unit of water, b the basic water charge, λ the coefficient capturing loss pressure associated with sunk or unused quota costs, Q the traded water volume, and $\overline{\eta}_R$ and $\overline{\eta}_S$ the expected marginal values of water for the surplus and deficit nodes, respectively. Thus, A_R summarizes whether the surplus node perceives water transfer as preferable to retention, after accounting for price, basic-charge burden, and opportunity cost. Similarly, A_S indicates whether the deficit node views purchased water as sufficiently valuable, relative to the transaction price, to justify participation in trade.

If $A_R \leq 0$, trade remains unattractive to the surplus node even when the deficit node is willing to transact, because the opportunity cost of releasing water and the basic-price burden outweigh the expected gains from transfer. If $A_S \leq 0$, the deficit node does not perceive the acquired water as valuable enough to justify its purchase. Accordingly, only when $A_R > 0$ and $A_S > 0$ can the Trade–Trade equilibrium become locally attractive. Under these conditions, the critical behavioral thresholds are defined as:

$$y^* = \frac{C_R}{A_R}, \quad x^* = \frac{C_S}{A_S}. \tag{19}$$

In this notation, y^* is the minimum participation probability of the deficit node required for the surplus node's propensity to trade to increase, whereas x^* is the corresponding minimum participation probability of the surplus node required for the deficit node's propensity to trade to increase. The parameters C_R and C_S denote the transaction costs borne by the surplus and deficit nodes, respectively. When $y > y^*$, the surplus node's likelihood of choosing trade rises over time; when $x > x^*$, the deficit node's likelihood of choosing trade rises. The basin of attraction for mutual trade therefore depends jointly on institutional and market parameters $(p, b, \lambda, C_R, C_S)$, belief-based efficiency expectations embedded in ρ and σ, and the initial participation tendencies (x_0, y_0).

To verify local stability formally, the replicator system can be defined as:

$$\dot{x} = f(x,y) = x(1-x)(yA_R - C_R), \tag{20}$$

$$\dot{y} = g(x,y) = y(1-y)(xA_S - C_S), \tag{21}$$

where A_R and A_S are the net strategic incentive terms defined above. The Jacobian matrix is:

$$J(x,y) = \begin{pmatrix} (1-2x)(yA_R - C_R) & x(1-x)A_R \\ y(1-y)A_S & (1-2y)(xA_S - C_S) \end{pmatrix}. \tag{22}$$

Evaluating $J(x,y)$ at the four corner equilibria yields the following results. At (0,0), the eigenvalues are $-C_R$ and $-C_S$, so the No Trade equilibrium is always locally asymptotically stable. At (1,0), the eigenvalues are C_R and $A_S - C_S$, implying instability because $C_R > 0$.

At (0,1), the eigenvalues are $A_R - C_R$ and C_S, implying instability because $C_S > 0$. At (1,1), the eigenvalues are $C_R - A_R$ and $C_S - A_S$. Therefore, the Trade–Trade equilibrium is locally asymptotically stable if and only if $A_R > C_R$, $A_S > C_S$. If $A_R > C_R$ and $A_S > C_S$, an interior equilibrium exists at:

$$E^* = (x^*, y^*) = \left(\frac{C_S}{A_S}, \frac{C_R}{A_R} \right). \tag{23}$$

At E^*, the Jacobian has zero trace and negative determinant:

$$\det J(E^*) = -x^*(1 - x^*)y^*(1 - y^*)A_R A_S < 0. \tag{24}$$

where E^* is a saddle point. Hence, $A_R > 0$ and $A_S > 0$ are necessary but not sufficient; the sufficient local stability condition for (1,1) is that each side's incentive surplus must exceed its own transaction cost.

This formulation offers several analytical advantages. First, it provides a concise and interpretable set of conditions for assessing whether mutually beneficial trade can emerge under bounded rationality. Second, the threshold structure makes the model especially suitable for managerial and policy applications, because it clearly identifies the parameters through which intervention can improve coordination outcomes. For example, lower transaction costs, reduced information asymmetry, lower basic water charges, and stronger loss pressure associated with idle quota all enlarge the parameter space in which trade becomes feasible and stable. Third, the framework is well suited to CSR and environmental management analysis because it links institutional design and behavioral expectations to cooperative water-allocation outcomes. In this sense, the model not only explains whether trade occurs, but also clarifies how governance reforms and credibility-enhancing mechanisms can accelerate convergence toward a socially desirable trading equilibrium.

5.6. Evolutionary Game Mechanism of Corporate-Oriented Water Rights Trading in Sustainable Water Supply Chain Management

Figure 3 and Table 1 present the mechanism of the evolutionary game model for corporate-oriented water rights trading in sustainable water supply chain management. The figure structures the problem around two boundedly rational actors: a water-rich surplus node (R) and a water-scarce deficit node (S). The upper-left panel characterizes the surplus node as holding transferable quota surplus while facing transaction costs, opportunity costs of self-use, and loss pressure associated with sunk basic water fees. In contrast, the deficit node is characterized by production-related water shortage, a positive marginal value of additional water, and transaction costs associated with acquiring quota. The central payoff matrix formalizes the strategic interaction between these two actors under the alternative choices of Trade (T) and No Trade (N). It shows that mutual trade generates gains when the transaction price, expected marginal water values, and transaction costs jointly favor exchange, whereas unilateral willingness to trade without counterpart participation leads to incomplete or failed transactions with associated cost penalties. In this way, the matrix captures the core institutional tension of the model: the surplus node must decide whether releasing quota is preferable to retaining it for future internal use, while the deficit node must decide whether the expected value of additional water justifies the purchase price and transaction costs.

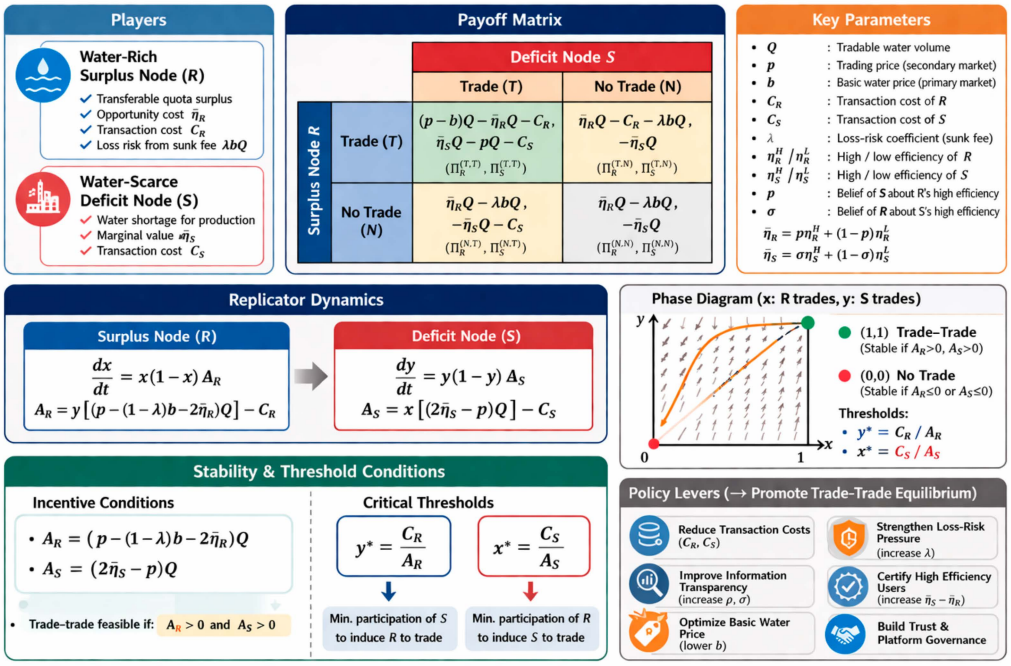


Figure 3. Mechanism of the evolutionary game model for corporate-oriented water rights trading in sustainable water supply chain management.

Table 1. Local stability classification of the replicator system.

Equilibrium	Eigenvalues of J	Local Stability	Interpretation
(0,0)	$(-C_R, -C_S)$	Stable	No Trade equilibrium always locally stable
(1,0)	$(C_R, A_S - C_S)$	Unstable	Water-rich node cannot remain at Trade when deficit node stays at No Trade
(0,1)	$(A_R - C_R, C_S)$	Unstable	Water-scarce node cannot remain at Trade when surplus node stays at No Trade
(1,1)	$(C_R - A_R, C_S - A_S)$	Stable if $A_R > C_R$ and $A_S > C_S$	Mutual trade requires incentives to dominate own transaction costs
$E^* = \left(\frac{C_S}{A_S}, \frac{C_R}{A_R}\right)$	$\pm\sqrt{x^*(1-x^*)y^*(1-y^*)A_RA_S}$	Saddle	Separates the basins of attraction of (0,0) and (1,1)

The lower panels extend this static interaction into a dynamic evolutionary framework. The replicator dynamics equations describe how the probabilities of choosing trade evolve over time for both actors, reflecting adaptive learning rather than perfect one-shot rationality. The figure further highlights the key incentive conditions, A_R and A_S, which determine whether trade is individually attractive to the surplus and deficit nodes, respectively, as well as the critical thresholds y^* and x^*, which indicate the minimum participation levels required to induce each party to move toward trade. The phase diagram illustrates that the Trade–Trade equilibrium becomes stable only when both incentive conditions are positive, whereas No Trade remains stable when one or both sides lack sufficient incentive to participate. Finally, the policy-lever panel translates the model into managerial and governance implications by showing that lower transaction costs, stronger information transparency, optimized basic water pricing, stronger loss-risk pressure, credible certification of efficient water users, and trust-building platform governance can all enlarge the basin of attraction of the socially desirable Trade–Trade equilibrium. Thus, Figure 3 not only summarizes

the internal logic of the model but also demonstrates how institutional design and CSR-oriented governance mechanisms can facilitate efficient and responsible water reallocation across supply chain nodes.

5.7. Game Parameter Setting and Simulation Design

The simulation adopts a stylized parameterization based on the Zhengzhou–Nanyang case. In that case, a water rights transaction involving 200 million m^3 was considered under the Middle Route of the SNWDP to ease quota pressure in a high-demand city while making productive use of surplus quota held by another region. The present study does not attempt to estimate the exact contractual payoffs of that transaction. Rather, it uses the case as an illustrative benchmark for constructing a corporate-oriented sustainable water supply chain model.

The baseline parameters are set as follows: $Q = 200$ million m^3, $p = 0.87$ yuan/m^3, $b = 0.09$ yuan/m^3, $C_R = 6$ million yuan, $C_S = 8$ million yuan, $\lambda = 0.70$, $\eta_R^H = 0.65$, $\eta_R^L = 0.20$, $\eta_S^H = 1.10$, and $\eta_S^L = 0.35$. These values suggest that, in general, the deficit node can generate greater expected value from additional water than the surplus node can from retaining the same amount of water, although this conclusion depends on the actors' beliefs. To capture information asymmetry, the simulation assigns ρ and σ values of 0.1, 0.5, and 0.9, representing low, moderate, and high perceived probabilities that the counterpart is in the high-efficiency state. This design follows the logic, in which three belief levels were used to reflect different informational conditions.

The dynamic simulation solves the replicator equations numerically using a discrete-time approximation with a modest learning-rate parameter to produce smooth adjustment paths. Unless otherwise specified, the initial conditions are set at $x_0 = 0.40$ and $y_0 = 0.40$. These values represent an institutional setting in which both nodes are moderately receptive to trading but have not yet developed a firm commitment to participate. The sensitivity analysis then varies key institutional parameters while maintaining an information environment that is sufficiently favorable for the Trade–Trade equilibrium to emerge in the baseline case. Specifically, the analysis examines changes in transaction costs, the basic water price, and the loss-risk coefficient. These parameter ranges are intended to be illustrative rather than econometrically estimated: transaction costs are varied from high-friction to low-friction conditions, the basic water price is set between 0.03 and 0.18 yuan/m^3, and the loss-risk coefficient ranges from 0.30 to 0.90.

To clarify the empirical status of the baseline values, the parameter set is divided into three groups:

$$\Theta = \Theta^{obs} \cup \Theta^{cal} \cup \Theta^{lat}, \tag{25}$$

where Θ^{obs} contains observed or policy-anchored parameters, Θ^{cal} contains calibrated institutional friction parameters, and Θ^{lat} contains latent behavioral parameters. In the current study:

$$\Theta^{obs} = \{Q, p, b\}, \ \Theta^{cal} = \{C_R, C_S, \lambda\}, \ \Theta^{lat} = \left\{\eta_R^H, \eta_R^L, \eta_S^H, \eta_S^L, \rho, \sigma\right\}. \tag{26}$$

The tradable volume $Q = 200$ million m^3 is anchored in the Zhengzhou–Nanyang water rights transaction context reported by Henan Province. The basic water price $b = 0.09$ yuan/m^3 corresponds to the officially published middle-route basic water price for the Henan Nanyang section. The trading price $p = 0.87$ yuan/m^3 is used as a benchmark transaction price drawn from documented cross-regional water rights trading practice in Henan rather than as a model-derived equilibrium trade. By contrast, C_R, C_S, and λ are not directly observed microdata; they are calibrated to represent plausible institutional

frictions and carrying-cost pressure. The efficiency-state and belief parameters are latent by construction and are therefore interpreted as scenario variables.

Table 2 presents the directional interpretation of the calibrated parameters and clarifies how each parameter shapes the strategic evolution of water rights trading within the model. Taken together, the results indicate that trading outcomes are influenced not only by economic incentives, but also by institutional frictions, pricing arrangements, loss perceptions, and information-related beliefs.

Table 2. Directional interpretation of calibrated parameters.

Parameter	Directional Result in Model	Interpretation Level
C_R, C_S	Higher values slow convergence to Trade–Trade	Institutional friction mechanism
b	Higher value weakens quota-release incentives	Pricing-rule mechanism
λ	Higher value strengthens quota-release incentives	Carrying-cost/loss-salience mechanism
ρ, σ	Belief shifts can change equilibrium selection	Information-governance mechanism

5.8. Game Strategy Set for CSR and Environmental Management

A final methodological clarification is important. The model's payoff parameters should not be interpreted in narrowly financial terms. In the context of a CSR and environmental management study, the value of water extends beyond short-term monetary returns to include broader dimensions such as higher output with lower water intensity, reduced waste discharge, stronger community benefits, cleaner production processes, and greater regulatory and social credibility. Accordingly, the deficit node's expected water-use value, $\overline{\eta}_S$, is interpreted as a composite indicator of both productive performance and socially responsible water use, rather than short-run revenue alone. Similarly, the surplus node's opportunity-cost term, $\overline{\eta}_R$, reflects not only the current value of retaining water, but also the possibility that unused quota may support future economic development or provide strategic flexibility.

By incorporating these broader considerations, the model remains economically consistent while engaging directly with the sustainability literature. This methodological design enables the subsequent analysis to examine not only whether trade occurs, but also the governance conditions under which trade contributes to sustainable water supply chain management. All figures and tables reported in the following section are derived from the model developed here.

The numerical simulation of the replicator dynamics system was implemented in MATLAB R2024a. The discrete-time approximation of the evolutionary game model was coded directly from Equations (1) and (24), and all baseline and sensitivity results were generated using the same simulation program. The simulations were run on a 64-bit Windows 11 computer with an Intel Core i7 processor and 16 GB RAM. Because the model is deterministic and computationally lightweight, the reported equilibrium outcomes and convergence periods were stable across repeated runs under identical parameter settings. Algorithm A1 (Appendix A) explains the numerical simulation procedure for the corporate-oriented evolutionary game of water rights trading.

6. Results and Discussion

6.1. Baseline Equilibrium Logic

The baseline simulation represents a governance setting in which both actors show a moderate initial willingness to trade, but successful agreement still depends on institutional conditions and beliefs about counterpart efficiency. Table 3 presents the main scenario results for different combinations of ρ and σ, where ρ denotes the probability assigned by the deficit node that the surplus node is highly efficient, and σ denotes the probability assigned by the surplus node that the deficit node is highly efficient. Figure 4 complements these results by showing a heat map of the final average trading propensity across a broader range of belief combinations. Taken together, the table and figure reveal a clear result: the Trade–Trade equilibrium does not arise automatically. Rather, it emerges only within a specific region of the parameter space, namely where the surplus node perceives the deficit node as sufficiently efficient and the deficit node perceives the surplus node as having a relatively low marginal value of retaining water. In this sense, mutual trade depends not only on formal incentives, but also on the informational and institutional environment in which the two actors form their expectations.

Table 3. Scenario outcomes under asymmetric efficiency beliefs.

ρ	σ	$\bar{\eta}_R$	$\bar{\eta}_S$	Final x	Final y	Equilibrium Outcome	Convergence Period
0.1	0.1	0.245	0.425	0.0	0.0	No Trade–No Trade	27.54
0.1	0.5	0.245	0.725	1.0	1.0	Trade–Trade	6.24
0.1	0.9	0.245	1.025	1.0	1.0	Trade–Trade	4.88
0.5	0.1	0.425	0.425	0.0	0.0	No Trade–No Trade	12.72
0.5	0.5	0.425	0.725	0.0	0.0	No Trade–No Trade	34.3
0.5	0.9	0.425	1.025	0.0	0.0	No Trade–No Trade	56.8
0.9	0.1	0.605	0.425	0.0	0.0	No Trade–No Trade	9.42
0.9	0.5	0.605	0.725	0.0	0.0	No Trade–No Trade	16.72
0.9	0.9	0.605	1.025	0.0	0.0	No Trade–No Trade	20.82

If Final $x \approx 1$, the surplus node evolves toward trading. If Final $x \approx 0$, it evolves toward No Trade. If Final $y \approx 1$, the deficit node evolves toward trading. If Final $y \approx 0$, it evolves toward No Trade.

Under the baseline parameter setting, the Trade–Trade equilibrium arises when $\rho = 0.1$ and σ is at a medium or high level. When $\rho = 0.1$ and $\sigma = 0.5$, both x and y converge to 1, and convergence occurs after about 6.24 simulation periods under the more conservative initial condition used in the sensitivity figures. When $\rho = 0.1$ and $\sigma = 0.9$, convergence is faster, taking about 4.88 periods. Substantively, this result implies that trading attains evolutionary stability when the deficit node believes that the surplus node generates comparatively limited productive returns from retaining its quota, and when the surplus node believes that the deficit node can utilize the transferred water more productively and in a socially responsible way. This outcome aligns with the core argument advanced in this study, namely that the feasibility of trading rests on an efficiency differential that is mutually recognized, or at minimum credibly inferred, by the transacting parties.

The non trading scenarios are equally informative. When $\rho = 0.1$ but $\sigma = 0.1$, the deficit node is willing to believe that the surplus node faces a low opportunity cost of releasing water, yet the surplus node does not believe that the deficit node can use the water efficiently enough to justify transfer. Under these conditions, the model converges to No Trade. A similar pattern appears when ρ increases to 0.5 or 0.9. As the deficit node becomes more likely to view the surplus node as an efficient self-user of the quota, the implied reservation value of water rises and the range of conditions supporting trade becomes narrower, even when σ remains relatively favorable. In the most pessimistic

cases, both nodes move quickly toward non-participation. In more uncertain cases, such as $\rho = 0.5$ and $\sigma = 0.9$, the deficit node initially shows a stronger willingness to trade, but the surplus node withdraws first, after which the deficit node also abandons the attempt. These dynamics help explain why some water rights markets remain underused despite apparently positive aggregate gains. When beliefs about counterpart efficiency are not aligned, one actor may continue to express interest while the other withdraws, preventing a stable agreement from emerging.

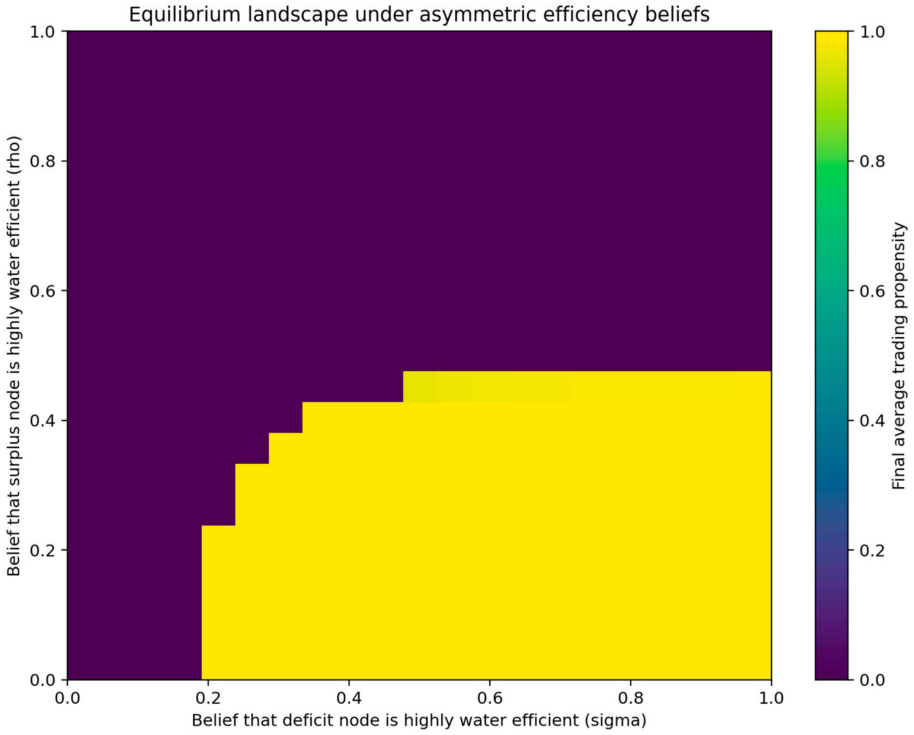


Figure 4. Equilibrium landscape under different beliefs about counterpart water-use efficiency. Note: In the image rho = ρ and sigma = σ.

For CSR and environmental management, this baseline finding has important implications. It suggests that market design alone is not enough when actors lack confidence that additional water will be used efficiently and responsibly. Corporate-oriented trading therefore depends on credible signals of water productivity, discharge control, and governance quality. In practice, such signals may include third party certification of water-use efficiency, disclosure of water reuse rates, digital records of past transactions, and performance-based eligibility criteria for buyers. Without these mechanisms, even well-designed trading rules may fail to change behavior, and actors may continue to rely on defensive hoarding and institutional inertia.

Across the nine simulated belief configurations, mutual trade appears in only two cases (22.2%), whereas seven cases (77.8%) converge to No Trade–No Trade. This should be interpreted as the central result of Table 4, not as a secondary detail. It indicates that secondary water rights trading under the SNWDP is a conditional governance mechanism with a narrow basin of attraction: unless the surplus node believes that the deficit node is a sufficiently efficient and responsible user of water, and unless the deficit node believes that the surplus node's reservation value is low enough to release quota, the system reverts to strategic non-participation. In other words, the default tendency of the model is institutional inertia rather than exchange. This conclusion is consistent with the broader literature showing that water markets often remain thin or underused when information is imperfect, transaction rules are cumbersome, and the legitimacy of reallocation is uncertain [53,55,61].

Table 4. Concentration of trade outcomes across the nine simulated scenarios.

Indicator	Result	Interpretation
Total simulated scenarios	9	Full baseline belief grid
Trade–Trade scenarios	2/9 (22.2%)	Mutual trade is a minority outcome
No Trade–No Trade scenarios	7/9 (77.8%)	Non-trade is the dominant equilibrium pattern
Trade by ρ	ρ = 0.1: 2/3; ρ = 0.5: 0/3; ρ = 0.9: 0/3	Seller-side reservation-value beliefs are decisive
Trade by σ	σ = 0.1: 0/3; σ = 0.5: 1/3; σ = 0.9: 1/3	Buyer-side efficiency beliefs help but are not sufficient alone

Table 4 and Figure 5 make this pattern explicit. Looking across rows, lowering ρ from 0.5 or 0.9 to 0.1 is decisive, because trade disappears completely once the deficit node assigns even a moderate probability to the surplus node being a high-efficiency self-user. Looking across columns, higher σ helps but is not sufficient by itself: even when σ = 0.9, trade still fails unless ρ is also at its most favorable level. The asymmetry matters. A favorable view of the buyer is necessary, but the seller's willingness to release surplus quota is the tighter bottleneck. The managerial implication is cautionary. The model does not show that secondary markets routinely solve water scarcity; it shows that such markets require unusually strong informational and institutional support before they can work reliably. For CSR-oriented water governance, this means that transparency, verified efficiency certification, and low-friction platform design are not complementary refinements; they are preconditions for market emergence.

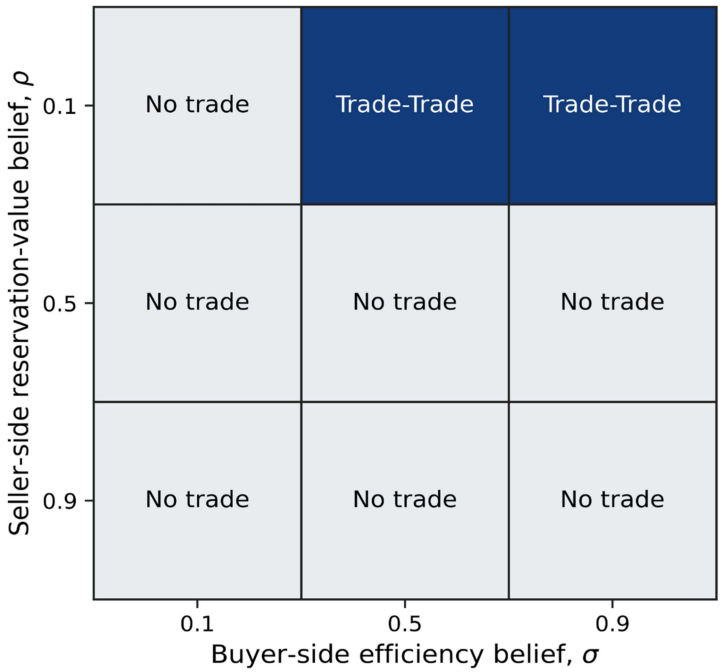


Figure 5. Binary classification of equilibrium outcomes across the nine simulated scenarios.

6.2. Information Asymmetry and the Emergence of Responsible Trading

Figure 6 highlights the role of information asymmetry by showing the time paths of trading propensity under three representative scenarios: a pessimistic case ($\rho = 0.1, \sigma = 0.1$), a threshold favorable case ($\rho = 0.1, \sigma = 0.5$), and a highly favorable case ($\rho = 0.1, \sigma = 0.9$). The trajectories indicate that the model is highly sensitive to even modest changes in beliefs. In the pessimistic case, both x and y decline steadily over time, although not at the same

rate. The surplus node becomes less willing to trade because it perceives the counterpart as insufficiently efficient. The deficit node then interprets this as a signal that trading is unlikely to succeed, which further reduces its own willingness to participate. The result is a mutually reinforcing withdrawal from exchange. This pattern shows that unsuccessful trading is not simply the outcome of weak economic incentives, but also of negative expectations that spread through the interaction process. Once one actor begins to lose confidence in the value or feasibility of trade, the other actor responds in kind, and the system gradually converges toward non-participation.

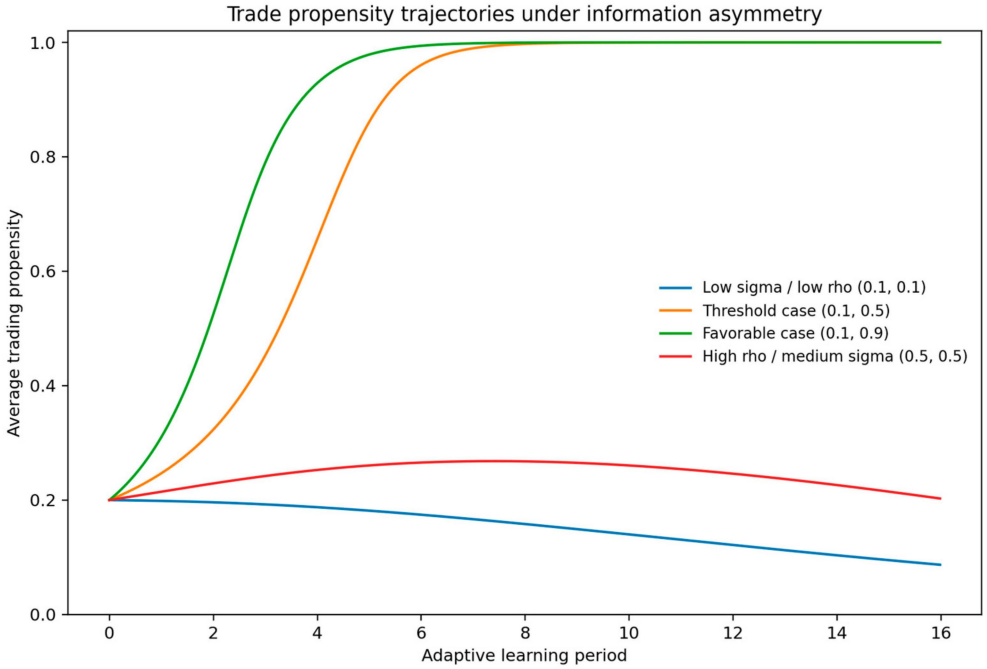


Figure 6. Trade propensity trajectories under representative information-asymmetry scenarios. Note: In the image rho = ρ and sigma = σ.

In the threshold-favorable case, both actors pass the critical thresholds and move toward one. The transition is not instantaneous, because evolutionary adjustment reflects adaptive learning rather than one-shot optimization. Yet once both nodes observe sufficient counterpart willingness, the positive feedback becomes self-reinforcing. The highly favorable case intensifies this mechanism: higher σ implies stronger confidence that the deficit node can generate high-value and responsible use from purchased water, so the surplus node shifts more quickly toward participation. The deficit node then reads the surplus node's willingness as confirmation that trading is feasible, and convergence accelerates further. This is precisely the type of dynamic one would expect in a maturing water rights platform where reliable efficiency information and procedural predictability have reduced uncertainty.

The managerial interpretation is that information asymmetry functions as a hidden transaction cost. Formal search and negotiation expenses may be modest relative to the welfare stakes of a water transfer, yet uncertainty about the other party's productivity or responsible use can freeze the market. In a CSR context, this has two consequences. First, transparency is not merely a reporting issue; it becomes an allocative instrument. Second, high-efficiency users must be able to communicate that efficiency credibly, otherwise the market cannot distinguish between productive demand and opportunistic demand. This helps explain why supply chain water stewardship programs increasingly emphasize data, auditability, and basin-level collaboration. A buyer that discloses verified water productiv-

ity, recycling investment, wastewater treatment compliance, and supplier engagement may be a more credible recipient of additional water than a buyer that offers only price.

The result also contributes to the theoretical debate over whether water markets favor only economically powerful actors. In the present model, market success does not depend simply on willingness to pay. It depends on perceptions of responsible efficiency and on rules that permit those perceptions to influence behavior. If trading eligibility were linked to environmental and social performance (for example through minimum water reuse benchmarks, pollution-control compliance, or public-interest screening) then corporate-oriented water trading could channel water toward users who generate broader value rather than merely higher cash bids. This is one of the most important ways in which the model departs from a narrow privatization narrative and aligns more closely with CSR and environmental management concerns.

6.3. Transaction Costs and Market Maturation

Figure 7 and Table 5 illustrate how transaction costs influence the outcomes under an information setting that favors trading. Specifically, they show how variations in transaction costs affect the willingness and ability of participants to engage in trade, thereby shaping the overall efficiency and effectiveness of the trading process. The model compares four cost scenarios: a high-friction case $(C_R = 10,\ C_S = 12)$, a moderately high case $(8, 10)$, the baseline case $(6, 8)$, and a low-friction case $(4, 6)$. The results are clear and consistent. As transaction costs decline, the time required to reach the Trade–Trade equilibrium also decreases. Under the conservative initial condition, convergence falls from about 7.42 periods in the high-friction scenario to 5.82 periods in the low-friction scenario. This difference is substantively important. From an institutional perspective, it indicates that even when trade is welfare improving in principle, procedural complexity can slow or even discourage its realization. In other words, the existence of mutual gains is not sufficient by itself. When search, negotiation, verification, and approval processes remain costly or cumbersome, actors may take much longer to coordinate, thereby weakening the practical effectiveness of the trading mechanism.

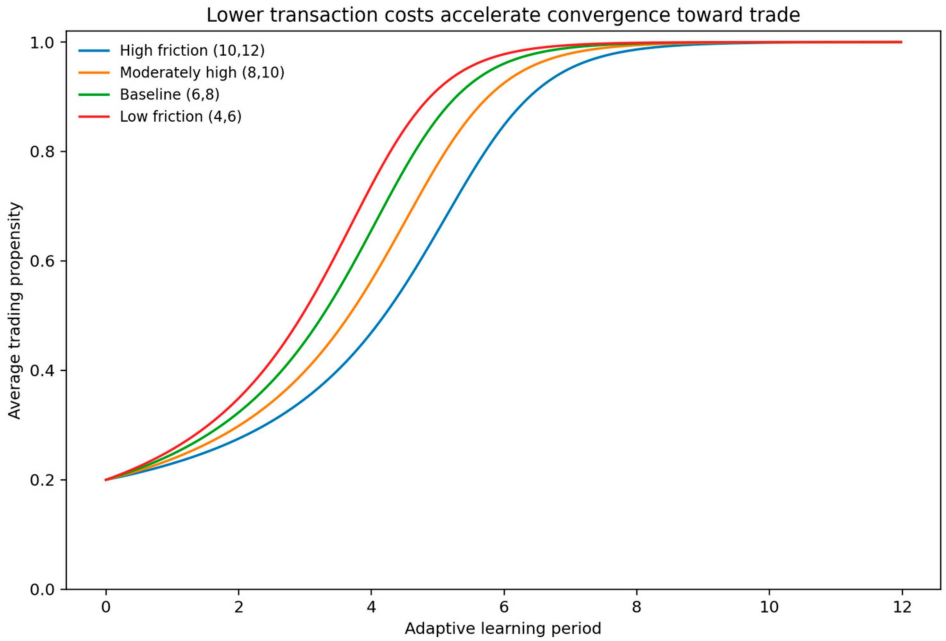


Figure 7. Lower transaction costs accelerate convergence toward a Trade–Trade equilibrium.

Table 5. Sensitivity summary for transaction costs, basic water price, and sunk-fee loss risk.

Scenario Group	Parameter Setting	Convergence Period	Interpretation
High friction	$(C_R = 10, C_S = 12)$	7.42	Slowest convergence; highest procedural burden
Baseline	$(C_R = 6, C_S = 8)$	6.24	Moderate convergence under existing institutional friction
Low friction	$(C_R = 4, C_S = 6)$	5.82	Fastest convergence under cost reduction
Higher basic price	b = 0.18	6.66	Surplus holders more reluctant to release quota
Lower basic price	b = 0.03	5.98	Faster release of quota into the secondary market
Lower loss-risk pressure	λ = 0.30	6.82	Idle quota remains relatively tolerable
Higher loss-risk pressure	λ = 0.90	5.98	Unused quota becomes more costly to hold

This finding is consistent with the broader literature on market design in environmental governance. Water markets often operate in settings where legal review, hydrological verification, approval procedures, metering requirements, price negotiation, and inter-agency coordination generate substantial overhead. In diversion systems, these frictions may be amplified by infrastructure scheduling, public-interest review, and cross-jurisdictional oversight. From a corporate-oriented supply chain perspective, such delays can be costly because water shortages can interrupt production, reduce procurement reliability, and weaken the credibility of sustainability commitments. A manufacturer facing uncertain water availability may delay investment, hold excessive inventory, or shift sourcing in ways that create additional environmental burden elsewhere.

The model suggests that, under friction conditions comparable to the calibrated scenarios, institutional intermediation such as standardized contracts, digital platforms, and clearer verification procedures would likely accelerate coordination. This should be interpreted as a conditional comparative-static implication rather than a transaction-specific forecast. Specialized "water rights storage and transfer centers," digital trading platforms, standardized contracts, approved valuation methods, and shared measurement protocols can all reduce the effective cost of exchange. These mechanisms do not eliminate the need for regulation; rather, they make regulation operationally usable. A well-designed platform can lower search and bargaining expenses, reduce information asymmetry, speed up due diligence, and create a clearer record of compliance. For CSR and environmental management, this is important because firms are more likely to integrate water trading into sustainability strategies when the process is predictable and auditable.

There is also an important equity dimension. High transaction costs tend to favor actors with greater administrative capacity, legal sophistication, or political access. By lowering these costs through standardized institutional infrastructure, regulators can improve participation for smaller utilities, medium-sized firms, or less politically connected regions. In this sense, transaction-cost reduction is not merely an efficiency reform; it is also a fairness reform. A corporate-oriented trading regime that remains too cumbersome could unintentionally exclude the very actors whose responsible water use should be encouraged.

6.4. Basic Water Price and the Incentives of Surplus Holders

Figure 8 reports sensitivity to the basic water price in the primary market. Holding other parameters constant and using the same favorable information setting, the model compares b values from 0.18 yuan/m^3 down to 0.03 yuan/m^3. The direction of the effect is again consistent: lower basic water prices lead to faster convergence toward trading, with the model's convergence time dropping from roughly 7.02 periods at the higher end to around 5.64 periods at the lower end under the conservative starting condition. Although

the numeric differences are moderate, the conceptual effect is important because the basic water price links primary-market design to secondary-market behavior.

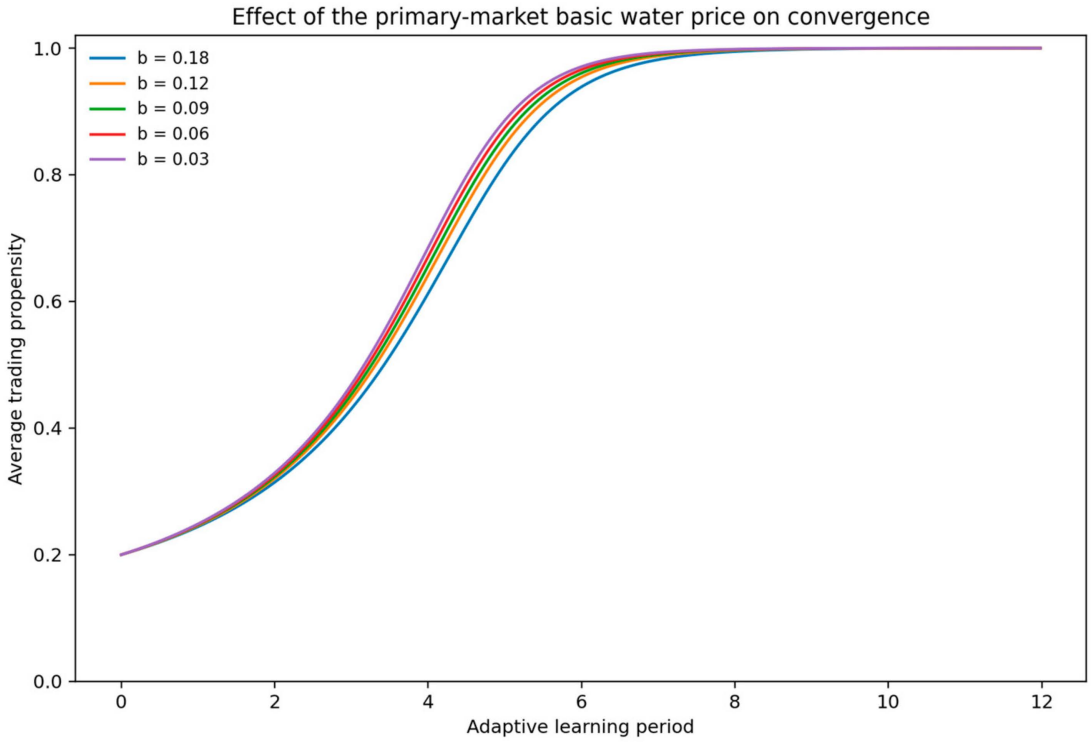


Figure 8. Lower primary-market basic water prices speed convergence toward trading. Note: In the image b = price.

A higher basic water price increases the sunk-cost burden attached to initially allocated quota. If the surplus holder has already paid a substantial base charge, it may become more protective of its entitlement, especially when future demand is uncertain. Under such circumstances, even unused quota can acquire option value: the holder may prefer to keep it as a hedge against future growth rather than risk releasing it. A lower basic price reduces the psychological and financial weight of this sunk-cost burden and therefore weakens the motive to hoard. In the model, this helps the surplus node move more readily toward trading.

From a policy perspective, the result suggests that sustainability-oriented water governance cannot ignore how primary-market pricing affects secondary flexibility. An administratively allocated quota system with overly rigid or excessively high basic charges may unintentionally suppress efficient reallocation even when a secondary market exists. For institutional settings resembling the middle-route price structure used in the calibration, the model indicates that lower basic-charge burdens would tend to improve sellers' willingness to release surplus quota. If the basic price is set solely for revenue recovery without regard to reallocation incentives, then the system may achieve financial balance at the cost of allocative inefficiency.

The CSR relevance of this result lies in institutional alignment. Firms and utilities cannot be expected to behave as collaborative stewards if the pricing system rewards defensive retention of unused resources. A more coherent governance architecture would set the basic charge at a level that supports system financing while preserving incentives for socially desirable transfers. Such alignment is especially important where water-intensive industries are expected to meet ESG goals. If the primary allocation regime discourages

secondary adaptation, then firms may invest heavily in plant-level efficiency yet remain trapped in a regionally inefficient water system.

6.5. Loss-Risk Coefficient and the Behavioral Economics of Quota Release

Figure 9 examines the loss-risk coefficient λ, which captures the extent to which the surplus node perceives unrecovered basic water fees as a meaningful loss if quota remains unused. Increasing λ from 0.30 to 0.90 accelerates convergence toward trade. Under the conservative initial condition, convergence declines from approximately 7.64 periods at λ = 0.30 to 5.64 periods at λ = 0.90. This effect reflects a behavioral mechanism that is rarely discussed in the CSR literature but highly relevant in practice: actors often respond not only to expected gains from exchange but also to the salience of losses associated with inactivity.

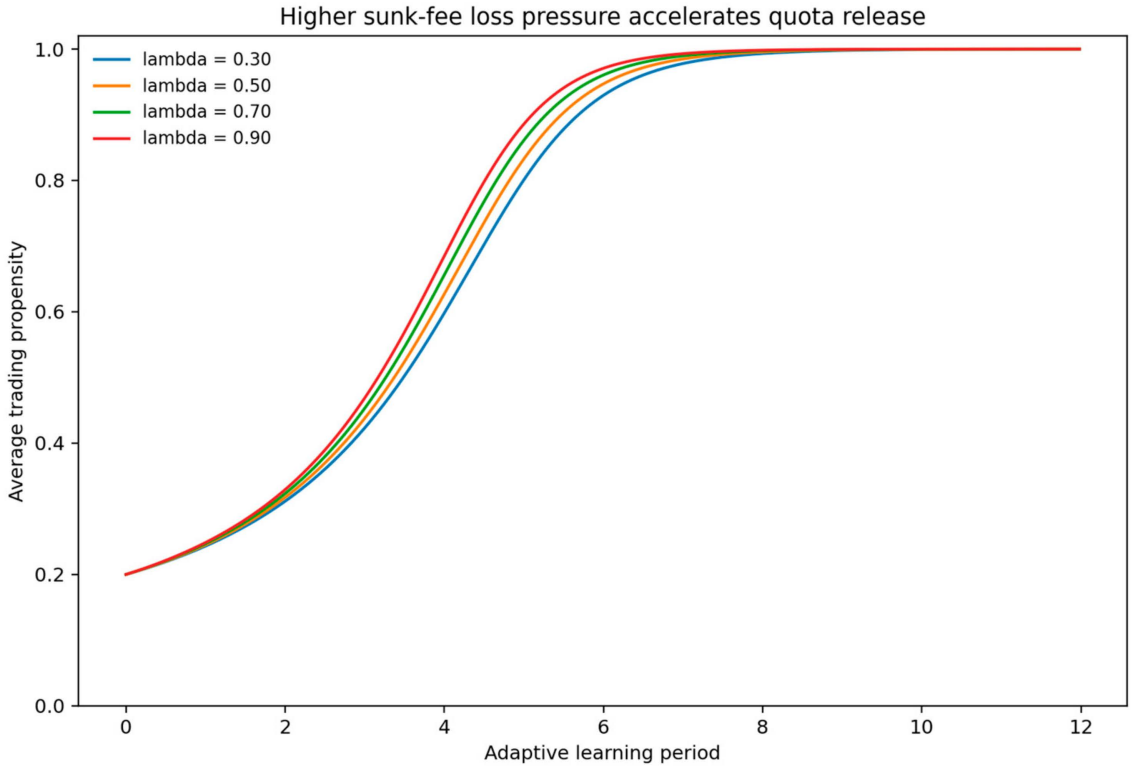


Figure 9. Higher loss-risk pressure associated with sunk basic fees accelerates quota release. Note: In the image lambda = λ.

In the context of the SNWDP and similar systems, a surplus holder may tolerate unused quota for some time if the perceived cost of holding it is low. However, as unrecovered fixed charges become more salient, the holder is increasingly motivated to monetize or otherwise deploy the quota. In the model, higher λ strengthens this motivation and pushes the surplus node toward trading. This mechanism is important because it highlights how accounting and pricing conventions shape stewardship behavior. A system that treats idle quota as relatively costless is more likely to induce hoarding; a system that makes the cost of idle quota visible may encourage circulation.

For environmental management, the implication is subtle but significant. Idle quota is not environmentally benign merely because it is not currently abstracted. In a large diversion project, underused allocations can represent foregone social value, stranded infrastructure capacity, and delayed support for higher productivity or more sustainable users elsewhere in the system. Making the opportunity cost of idleness more visible can therefore support better overall resource governance. At the same time, the design of such

incentives must remain bounded by social protections. Higher loss pressure should not coerce actors into releasing quota needed for basic domestic supply, ecological security, or legitimate future planning. Instead, it should discourage the purely strategic retention of clearly surplus water.

This result also resonates with behavioral approaches to sustainability management. Organizations do not always respond proportionally to objective efficiency gains; they often react more strongly to framed losses than to equivalent gains. Policy instruments that recognize this asymmetry may be more effective than purely informational interventions. In practical terms, regulators could signal carrying costs more explicitly, create time-bound review mechanisms for persistent quota underuse, or provide structured options for temporary leasing rather than permanent surrender. Such mechanisms would preserve flexibility while reducing the incentive to keep socially valuable water dormant.

6.6. Integrating the Results into CSR and Environmental Management Theory

The simulation findings reinforce three broader theoretical claims. First, market-oriented water rights trading can be compatible with CSR and environmental management when it is designed as a performance-sensitive governance mechanism rather than a purely price-driven exchange. The model repeatedly shows that who uses water matters. Trading is most stable when the receiving node is believed to be efficient and responsible in its use of additional water. This supports a stewardship interpretation of markets in which institutional design channels water toward users who combine higher productivity with better environmental management.

Second, transparency emerges as a central governance capability. The results on rho and sigma show that information asymmetry can block welfare-improving exchange even when prices and quantities appear favorable. This implies that disclosure, auditing, and digital traceability are not peripheral to sustainable water governance; they are core conditions for market functionality. In supply chain terms, credible information about water-use efficiency, reuse rates, wastewater treatment performance, and resilience planning can increase trading eligibility and improve system-wide allocation. This complements the SSCM literature, which has long argued that sustainable performance depends on the quality of inter-organizational information.

Third, the study suggests that public infrastructure governance and corporate sustainability strategy are interdependent. Diversion systems such as the SNWDP are often understood as state-led engineering projects, while CSR is treated as a firm-level management agenda. The present analysis shows that the two domains cannot be separated cleanly. Public rules governing quota ownership, pricing, and transferability influence the ability of firms and utilities to meet sustainability commitments. Conversely, the environmental performance of firms influences whether secondary reallocation is socially desirable. A corporate-oriented water rights system is therefore not a retreat of the state; it is a more sophisticated state–market–corporate arrangement in which public rules enable adaptive, accountable reallocation.

These conclusions align with the broader movement in environmental management toward systems thinking. Water security cannot be delivered by infrastructure alone, by market mechanisms alone, or by firm-level stewardship alone. It requires the combination of all three: physical supply, institutional flexibility, and organizational responsibility. The present model offers a tractable way to analyze that combination and to show why some reforms succeed while others stall.

7. Findings

The first major finding is that sustainable water supply chain management under a diversion project depends on more than the existence of tradable water rights. What determines whether trading emerges is the interaction between efficiency perceptions and institutional incentives. The model shows that a Trade–Trade equilibrium becomes stable only when the deficit node is perceived as likely to use additional water more productively and responsibly than the surplus node would use the same water if retained. This indicates that a water rights market suitable for CSR and environmental management cannot be blind to qualitative differences among users. In practice, efficient and responsible water use must be visible, measurable, and institutionally recognized if trading is to direct water toward socially desirable applications.

The second finding is that information asymmetry is not a marginal friction but a decisive determinant of market viability. When the surplus node does not believe the deficit node is a high-efficiency user, trading collapses even when the physical need for water is obvious. When the deficit node believes the surplus node has high opportunity cost from retaining water, it assumes that agreement is unlikely and becomes less willing to pursue exchange. These results help explain why some pilot trading arrangements remain symbolic or intermittent. Without reliable information architecture (such as third-party efficiency verification, transparent baselines, standardized disclosure, and credible market records) actors may never coordinate on the welfare-improving equilibrium. From a CSR perspective, this finding implies that disclosure quality and accountability structures can have direct allocative consequences.

The third finding is that transaction costs remain a foundational barrier, even under favorable information conditions. Lower transaction costs consistently speed convergence toward trade in the model. This supports earlier market-design research while adding a supply chain interpretation: costly procedures slow not only the exchange itself but also the capacity of firms, utilities, and industrial clusters to respond to water stress in real time. Standardized platforms, pre-approved contracts, digital verification systems, and intermediary institutions should therefore be seen as sustainability infrastructure, not mere administrative conveniences. In particular, they can help smaller actors participate on fairer terms and can reduce the risk that only the most administratively powerful organizations benefit from secondary allocation.

The fourth finding is that the architecture of the primary allocation market influences behavior in the secondary market. Lower basic water prices encourage trade by reducing the burden of sunk allocation charges, while higher loss-risk exposure associated with idle quota increases the incentive for surplus holders to release water rather than hoard it. This finding is theoretically significant because it links the economics of primary allocation to the dynamics of secondary reallocation. It suggests that policy reforms aimed at improving water markets cannot focus narrowly on trading procedures alone; they must also examine how basic pricing, carrying costs, and fee recovery shape incentives. For environmental managers, the implication is that market inefficiency may originate upstream in pricing design rather than downstream in negotiation failure.

The fifth finding is normative. The study indicates that market-oriented water rights trading can be aligned with CSR and environmental management, but only if it is bounded by strong public-interest safeguards. The model assumes that emergency allocations, basic domestic needs, and ecological requirements are protected before trading occurs. It also interprets high water-use efficiency as compatible with lower waste and stronger environmental performance, not simply higher private revenue. Consequently, the article does not support an unrestricted commodification of water. Instead, it supports a bounded market logic in which public authorities define the non-negotiable floor of social and

ecological protection, while secondary exchange allows water to move adaptively among eligible users who satisfy responsibility criteria.

8. Conclusions

This research set out to answer a question that sits at the intersection of environmental governance and corporate sustainability: how can a large, administratively allocated diversion system create enough institutional flexibility to move water toward more responsible and productive uses when real demand changes over time? Building on the analysis of quota imbalance under the South-to-North Water Diversion Project, the study argued that sustainable water supply chain management requires more than engineering capacity and more than firm-level water stewardship. It requires a secondary allocation mechanism capable of redistributing water adaptively among eligible users while preserving public-interest safeguards. To capture that mechanism, the article introduced the idea of corporate-oriented water rights trading and developed an evolutionary game model between a surplus supply chain node and a deficit demand node.

The analysis produced a clear conclusion. Market-based secondary trading can improve the sustainability performance of a diversion system, but only under specific institutional and informational conditions. The socially desirable Trade–Trade equilibrium becomes most likely when the deficit node is perceived as a high-efficiency, responsible user of additional water and when the surplus node is perceived as having relatively low opportunity cost from retaining unused quota. Lower transaction costs, lower basic water prices, and higher salience of sunk-fee loss all strengthen the incentive to trade. In contrast, opaque information, high friction, and poorly aligned pricing rules encourage inertia and quota hoarding. In short, water rights trading is not self-executing. It becomes a sustainability instrument only when the governance environment rewards transparency, credible efficiency, and adaptive cooperation.

The research therefore contributes to a more nuanced understanding of market mechanisms in environmental management. It neither rejects administrative allocation nor romanticizes marketization. Instead, it shows that primary administrative allocation and secondary-market correction should be viewed as complementary layers of governance. Public authorities remain essential in defining rights, protecting ecological and domestic minimums, and supervising legitimacy. At the same time, secondary exchange can create the flexibility needed to align water allocation with changing production patterns, urban growth, and corporate sustainability performance. This conclusion is especially relevant in an era when companies are expected to manage not only cost and compliance but also resilience, disclosure quality, and shared resource stewardship.

9. Theoretical and Practical Implications

The practical implications are conditional rather than predictive. The model does not estimate the exact response of any specific Chinese transaction. Instead, it identifies directional institutional sensitivities: lower procedural frictions, more credible efficiency information, and pricing rules that reduce defensive quota retention are more likely to support trade when local conditions resemble the calibrated parameter ranges.

From a theoretical perspective, the study offers three implications. First, it extends CSR theory by showing that responsible water management must include allocative institutions, not only internal operational targets. A company may report admirable water-efficiency improvements, yet those improvements remain systemically constrained if regional water governance cannot move water toward higher social and environmental value uses. Second, it extends sustainable supply chain management by treating water rights trading as part of supply chain governance rather than as an external public-policy actor. Third, it

contributes to water rights scholarship by demonstrating that evolutionary game models can incorporate responsibility-oriented efficiency perceptions and thus better reflect the behavioral conditions under which sustainable markets emerge.

The practical implications are equally direct. Regulators and basin authorities should build transparent trading platforms that lower procedural cost, publish standardized efficiency indicators, and require verified disclosure from participants. Water-rich quota holders should be given structured mechanisms (temporary leases, exchange windows, storage and transfer centers, or performance-based release rules) that reduce the incentive to sit on surplus quota indefinitely. Water-scarce corporate users and utilities should improve water productivity, wastewater treatment, and data transparency, because these factors increase the credibility needed to attract willing sellers. Corporate sustainability managers should treat water governance engagement as part of supply chain risk management: participation in basin platforms, collaboration with utilities, and investment in monitoring systems can all become strategic capabilities rather than peripheral CSR activities.

An especially important implication concerns the design of eligibility and safeguards. If water rights trading is to support CSR and environmental management objectives, regulators should avoid designing the system as a purely price-based auction. Eligibility can instead be conditioned on environmental compliance, minimum reuse rates, leakage reduction performance, sectoral importance, or demonstrated social value. Such criteria would help ensure that water moves toward users who are not only willing to pay but also able to deploy the resource responsibly. This is the essence of the "corporate-oriented" approach developed in the article.

10. Research Limitation

Notwithstanding its contributions, this study has several limitations that should be interpreted not merely as boundary conditions, but as factors that may influence the robustness, transferability, and policy relevance of the findings. First, the model adopts a two-player representation of a much more complex water governance system. Although this simplification is useful for isolating the behavioral logic of water rights trading, it may overstate the clarity and stability of strategic interaction by excluding coalition formation, multi-buyer competition, sequential bargaining, and network spillovers across interconnected supply chains. As a result, the equilibrium outcomes identified here should be understood as stylized rather than system-wide predictions. Future research should test the robustness of these results in multi-agent settings and through sensitivity analysis that varies the number and types of actors involved.

Second, the trading price is treated as exogenous. This assumption improves analytical tractability, but it limits the model's capacity to reflect real-world price formation, which is often shaped by bargaining power, regulatory intervention, scarcity shocks, and institutional design. The omission of endogenous pricing may therefore understate volatility in trade incentives and overstate the predictability of agreement formation. A formal sensitivity analysis of price-related parameters would help clarify how strongly the model's equilibrium depends on this assumption.

Third, the study relies on illustrative rather than econometrically estimated parameter values. While these values are grounded in the Zhengzhou–Nanyang case and reflect plausible institutional and efficiency conditions, they are not derived from proprietary transaction-level data. This limits the model's predictive precision and means that the simulation results should be interpreted primarily as analytical demonstrations of causal mechanisms. Sensitivity analysis would be especially valuable here, as it could show whether the main conclusions remain stable under alternative parameter ranges.

Fourth, the model uses a composite interpretation of water-use value that combines economic, environmental, and responsibility-related considerations. Although this approach is conceptually aligned with CSR and environmental management, it may obscure trade-offs among productivity, ecological performance, and social benefit. Consequently, the model may simplify tensions that are highly relevant in practice. Future studies should disaggregate these dimensions and examine whether different weighting structures alter strategic behavior and equilibrium outcomes.

Fifth, institutional heterogeneity remains a significant limitation. The governance conditions of the SNWDP differ from those of other inter-basin transfer projects and water rights systems in terms of legal enforceability, metering capacity, environmental monitoring, public participation, and property rights traditions. This means that the framework is transferable only in principle, not automatically in practice. A SWOT-type comparative assessment could help evaluate the practical feasibility of applying the model across different governance settings by identifying institutional strengths, weaknesses, opportunities, and threats.

Taken together, these limitations indicate that the present findings offer a theoretically informed and policy-relevant framework, but not a universally generalizable solution. Their main value lies in clarifying the conditions under which corporate-oriented water rights trading may support adaptive and sustainable water governance, while also highlighting the need for further robustness testing and comparative institutional evaluation.

11. Future Research Implication

Several directions for future research follow from the present analysis. The first is model expansion. Multi-agent evolutionary games could include regulators, utilities, industrial parks, community representatives, and ecological actors in order to capture coalition formation and conflict among more than two parties. Such models would be especially useful in regions where multiple cities or sectors compete simultaneously for reallocated water. The second direction is endogenizing price. Incorporating bargaining, auction design, or dynamic price adjustment would enable researchers to study how price interacts with information asymmetry and responsibility criteria over time. The third direction is empirical measurement. Future work should move from illustrative calibration to econometric estimation using transaction data, metering records, and corporate water-performance disclosures.

A fourth direction is to differentiate the components of responsible water use more explicitly. The current model aggregates economic productivity, environmental performance, and broader social value into a composite efficiency term. Future research could instead develop a multi-criteria payoff structure in which output value, pollution intensity, recycling rate, and community benefit are modeled separately. This would allow scholars to examine whether certain institutional settings favor economically efficient but environmentally weak users, and how policy design can correct such tendencies. A fifth direction is technological. Digital twins, blockchain-based registries, smart metering, remote sensing, and basin-scale data platforms could radically reduce information asymmetry and transaction costs. Research is needed to determine how these technologies alter equilibrium behavior and whether they improve trust sufficiently to enlarge the basin of attraction for sustainable trading.

A sixth direction concerns comparative governance. The SNWDP provides a compelling empirical anchor, but the conceptual framework may also be relevant to other inter-basin transfers, river basin compacts, drought-sharing arrangements, and urban–industrial water systems. Cross-country comparison would help identify which elements of the model are universal and which depend on legal traditions, state capacity, or market maturity.

Finally, future research should investigate the relationship between corporate-oriented water trading and broader ESG outcomes. Does access to a transparent secondary water market improve corporate resilience, reduce supply disruptions, or strengthen investor confidence? Does it encourage deeper collaboration between firms and local governments on basin restoration and circular water use? These questions would connect water rights research even more directly to mainstream management and sustainability scholarship.

Overall, the article argues that sustainable water supply chain management requires an institutional imagination equal to the scale of contemporary water stress. Infrastructure delivers water, but governance determines whether that water creates the greatest social and environmental value. Corporate-oriented water rights trading, when carefully bounded and transparently managed, offers one promising path toward that objective.

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Abbreviations

The following abbreviations are used in this manuscript:

CSR	Corporate Social Responsibility
ESG	Environmental, Social, and Governance
SSCM	Sustainable Supply Chain Management
SNWDP	South-to-North Water Diversion Project
CDP	Carbon Disclosure Project
PPP	Public–Private Partnership
DEA	Data Envelopment Analysis
TWAIL	Third World Approaches to International Law
NGO	Non-Governmental Organization

Appendix A

Algorithm A1 Numerical simulation procedure for the corporate-oriented evolutionary game of water rights trading

Input:
Baseline parameters $Q, p, b, C_R, C_S, \lambda, v_R^H, v_R^L, v_S^H, v_S^L$;
belief parameters ρ and σ;
initial strategy proportions x_0 and y_0;
step size h; maximum number of iterations N; convergence tolerance ε.
Output:
Final strategy proportions (x^*, y^*), equilibrium outcome, and convergence period.

1. Set the baseline parameters according to Table 2:
   $Q = 200,\ p = 0.87,\ b = 0.09,\ C_R = 6,\ C_S = 8,\ \lambda = 0.70,$
   $v_R^H = 0.65,\ v_R^L = 0.20,\ v_S^H = 1.10,$ and $v_S^L = 0.35$
2. Select one information-asymmetry scenario for the two belief parameters, where $\rho, \sigma \in \{0.1, 0.5, 0.9\}$ Here ρ is the probability assigned by the deficit node that the surplus node is in the high-efficiency state, and σ is the probability assigned by the surplus node that the deficit node is in the high-efficiency state.
3. Compute the expected marginal values of water for the two nodes:

$$\bar{v}_R = \rho v_R^H + (1-\rho) v_R^L,$$
$$\bar{v}_S = \sigma v_S^H + (1-\sigma) v_S^L.$$

These correspond to the expected water-use values defined in Equations (1) and (2).

4. Substitute $\bar{v}_R$ and $\bar{v}_S$ into the payoff functions of the surplus node and deficit node, as given in Equations (3)–(8), and derive the payoff-difference terms for the two players using Equations (11) and (15).
5. Initialize the trading propensities of the two nodes:

$$x_0 = 0.50, y_0 = 0.50,$$

unless an alternative initial condition is specified for sensitivity analysis. This matches the research assumption that both nodes begin with moderate willingness to trade.

6. To enhance methodological transparency and reproducibility, the numerical controls adopted in the simulation should be reported explicitly. A reproducible implementation may, for instance, use h = 0.01, N = 10,000, and ε = 10^{-6}. Stating these values directly is important because the current draft refers only to a discrete-time approximation with a modest learning rate, without specifying the exact numerical settings employed. Providing these details would strengthen the rigor of the study and facilitate more reliable replication of the simulation procedure.
7. For each iteration t = 0, 1, 2,. . ., $N - 1$, update the strategy proportion of the surplus node using the replicator dynamic equation:

$$x_{t+1} = x_t + h \cdot x_t(1 - x_t)\Delta_R(y_t),$$

where $\Delta_R(y_t)$ is the payoff advantage of Trade over No Trade for the surplus node. This step operationalizes Equation (12).

Algorithm A1 *Cont.*

8. Update the strategy proportion of the deficit node using the replicator dynamic equation:

$$y_{t+1} = y_t + h \cdot y_t(1 - y_t)\Delta_S(x_t),$$

where $\Delta_S(x_t)$ is the payoff advantage of Trade over No Trade for the deficit node. This step operationalizes Equation (16).

9. Impose feasibility constraints to keep both strategy proportions within the interval [0, 1]. If $x_{t+1} < 0$, set $x_{t+1} = 0$; if $x_{t+1} > 1$, set $x_{t+1} = 1$. Apply the same rule to y_{t+1}. This preserves the interpretation of x and y as probabilities.
10. Check the convergence condition after each update. If

$$\max(|\, x_{t+1} - x_t \,|, |\, y_{t+1} - y_t \,|) < \varepsilon$$

for a fixed number of consecutive iterations, stop the simulation and record the stopping time. This stopping time defines the convergence period.

11. Classify the equilibrium outcome according to the final values of (x,y):
    - if $x^* \to 1$ and $y^* \to 1$, classify the outcome as Trade–Trade;
    - if $x^* \to 0$ and $y^* \to 0$, classify the outcome as No Trade–No Trade;
    - otherwise, classify the result as an interior or mixed adjustment state.

This corresponds to the equilibrium logic discussed in Sections 5.5 and 6.1.

12. Repeat Steps 2–11 for all nine combinations of (ρ, σ) to generate the scenario outcomes reported in Table 4 and Figure 4. Then vary C_R, C_S, b and λ over the ranges described in Section 5.7 to perform the sensitivity analyses reported in Sections 6.3–6.5.
13. Store the final values of x and y, the equilibrium classification, and the convergence period for each scenario, and use these outputs to construct the tables and figures in the Section 6

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