Water Economics and Policy, Vol. 11, No. 3 (2025) 2530003 (57 pages)

DOI: 10.1142/S2382624X25300038

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Recent Advances in Water-Related Policies and their Performance in China: Effectiveness, Efficiency and Welfare Distribution

Jinxia Wang*, Ruoying Mei and Wei Chao

China Center for Agricultural Policy
School of Advanced Agricultural Sciences
Peking University, Beijing, P. R. China
**jxwang.ccap@pku.edu.cn*

Received 28 August 2025
Accepted 29 August 2025
Published 25 September 2025

As China confronts intensifying water scarcity, pollution and regional disparities, it has implemented a series of advanced and often experimental water-related policies. This article provides a comprehensive review and critical synthesis of these policies by drawing upon an extensive body of existing empirical literature. Anchored in the triadic evaluative framework of effectiveness, efficiency and welfare distribution, the paper assesses major national strategies — including the Strictest Water Resources Management Policy, water pricing and rights reforms, agricultural water-saving initiatives, groundwater overdraft control, the South–North Water Diversion Project and pollution mitigation mechanisms such as the River Chief System and interprovincial ecological compensation. By systematically compiling and analyzing empirical findings from both quantitative and qualitative studies, the review highlights policy impacts, regional variations in implementation and emerging trade-offs such as rebound effects and equity concerns. The study further situates China's experience within broader theoretical frameworks in water economics and public policy, revealing a distinct hybrid governance model that integrates command-and-control regulation with market-based instruments. This review not only consolidates existing knowledge but also identifies gaps for future inquiry, offering conceptual and practical insights for other countries navigating the complexities of integrated and equitable water resource governance.

Keywords: Advanced water-related policies; performance; effectiveness; efficiency; welfare distribution; China.

*Corresponding author.

1. Introduction

Water scarcity, spatial misalignment and pollution have long characterized China's water crisis. Although the country possesses the sixth largest volume of freshwater resources globally, per capita availability is only one-fourth of the world average (Piao *et al.* 2010; Liu and Yang 2012; Ma *et al.* 2020; MWR 2023). The problem is further compounded by extreme regional disparities: northern China supports more than 60% of agricultural output, yet holds less than 23% of national water resources (MWR 2023; NBSC 2024). These imbalances have resulted in widespread overexploitation of aquifers, ecological degradation and intensifying water stress in major grain-producing and industrial centers. Simultaneously, rapid urbanization and industrial expansion have driven alarming levels of water pollution. By 2024, among 210 major lakes and reservoirs, those with poor water quality accounted for 22.9%; 22.1% of groundwater monitoring points were classified as having poor water quality (MEE 2024).

In response, China has launched a suite of far-reaching and often pioneering water-related policy reforms. These include the Strictest Water Resources Management Policy (SWRMP), water pricing reforms differentiated by sector, pilot programs for tradable water rights, comprehensive control of groundwater overdraft, promotion of water-saving technologies, the South–North Water Diversion Project (SNWDP), the River and Lake Chief System (RLCS), Water Pollution Prevention and Control Action Plan (WPPCAP) and Interprovincial Ecological Compensation Mechanisms (Wu *et al.* 2015; Wang *et al.* 2017; Li *et al.* 2021a; Deng *et al.* 2021; Liu *et al.* 2023a; Huang *et al.* 2025). Together, these policies reflect an evolving governance paradigm that combines command-and-control regulation, economic incentives and technological modernization. This hybrid approach — balancing administrative authority with market-based instruments — has positioned China as a critical testbed for integrated water policy innovation in developing economies.

Despite the extensive rollout of water-related reforms in China, a comprehensive synthesis of their policy performance remains limited in the academic literature. Existing studies have primarily focused on individual instruments — such as pricing mechanisms, rights trading or pollution control — often within narrowly defined case contexts (Calow *et al.* 2010; Zhang and Oki 2023; Li *et al.* 2021a; Feng *et al.* 2025). As a result, there is a lack of integrative reviews that systematically compare outcomes across policy types and spatial scales, particularly from the perspective of interdependent policy goals. In recent years, water economics literature has increasingly emphasized the need to evaluate water policies through a triad of effectiveness (goal attainment), efficiency (optimal allocation) and welfare distribution (equitable allocation) (Roa Garcia 2014; Hu *et al.* 2016; Wichman 2024). While this evaluative lens is well-established internationally, its application to China's rapidly evolving policy landscape has yet to be comprehensively explored. This is particularly important as China shifts toward sustainability-oriented governance, facing complex challenges related to climate adaptation, rural-urban disparities and institutional fragmentation (Whyte 2010; Ng and Ren 2018). Addressing this gap, this review draws upon a wide range of empirical studies to assess China's advanced water policies through an integrated and multidimensional framework, aiming to consolidate fragmented findings and identify cross-cutting patterns, lessons and implications.

To address this gap, this review offers a theory-informed and empirically grounded synthesis of China's most recent advanced water-related policies. Drawing upon established frameworks in water economics — including resource allocation theory, environmental externality correction and welfare distribution principles — this paper evaluates policy performance across key domains such as quantity control, demand management, technological adoption and pollution governance. By organizing the analysis around three interrelated dimensions — effectiveness, efficiency and welfare distribution — we seek to move beyond fragmented or policy-specific assessments, and instead develop a holistic understanding of how China's water governance functions as an integrated system. In doing so, we incorporate evidence from a wide array of empirical studies — spanning national-level strategies and subnational pilot programs — to reveal spatial, institutional and sectoral heterogeneity in policy outcomes and implementation dynamics.

The contributions of this review are threefold. First, it constructs a structured mapping of China's water policy tools against classical and contemporary economic theories, enabling a clearer linkage between policy practice and academic discourse. Second, it systematically consolidates a growing body of empirical findings — including econometric analyses, case studies and policy evaluations — on the effectiveness, efficiency and welfare distribution of major reforms such as water pricing, rights trading, irrigation technologies and pollution mitigation mechanisms. Third, the review identifies cross-cutting lessons and implementation challenges embedded in China's hybrid governance model — for instance, efficiency-equity trade-offs in pricing schemes, rebound effects from technology-led conservation and institutional constraints in interregional coordination initiatives. These synthesized insights offer not only a more coherent picture of China's water policy landscape, but also practical implications for policy refinement.

More broadly, the Chinese case illustrates both the opportunities and limitations of integrated water governance in contexts characterized by rapid socio-economic transformation, regional disparity and institutional complexity. The findings of this review hold relevance for other developing countries navigating similar challenges of resource scarcity, ecological stress and policy fragmentation. By critically reflecting on China's experience, this paper aims to contribute to international dialogue on adaptive and evidence-based water policy design, and to support more resilient, efficient and equitable approaches to water management in the Global South and beyond.

The remainder of this paper is structured as follows. Section 2 introduces the theoretical foundations underpinning the analysis, including key concepts from water economics related to policy effectiveness, efficiency and welfare distribution. Section 3 provides an overview of China's major advanced water-related policy initiatives, with a focus on institutional design and implementation mechanisms across multiple domains. Section 4 evaluates the performance of these policies based on empirical evidence from recent literature, systematically analyzing their outcomes along the three evaluative dimensions. Section 5 concludes by summarizing key findings, highlighting policy implications and outlining avenues for future research to advance the understanding and practice of integrated water governance in China and other developing contexts.

2. Theoretical Background

The formulation and assessment of water-related policies are deeply rooted in foundational theories of resource economics and public policy design. Effective water governance requires not only institutional coordination and technical capacity but also a clear understanding of the economic principles underlying resource allocation, externality correction and social equity. In recent decades, water economics has developed a rich set of analytical tools — ranging from market-based pricing models to welfare distribution metrics — to evaluate how policy instruments can balance competing objectives: maximizing efficiency, ensuring equity and sustaining ecological viability. These theoretical perspectives are particularly relevant to the Chinese context, where administrative command mechanisms are increasingly being complemented by economic instruments and decentralized governance models. Against this backdrop, this section outlines the conceptual foundations for analyzing water policy performance, focusing on three interrelated dimensions: effectiveness (the extent to which policies meet their intended objectives), efficiency (the optimal use of water resources with minimal waste) and welfare distribution (the equitable allocation of benefits and burdens across populations and sectors).

2.1. *Overview of economic theories related to water resource management*

Water resource management has been a central concern in resource economics, leading to the development of various economic theories and frameworks aimed at optimizing water allocation and usage. These theories primarily focus on the role of market mechanisms versus command-and-control approaches in achieving efficient and equitable water distribution.

Market-based approaches:
Market-based approaches to water management leverage economic incentives to encourage efficient water use and allocation. These mechanisms include water pricing and tradable water rights, which aim to reflect the true economic value of water and promote its conservation and optimal use. For instance, the concept of tradable water rights allows for the transfer of water usage rights from lower-value to higher-value uses, thereby enhancing overall economic efficiency. However, the implementation of such market mechanisms requires well-defined property rights to prevent over-extraction and ensure equitable access (Rosegrant and Binswanger 1994; Chong and Sunding 2006; Holley and Sinclair 2016). The application of market-based instruments has been widely discussed in economic literature, suggesting that they can improve water resource allocation by encouraging efficient usage and market-driven solutions (Howe *et al.* 1986; Anderson and Leal 1996; Garrick *et al.* 2013; Gómez *et al.* 2018). In practice, market-based instruments have been applied in diverse contexts, such as water markets in Australia's Murray-Darling Basin and Chile, and water banks in the western United States, where they have helped reallocate water more efficiently and respond to scarcity (Zhao *et al.* 2024; Bauer 2004; Seely 2021).

Command-and-control approaches:
In contrast, command-and-control approaches involve direct government intervention to control water usage through measures such as quotas, permits, standards and restrictions. These command-and-control strategies aim to prevent overuse and pollution of water resources. While effective in certain contexts, command-and-control approaches can be inflexible and may not always lead to cost-effective outcomes (Thompson 1999; Olmstead and Stavins 2009). They often face challenges related to enforcement, given their associated high transaction costs, and may not provide enough incentives for users to innovate or reduce consumption beyond the mandated levels. For example, while standards can contribute to restricting pollution levels, they might fail to addressing underlying inefficiencies in water use, leading to suboptimal outcomes in terms of both resource conservation and economic growth (Esty 1999; Graversgaard 2024).

Integration of market and command-and-control approaches:
Recent economic theories advocate for an integrated approach that combines market mechanisms with command-and-control oversight. This hybrid model seeks to harness the efficiency of market-based instruments while ensuring that social and environmental objectives are met (Tu *et al.* 2015; Holley and Sinclair 2016). For example, implementing water pricing mechanisms alongside regulations that set minimum water quality standards can encourage conservation and innovation without compromising public health and environmental integrity. This integrated approach allows for a balance between economic efficiency and the protection of public goods. The challenge lies in designing policies that balance economic efficiency with social equity and environmental sustainability. Studies show that policies blending market incentives and command-and-control oversight can lead to more effective water management solutions, addressing both resource scarcity and pollution control in a sustainable manner (Furlong 2010; Maila *et al.* 2018).

The debate between market-based and command-and-control approaches to water resource management continues to evolve. Economic theories suggest that a nuanced understanding of local contexts, coupled with a combination of market incentives and command-and-control measures, can lead to more effective and sustainable water management practices (Furlong 2010; Maila *et al.* 2018). The integration of these approaches has the potential to not only improve water resource allocation but also promote broader environmental and social sustainability.

2.2. *Key concepts: Effectiveness, efficiency and welfare distribution*

In the realm of water economics, the concepts of effectiveness, efficiency and welfare distribution are fundamental to understanding and evaluating water resource management strategies. These concepts are interrelated and essential for formulating policies that promote sustainable and equitable water use.

Effectiveness:
Effectiveness in water economics refers to the extent to which policies and interventions achieve their intended objectives, including improving water access, quality, reliability and resilience (Araral 2010; Duncan *et al.* 2019). It is a multi-dimensional concept shaped by factors such as institutional capacity, technological innovation and community engagement. The World Bank's Water for Shared Prosperity report (Zhang and Borja-Vega 2024) highlights that effective water management must address pressing challenges like scarcity and quality, particularly for vulnerable populations. Technological advancements — such as smart meters, automated leak detection and remote sensing — are crucial tools that

enhance water systems' effectiveness by reducing waste and improving monitoring and service delivery. However, effectiveness depends not only on ambitious policy design but also on robust implementation and evaluation mechanisms to ensure that interventions produce tangible benefits.

Critically, the effectiveness of water management policies is intertwined with climate resilience and broader goals of sustainability and social equity (Rasul and Chowdhury 2010; Pittock 2011; Khan *et al.* 2024). Climate change, extreme weather events and shifting rainfall patterns necessitate adaptive strategies that enhance the long-term viability of water systems. Yet even well-intentioned projects may falter due to poor implementation, inadequate coordination, or insufficient funding, as seen in some underperforming water supply and sanitation projects. Thus, while effectiveness encompasses achieving immediate goals like improved water quality or expanded access, it must also consider the equitable distribution of resources and long-term socio-economic and environmental impacts (Ziolkowska and Ziolkowski 2016; Tsani *et al.* 2021). Ultimately, policies that are adaptive, inclusive and evidence-based are best positioned to ensure water system sustainability and the equitable sharing of benefits.

Efficiency:
Efficiency in water economics involves the optimal allocation and use of water resources to maximize benefits and minimize waste, encompassing both technical and economic dimensions (Cai *et al.* 2003). Economic efficiency ensures that water is directed to its highest-value uses, equalizing marginal benefits across sectors and improving overall welfare (Dinar 1993; Wichelns 1999; Cai *et al.* 2003). Key tools to promote this include demand-based water allocation and pricing mechanisms that reflect the full costs of provision, thereby encouraging responsible use and reducing waste. However, such pricing structures must be balanced to avoid disproportionate burdens on low-income households. Technical efficiency, meanwhile, addresses minimizing physical water losses in distribution systems — reducing non-revenue water through investments in modern infrastructure and technologies like smart meters and automated controls (Cai *et al.* 2003; Evans and Sadler 2008; Bwambale *et al.* 2022).

Moreover, efficiency in water management is vital for both economic productivity and environmental sustainability. In agriculture — the sector with the highest water consumption — water-saving technologies such as drip irrigation, precision farming and soil moisture monitoring not only enhance yields but also conserve water, preserving vital ecosystems (Hamdy *et al.* 2003; Lakhiar *et al.* 2024). Yet, challenges remain: institutional constraints, limited investments, and regulatory gaps can impede efficiency gains, while the need to balance efficiency with equity and environmental protection adds complexity to policymaking (Brooks and Linton 2013). Achieving long-term water management success thus requires integrating economic and technical efficiency with social equity and ecological sustainability.

Welfare distribution:
Welfare distribution in water economics addresses how the benefits and costs of water use are shared across different social groups, ensuring that water policies are both economically efficient and socially just (Peña 2011). It emphasizes that the poorest and most vulnerable populations must have secure access to water for basic needs and livelihoods. However, water management policies can sometimes disproportionately favor wealthier households if they are not carefully designed. For instance, water pricing strategies can impose regressive burdens on low-income households unless accompanied by subsidies or progressive tariffs (Cardoso and Wichman 2022; Patterson *et al.* 2023). The World Bank's Water for Shared Prosperity report (Zhang and Borja-Vega 2024) reinforces the need to ensure that infrastructure investments also prioritize equitable access in rural and marginalized urban areas, directly tackling persistent disparities.

Beyond immediate equity concerns, welfare distribution is fundamental to the social sustainability of water management policies. If policies overlook the social and economic impacts on vulnerable communities, they risk resistance and policy failure, as seen in various contexts. Intergenerational equity is also a crucial dimension, requiring water management to balance the needs of present and future generations to maintain long-term sustainability (Loucks 2000; Richter *et al.* 2003; Lv *et al.* 2025). Integrating welfare distribution into water policy frameworks thus ensures that interventions not only achieve economic and environmental goals but also foster inclusive and resilient water governance.

3. Progress in Reform of Recent Advanced Water-related Policies in China

China's approach to water governance has undergone a significant transformation in recent decades, evolving from a fragmented, supply-driven system into a more integrated and adaptive policy regime. Responding to mounting challenges such as resource scarcity, uneven spatial distribution and water pollution, the country has implemented a suite of reforms aimed at strengthening institutional control, enhancing efficiency through market-based instruments and promoting ecological sustainability. These efforts have been supported by a maturing legal foundation — including the Water Law and the National Water Resources Master Plan — and are reflected in a diverse range of initiatives, from quota-based management systems and groundwater protection to rights trading, pricing reforms and pollution control strategies. This section reviews the recent progress of China's advanced water-related policies, highlighting their institutional designs, implementation pathways and contributions to reshaping water governance at both national and local levels.

3.1. *The strictest water resources management policy (SWRMP)*

China's SWRMP, introduced in 2012, represents a landmark shift toward institutionalized, target-oriented water governance (Table 1). Issued through the State Council's Opinions on Implementing the Strictest Water Resources Management System, the policy outlines a rigorous and integrated framework for controlling water quantity, improving efficiency and safeguarding aquatic ecosystems. At its core, the SWRMP operationalizes a "three red lines" system, supported by four institutional mechanisms, to comprehensively regulate water withdrawal, utilization and discharge (Wang *et al.* 2018; Zhao *et al.* 2023).

The three red lines define legally binding thresholds for key dimensions of water governance. First, a cap on total water use mandates that national water consumption must not exceed 700 billion cubic meters by 2030. Second, water use efficiency targets require that industrial water use per 10,000 RMB of added value fall below 40 cubic meters, and that the effective utilization coefficient for agricultural irrigation water rise above 0.6. Third, the pollution discharge line stipulates that water quality compliance in functional zones must exceed 95%, and total pollutant loads remain within the environmental carrying capacity. These red lines serve as enforceable constraints, signaling a shift from loosely coordinated objectives to quantified governance commitments.

To support implementation, four institutional pillars have been established: (1) a total water use control system, (2) an efficiency supervision system, (3) a pollutant discharge management system for water function zones and (4) a performance evaluation system linked to administrative responsibility. Together, these mechanisms institutionalize a full-cycle management approach spanning supply-side control, demand regulation and pollution mitigation. By aligning technical standards with policy accountability, the SWRMP promotes a coherent governance model that balances economic development with ecological sustainability.

Innovatively, the policy embeds spatially differentiated targets into provincial performance contracts, creating a vertical integration mechanism between central mandates and local actions. This not only enhances regulatory enforceability but also facilitates adaptive water management tailored to regional hydrological and socio-economic conditions. The SWRMP thus marks a significant departure from previous fragmented efforts, establishing a unified national framework that integrates physical thresholds, institutional capacity and policy accountability into a single governing logic.

From a theoretical standpoint, the SWRMP reflects a predominantly command-and-control regulatory model, wherein quantitative targets, mandatory efficiency thresholds and performance-based assessments serve to internalize externalities associated with water overuse and pollution. As discussed in Sec. 2.1, such top-down mechanisms are effective in situations requiring enforceable constraints and centralized oversight, particularly in contexts of limited market maturity or weak property rights. However, their implementation efficiency often hinges on administrative capacity and enforcement compliance, which may vary across regions. The inclusion of spatially differentiated targets and cross-tier coordination in the SWRMP represents an institutional response to such challenges, aligning with emerging theories of adaptive regulation in environmental governance.

3.2. ***Policies addressing water scarcity***

3.2.1. *Water pricing reforms*

Reforming water pricing has been a central component of China's strategy to address growing water scarcity and to improve the efficiency of water allocation. Since the late 1970s, water price reform has gradually shifted from a cost-recovery paradigm to a demand-side management tool that reflects marginal use values and supports conservation. China's pricing reforms span three major domains — agricultural, domestic and industrial — each governed by distinct institutional and economic considerations.

Agricultural water pricing represents the most complex and politically sensitive arena for reform. Historically, irrigation water was heavily subsidized, with user charges recovering only a fraction of supply costs — estimated at approximately one-third by the early 2000s (Li and Tian 2016; Wang *et al.* 2020b). Early reform efforts focused on cost-based pricing principles, as articulated in the 1985 Water Tariff Formulation and Collection Management Methods (Table 1). However, low agricultural profitability, institutional fragmentation and weak enforcement hindered implementation. A more structured approach, known as the comprehensive price reform, emerged in 2007 with pilot programs launched across 14 districts in eight provinces, subsequently expanded to over 150 counties by 2013. These pilots combined engineering-based interventions (e.g., canal lining, metering) with institutional innovations such as volumetric pricing, subsidy reallocation and participatory water user associations. The 2014 joint directive by four ministries further deepened reform, scaling pilots to 80 counties and over 130,000 hectares (Feng *et al.* 2022). Since 2016, a nationwide roadmap has promoted diversified pricing mechanisms, including two-part tariffs, end-use pricing, progressive block rates, seasonal adjustments and even electricity-based discounts for pumping efficiency (Sun *et al.* 2017; Wang *et al.* 2023a).

Domestic water pricing has evolved from a welfare-based model to one aligned with cost recovery and demand moderation. Following the 1988 Provisional Regulations on Urban Water Conservation, successive regulations mandated universal metering and the shift to per-household billing. By 2001, average residential tariffs rose nearly tenfold — from 0.14 to 1.27 RMB/m^3 — achieving cost recovery in most cities (Shen and Wu 2017). The 2013 directive by the National Development and Reform Commission and Ministry of Housing and Urban-Rural Development mandated progressive block tariffs in all qualified cities by 2015. These reforms significantly improved consumption efficiency, with cities like Beijing and Shanghai reporting reductions in per capita water use among high-consuming households and businesses (Zhai *et al.* 2021). As of 2025, nearly one-third of large and medium-sized cities had adopted tiered pricing systems, with the average base residential tariff at 2.1 RMB/m^3 and key cities averaging 2.41 RMB/m^3 (E20 Water Supply Research Center 2025).

Industrial water pricing has also been restructured to support more rational allocation. Between 1980 and 1997, pricing emphasized cost recovery, but post-1997 reforms introduced quota-based pricing with surcharges for excess use. The 2003 NDRC guidelines mandated tiered rates aligned with water intensity benchmarks. The 2011 No.1 Central Document further prioritized water pricing reform, calling for progressive pricing to penalize excessive use in water-intensive sectors and incentivize recycling and efficiency upgrades. By 2025, the average industrial water price reached 3.43 RMB/m^3, with most provinces enforcing over-quota surcharges and quota-linked monitoring (China Water Network 2025).

Taken together, China's water pricing reforms have progressively embedded economic incentives into governance by promoting conservation, reallocating water toward higher-value uses and incorporating environmental costs into decision-making. While implementation remains uneven — particularly in rural areas — China's pricing reform represents a foundational shift toward integrated and incentive-compatible water resource management.

Water pricing reform aligns closely with the principles of market-based governance, where price signals are leveraged to allocate scarce water resources efficiently. According to water economics theory, pricing mechanisms function best when marginal cost pricing can induce conservation behavior and redirect usage toward higher-value sectors. The application of progressive block tariffs, volumetric pricing and sector-specific adjustments illustrates the operationalization of this theoretical logic in China. However, the success of such mechanisms depends on elasticity of demand, cost recovery structures and the mitigation of regressive impacts. The hybrid pricing structures adopted in China — combining price incentives with subsidies or exemptions — demonstrate an evolving shift toward mixed governance models, balancing efficiency goals with equity considerations.

3.2.2. *Water rights reforms*

Water rights reform has become a critical institutional innovation in China's pursuit of sustainable and efficient water governance. Inspired by international experiences in countries such as Australia, the United States and Spain, where mature water trading systems have improved allocation efficiency and inter-sectoral equity, China began exploring water rights markets in the early 2000s to address the growing tension between water scarcity and economic development (Wang *et al.* 2020b; Svensson *et al.* 2021) (Table 1). The reform was driven by the recognition that clearly defined and transferable water use entitlements, embedded within a transparent governance framework, could facilitate more flexible and rational resource distribution among competing users.

The early stages of reform featured localized pilot transactions, most notably the 2002 intercity water trade between Dongyang and Yiwu in Zhejiang Province — widely regarded as China's first modern water rights transaction (Jin and Feng 2024). Since then, various provinces including Gansu, Ningxia, Fujian and Inner Mongolia have developed their own pilot programs. In 2014, the Ministry of Water Resources officially designated seven provinces as experimental zones for water rights trading, laying the foundation for a more coordinated national strategy. This culminated in the issuance of the Interim Measures for the Administration of Water Rights Trading in 2016 and the establishment of a unified national trading platform (Fang and Zhang 2020; Jiang *et al.* 2025).

China's water rights transactions have evolved into three primary types. Inter-regional trades, often negotiated between local governments or basin agencies, typically involve bulk transfers of surplus or reserved water across jurisdictions, conditional on basin authority approvals and infrastructure compatibility. Water withdrawal rights trading, by contrast, occurs at the user level — typically among industries or utilities — and requires formal updates to water abstraction permits post-transaction. Irrigation water rights trading, largely informal and intra-village in nature, is practiced among agricultural water user associations, though the initial allocation remains administratively controlled (Jin and Feng 2024; Wang *et al.* 2025). Notably, irrigation trades account for a high frequency of transactions but involve small individual volumes, while inter-regional trades are large in volume but few in number.

Despite these developments, the overall water rights market in China remains nascent. The total transaction volume constitutes only a minor fraction of national water use, and market depth is constrained by institutional, technical and political barriers. Key challenges include: the absence of standardized entitlements; limited tradability of water use rights beyond pilot regions; weak enforcement mechanisms; and fundamental conflicts between administrative command structures and emerging market signals (Wang *et al.* 2025). Moreover, the dual burden of high transaction costs and uncertain returns has discouraged broader participation, especially in rural and underfunded regions.

In this context, China's water rights reform has taken on a hybrid institutional form, combining centralized administrative control with selective adoption of market-based instruments. Rather than a wholesale transition to full market liberalization, the Chinese model emphasizes government-led market design, with trading mechanisms serving as complementary tools for policy implementation rather than autonomous allocation systems (Svensson *et al.* 2021). Local governments are encouraged to tailor water rights frameworks to their respective governance, hydrological and economic conditions — resulting in considerable variation in institutional arrangements across regions.

Ultimately, China's approach reflects a pragmatically adaptive regime — one that blends state authority with market experimentation in a manner consistent with its broader governance ethos. This hybrid model offers valuable insights for other countries navigating the complex interplay between economic efficiency, administrative capacity and equity in water resource management.

The water rights reform initiative is grounded in the property rights theory of resource allocation. By defining, assigning and enabling the transfer of water use rights, these reforms seek to reduce allocation inefficiencies and transaction frictions across competing sectors and regions. The emergence of trading platforms and the diversity of transaction types reflect the operationalization of market mechanisms, where water is treated as an economic good. However, the persistence of administrative barriers and selective tradability suggests that China's approach remains a government-led quasi-market, consistent with theories of hybrid institutional design in transition economies. This arrangement reflects a pragmatic compromise between allocative efficiency and regulatory oversight.

3.2.3. *Adopting agricultural water saving technologies*

Agricultural production in China remains the dominant water-consuming sector, accounting for over 60% of national water use. While the country has achieved notable progress in improving agricultural water use efficiency, the sector continues to face structural and technological challenges. Disparities in irrigation infrastructure, limited access to advanced technologies and fragmented land tenure systems have constrained broader adoption, particularly among smallholder farmers (Yu *et al.* 2020). Addressing these challenges is essential not only for conserving water but also for improving agricultural resilience and sustainability.

China's water-saving irrigation technologies can be conceptualized as a three-tiered system: (1) traditional surface irrigation methods, (2) modern efficient irrigation technologies and (3) scientifically regulated irrigation strategies. This layered approach reflects the diversity of China's agro-ecological zones and technological capacities, and it offers a practical pathway for incremental upgrading rather than a single, universal solution.

Traditional surface irrigation methods — including furrow, border, pit and hole irrigation — remain prevalent in small- to medium-scale farmlands. While these methods are low-cost and easy to implement, their technical efficiency is low due to substantial water losses from surface runoff and percolation. Nonetheless, their continued use reflects socioeconomic realities in many rural areas and highlights the need for localized upgrading strategies.

Modern high-efficiency irrigation technologies, such as drip irrigation, sprinkler irrigation, micro-sprinkling and subsurface drip systems, have been actively promoted in water-stressed regions. Drip irrigation — especially when combined with plastic mulch in subsurface configurations — is particularly effective in arid zones like Xinjiang and Inner Mongolia, where it enhances yield while reducing evaporation losses. Sprinkler and micro-sprinkler systems are widely applied in orchards and cash crop areas. However, barriers such as high capital costs, equipment maintenance and limited technical capacity among farmers continue to constrain adoption (Tang *et al.* 2016).

Complementing hardware-based solutions, China has also emphasized scientifically regulated irrigation practices that align water supply with crop physiological needs. These include intermittent irrigation (commonly used for rice), deficit irrigation, alternate furrow irrigation and precision irrigation. Such strategies optimize irrigation schedules by reducing water input during less critical growth stages or through alternating delivery patterns to encourage root development and soil moisture retention. While technically sound and resource-efficient, their field-level effectiveness depends on farmers' knowledge, extension services and real-time decision support tools.

As shown in Table 1, the promotion of agricultural water-saving technologies in China began with localized experimentation in the early 2000s and was significantly scaled up through nationally supported programs starting around 2013, particularly following the issuance of the Ministry of Agriculture's 2012 Opinion on Promoting the Development of Water-Saving Agriculture. However, despite

Table 1. Overview of Major Water-related Policy Reforms in China and Their Implementation Periods (Year of Launch – Year of Conclusion or Current Status)

Reform/Policy Name	Implementation Start Year	Implementation Status/ End Year
Strictest Water Resources Management Policy (SWRMP)	2012	Ongoing
Water Pricing Reforms (Domestic, Agricultural, Industrial)	1985 (initial), major reforms in 2007, 2013, 2016	Ongoing
Water Rights Reforms	2002 (first pilot), expanded in 2014, national measures in 2016	Ongoing
Agricultural Water-Saving Technologies Promotion	2000s (varied), major push since 2013	Ongoing
Comprehensive Groundwater Overdraft Control (incl. SLFP in Hebei)	2014 (policy), 2019 (national action), 2020–2023 (plans)	Ongoing through 2035
South–North Water Diversion Project (SNWDP) – Eastern Route	2002 (construction); operational since 2013	Ongoing
South–North Water Diversion Project (SNWDP) – Middle Route	2002 (construction); operational since 2014	Ongoing
River and Lake Chief System (RLCS)	2016	Ongoing
Water Pollution Prevention and Control Action Plan (WPPCAP/"Ten-Point Water Plan")	2015	Long-term, targets to 2030
Interprovincial Ecological Compensation Mechanisms	2011 (first pilot in Xin'an River)	Expanded since 2018; ongoing

significant policy and financial support, the nationwide uptake of modern water-saving technologies remains limited. As of 2020, only 15.6% of China's irrigated area was under advanced water-saving systems, even though over 50% of total irrigated land was classified as water-saving in a broader sense (Tang *et al.* 2016). Regional disparities are evident: northern and northwestern provinces — where water scarcity is more acute — have demonstrated faster adoption rates, while southern regions with relatively abundant water resources have lagged behind.

In recent years, pilot initiatives on smart irrigation systems have emerged, leveraging real-time data on soil moisture, weather patterns and crop phenology to achieve fine-tuned water and fertilizer delivery. These digital technologies offer significant promise for optimizing inputs and further reducing water footprints. However, their deployment is still at an early stage and constrained by high technological thresholds, limited broadband infrastructure and fragmented governance across agricultural and water sectors.

In conclusion, China's approach to agricultural water-saving reflects a multi-layered, regionally adaptive model combining infrastructural investment, technology dissemination and behavioral change. Moving forward, integrating smart technologies with traditional and modern irrigation methods, supported by pricing incentives and cooperative governance, will be essential to realizing the full potential of agricultural water conservation.

The promotion of water-saving technologies in agriculture embodies a mixed governance model combining economic, technological and administrative tools. While the adoption of precision irrigation systems and deficit irrigation techniques aligns with technical efficiency principles in water economics, their dissemination often relies on state subsidies, pilot programs and institutional coordination, characteristic of regulatory interventions. As highlighted in Sec. 2.1, such hybrid models aim to overcome market failures associated with underinvestment in public goods and asymmetric information. The observed rebound effects and regional disparities also mirror theoretical concerns over unintended consequences in technology-based policy instruments, emphasizing the need for integrated design and dynamic evaluation.

3.2.4. *Comprehensive control of groundwater overdraft*

The North China Plain, which produces over one-third of China's grain using merely 6% of the nation's water resources, is one of the world's most overexploited groundwater basins (Huang *et al.* 2019). With more than 70% of crops irrigated using groundwater, the region's heavy reliance on underground aquifers — especially in the Huang–Huai–Hai (3H) area — has led to the long-term formation of shallow and deep groundwater funnel zones covering 16,000 km^2 and 24,000 km^2, respectively. Over the past two decades, the cumulative groundwater overdraft across these basins has exceeded 90 billion cubic meters, causing severe declines in water tables and threatening agricultural sustainability (Wang *et al.* 2020a).

To address this critical challenge, a phased national governance framework has emerged. Initiated by the 2014 No.1 Central Document, groundwater control was later institutionalized through the 2019 Action Plan for Comprehensive Groundwater Over-extraction Management in North China, which set the ambitious target of achieving extraction-recharge balance by 2035 (Table 1). This was followed by the 2020 designation of 63 critical prefectures and the 2023 release of the 14th Five-Year Plan for Key Region Groundwater Over-extraction Management, extending the policy reach to new basins including Sanjiang, Songnen and Liaohe.

Hebei Province has been positioned as the national pilot for funnel zone remediation. Since 2014, Hebei has developed a structured "CCA-M" policy framework — Conservation, Control, Adjustment and Management — addressing both demand-side and supply-side interventions. Agricultural measures include Seasonal Land Fallowing Policy (SLFP), restricting groundwater irrigation through closing tubewells, conservation tillage, promoting adoption of drought-resistant wheat varieties modern water-saving irrigation technologies and water-fertilizer integration technology. On the supply side, this involves constructing infrastructure and transferring water from water-rich regions to replace groundwater with surface water for irrigation. Complementary governance reforms include adjustments in water pricing, water rights registration and decentralized institutional coordination.

Among these, SLFP stands out as a flagship initiative. It promotes seasonal rotation within dual-cropping systems to reduce winter wheat cultivation, which heavily depends on groundwater during dry seasons. Farmers receive fixed annual compensation of RMB 7,500 per hectare, irrespective of yield, region, or market variation, ensuring program uptake and income stabilization (Wang *et al.* 2023b). Unlike conventional fallowing programs that withdraw land from production entirely, SLFP maintains summer cropping, aligning with food security goals.

The governance of groundwater overdraft — particularly through the Seasonal Land Fallowing Policy (SLFP) — represents an incentive-based compensation scheme, forming a classic command-incentive hybrid model. This structure is consistent with economic theories advocating for the internalization of environmental costs via payments for ecosystem services (PES) or conditional subsidies. Such hybrid designs seek to align private farmer behavior with public conservation goals, particularly in contexts where market signals alone are insufficient to induce optimal use of groundwater due to resource externalities and fragmented water user groups. However, the sustainability of these mechanisms relies on long-term funding, administrative credibility and adaptive monitoring — factors often highlighted in critiques of mixed policy instruments.

3.3. *Policies resolving unequal water distribution*

A defining feature of China's national water governance has been its emphasis on large-scale infrastructure as a tool for achieving interregional water balance. At the center of this strategy lies the South–North Water Diversion Project (SNWDP) — a mega-infrastructure initiative designed to redirect water from the water-rich Yangtze River basin in the south to water-scarce regions in the north. The SNWDP represents not only the world's largest water transfer undertaking but also a flagship example of how infrastructure-led solutions are embedded within broader water security and economic development policies in China (Cui *et al.* 2025).

The SNWDP comprises three planned routes — Eastern, Middle and Western — with the former two operational since 2013 and 2014, respectively (Table 1). The Eastern Route, utilizing existing infrastructure such as the historical Grand Canal, transfers water from the lower Yangtze to Jiangsu and Shandong provinces. The Middle Route channels water from the Danjiangkou Reservoir in Hubei Province to Beijing, Tianjin and the provinces of Hebei and Henan via a 1,400 km gravity-fed canal system. The Western Route, intended to divert water from the upper Yangtze across the Qinghai-Tibet Plateau to the Yellow River, remains in the conceptual stage due to high costs and environmental complexity (MWR 2021).

By 2024, the Middle and Eastern Routes had delivered over 76.7 billion cubic meters of water, directly benefitting 45 cities and approximately 185 million people (The State Council of China 2014). While the majority of diverted water supports industrial and municipal uses, this also indirectly frees up agricultural water, improving rural ecosystem resilience and restoring crop production capacity in source regions. This strategic reallocation of water across sectors and regions underscores China's unique approach to spatial water equity and economic coordination.

The SNWDP's origins date back to 1952, when Chairman Mao Zedong first proposed the idea of "borrowing water from the South". However, the project remained at a conceptual level without tangible implementation initiatives for decades due to technical and fiscal limitations. It was not until the 1990s — under the Eighth Five-Year Plan — that formal planning commenced. The 2002 approval by the State Council marked the projects official launch, positioning the SNWDP as a national priority for addressing acute water scarcity in the northern economic corridor.

Despite its engineering and logistical achievements, the SNWDP has attracted considerable scrutiny regarding its economic efficiency and sustainability. With cumulative investments exceeding 266 billion RMB (Huang *et al.* 2025), the project exemplifies a top-down, capital-intensive approach to water reallocation. While it has demonstrably improved water access in critical northern regions, critics argue that its high financial and ecological costs necessitate a more comprehensive impact assessment, particularly in relation to long-term climate variability, water demand projections and ecosystem stability in donor basins.

The SNWDP exemplifies a state-led supply-side intervention, aligned with traditional public investment responses to resource misallocation. While not a market-based mechanism per se, the project reflects theoretical perspectives on infrastructure as an enabling condition for spatial equity and inter-regional coordination. It aims to address structural mismatches in water availability by reengineering distribution through physical infrastructure. From the lens of economic theory, this reflects a non-price allocation approach, often challenged for its high opportunity cost and weak adaptability. However, when viewed through the lens of spatial externality correction, large-scale diversion may be justified as a public good, particularly under governance regimes with strong implementation capacity. The projects limitations — such as ecological cost and weak demand-side regulation — underline the importance of integrating such supply projects with demand-side efficiency and decentralized management mechanisms.

3.4. *Policies mitigating water pollution*

3.4.1. *River and lake chief system (RLCS)*

In response to persistent water pollution and fragmented governance, China introduced the RLCS in 2016 as a nationally coordinated institutional innovation (Table 1). The RLCS establishes a multi-level accountability framework that designates officials at each administrative tier — provincial, municipal, county and township — as "chiefs" responsible for the governance of specific water bodies under their jurisdiction. Typically, the General River Chief is the top-ranking Party or government official in a province or municipality, ensuring integration of water governance into the core of political leadership structures.

The system assigns differentiated but hierarchical responsibilities, whereby principal water bodies such as major rivers and lakes are governed by senior officials, while segment-specific river chiefs oversee tributaries and smaller lakes at sub-provincial levels. To support administrative coordination and task execution, River Chief Offices are established at the county level and above, with flexible organizational structures adapted to local governance capacity and hydrological complexity.

The RLCS institutionalizes vertical accountability and horizontal coordination in managing water resources. Chiefs are tasked with a comprehensive portfolio, including water quality protection, shoreline management, aquatic ecosystem restoration, illegal discharge control and mitigation of harmful practices such as sand mining, overfishing and navigation obstruction. The system emphasizes cross-boundary coordination, requiring chiefs to facilitate joint prevention and control mechanisms between upstream and downstream regions, and across opposite riverbanks — addressing a major governance blind spot under previous sectoral models.

Crucially, the RLCS embeds a performance assessment and incentive mechanism into public administration. Chiefs are evaluated based on quantitative and qualitative water governance outcomes, including pollution reduction, compliance with water function zoning and public satisfaction metrics. Their performance is linked to promotion prospects and fiscal transfers, effectively creating internalized incentives for water stewardship within the bureaucracy. River Chief Offices serve as executing arms, tasked with translating high-level directives into enforceable actions through interdepartmental collaboration.

By redefining water governance as a politically visible responsibility, the RLCS enhances administrative commitment and policy coherence, distinguishing it from technocratic or sector-based regulatory models. It represents a hybrid institutional design that integrates command-and-control with performance-based governance, thereby improving implementation fidelity and adaptive management at scale.

Nevertheless, early evidence suggests variability in implementation effectiveness across regions. Challenges include administrative overlap, data asymmetry between departments and weak public participation. Moreover, the RLCS focuses primarily on institutional form, with less attention to underlying economic drivers of pollution, such as non-point source agricultural runoff or industrial water mispricing.

Future refinement should include better integration with market-based tools such as water rights trading, ecological compensation and real-time digital monitoring systems, as well as expansion of public participation and disclosure mechanisms to strengthen societal accountability. As a pioneering approach to institutionalized water responsibility, the RLCS offers valuable lessons for other countries facing governance fragmentation in river basin management.

The RLCS represents a bureaucratic accountability mechanism, aligning with command-and-control theories that assign environmental responsibility through hierarchical administrative structures. As discussed in Sec. 2.1, such governance models are often favored in contexts with complex interdepartmental coordination needs and limited market maturity. By embedding environmental targets into official performance assessments, the RLCS attempts to overcome enforcement failures common in fragmented systems. However, its heavy reliance on personnel incentives and qualitative assessments raises concerns regarding information asymmetry, enforcement consistency and long-term institutionalization — issues commonly associated with administrative coordination models in environmental regulation theory.

3.4.2. *Water pollution prevention and control*

To combat the widespread degradation of water quality caused by rapid industrialization and urbanization, China introduced the WPPCAP in April 2015. Known as the “Ten-Point Water Plan,” this policy represents a decisive shift from traditional end-of-pipe treatment approaches toward a more comprehensive and systemic strategy integrating legal, administrative, economic and technological tools (Table 1). Building upon the 2008 Water Pollution Prevention and Control

Law — which lacked detailed implementation measures — the WPPCAP laid out an operational framework that addresses pollution at the source and across sectors. It outlines ten interrelated domains of action, including sectoral pollution control (industrial, domestic, agricultural and port-based), industrial and spatial restructuring, wastewater treatment and recycling, ecological zoning, legal enforcement, technological innovation, market-based mechanisms (e.g., pricing and green finance), accountability systems and public participation. Altogether, the plan specifies 238 actions, including 136 improvement measures, 90 innovation-oriented reforms and 12 pilot research programs.

The WPPCAP sets ambitious national targets: by 2030, over 75% of water bodies in major basins should reach “good” quality, urban black-odor water bodies should be eliminated, and 95% of centralized drinking water sources are expected to meet Class III or higher standards. These targets reflect a shift toward performance-based environmental governance. Implementation results have been encouraging. By 2023, the proportion of high-quality water in key basins had already exceeded 75%, and most large urban centers had successfully eliminated black-odor water bodies. These outcomes underscore the effectiveness of WPPCAP’s hybrid governance model, which combines top-down regulatory command with bottom-up incentives and cross-sectoral cooperation.

Nevertheless, transboundary water pollution remains a persistent and complex governance issue in China. Approximately 80% of the country’s petroleum and chemical enterprises are located near rivers, with 20% straddling interprovincial boundaries. These geographic characteristics have contributed to over 11,000 significant water pollution incidents since 1995. Given the fragmentation of administrative authority and conflicting regional interests, these cross-boundary disputes often prove difficult to resolve through bilateral negotiation alone. To address this, the central government progressively institutionalized mechanisms for interprovincial coordination. Starting with the 2007 Notice on Strengthening River Pollution Control Work and the 2008 Policy on Joint Governance of Transboundary River Pollution, regulatory authorities began to clarify roles, establish joint monitoring platforms and implement shared accountability frameworks among upstream and downstream jurisdictions.

In parallel, China piloted and scaled a more innovative and incentive-compatible solution: interprovincial watershed ecological compensation (Table 1). Under this mechanism, downstream regions offer financial compensation to upstream governments for achieving agreed-upon water quality goals, thus aligning local incentives with basin-wide environmental outcomes. The Xin’an River Basin served as the first pilot in 2011, marking a critical step in operationalizing this model. By 2021, a total of 13 compensation agreements had been signed among

18 provinces, covering major watersheds such as the Yangtze and Yellow Rivers. These agreements institutionalize performance-linked payments and are supported by third-party monitoring, contract enforcement and central government coordination. The approach reflects a significant departure from command-based regulation toward market-aligned environmental governance.

Despite notable progress, key challenges remain. Non-point source pollution — particularly from agriculture — continues to pose a major regulatory blind spot. Additionally, the administrative and transaction costs associated with interregional compensation mechanisms are non-negligible, especially for less-resourced localities. Looking forward, the effectiveness and sustainability of WPPCAP could be further enhanced through several avenues: embedding ecological compensation schemes into national fiscal transfer mechanisms; scaling digital infrastructure for real-time water quality monitoring and enforcement; and expanding market instruments such as emissions trading and pollution discharge permits. Ultimately, China's WPPCAP illustrates an evolving paradigm in water pollution governance — one that blends regulatory stringency with institutional experimentation, and top-down mandates with bottom-up cooperation — offering valuable lessons for water-stressed countries pursuing economically efficient and institutionally resilient approaches to pollution control.

The WPPCAP exemplifies an increasingly integrated governance approach, combining legal enforcement, economic instruments, spatial planning and public participation. As a national-scale policy integrating over 200 distinct measures, it reflects both command-based controls (e.g., emission standards, inspections) and market-aligned mechanisms (e.g., ecological compensation, green finance). Such hybrid structures are particularly effective in managing cross-jurisdictional externalities and aligning incentives under fragmented authority. The plan's embrace of performance-based compensation for upstream regions, especially in transboundary pollution contexts, reflects a shift toward institutionalized ecological payments, bridging environmental economics with fiscal federalism. However, persistent spillover effects and uneven monitoring capacity suggest that further refinement is needed to stabilize these hybrid institutions over time.

4. Performance of Recent Advanced Water-related Policies in China

4.1. *Performance in terms of effectiveness*

4.1.1. *The strictest water resources management policy (SWRM)*

Research on the implementation of the Strictest Water Resources Management (SWRM) policy is still relatively limited, and the available findings remain mixed.

From the perspective of policy effectiveness — encompassing both goal attainment and resource optimization — evidence shows that SWRM has had a positive impact in reducing total water consumption, curbing pollution emissions and improving water use efficiency. For example, Wang *et al.* (2023c), based on cross-sectional comparisons, found that SWRM effectively constrained water use and pollution levels. Similar results were reported by Cheng *et al.* (2022), Wang *et al.* (2018) and Zhao *et al.* (2023), who identified reductions in withdrawals and emissions, along with improvements in efficiency indicators such as lower water use per 10,000 RMB of GDP. These studies suggest that SWRM not only addresses quantity control but also promotes more efficient allocation and utilization of water resources.

Despite these gains, concerns remain about the long-term robustness and regional adaptability of the policy. Wang *et al.* (2023c), using longitudinal projections, warned that by 2030 water demand in some regions could exceed SWRM's control targets by nearly 2 billion cubic meters, while Chemical Oxygen Demand (COD) in wastewater could rise by about 24% compared to 2021. Furthermore, although efficiency has generally improved, the pace of progress may fall short of policy benchmarks. Wang *et al.* (2023c) projected a potential 2% shortfall relative to the 2025 target of the "14th Five-Year Plan for Building a Water-Saving Society." Similarly, Shah *et al.* (2022) observed that in certain areas, SWRM may have inadvertently reduced water resource productivity, reflecting institutional and structural inefficiencies.

In sum, the SWRM policy demonstrates clear effectiveness in reducing water use and improving efficiency under supportive local conditions, but its outcomes are uneven and vulnerable to long-term demand pressures. Regional heterogeneity, implementation capacity and resilience under climate variability remain critical challenges. Future refinements should aim to integrate economic efficiency metrics with environmental goals and strengthen adaptability in order to sustain water governance outcomes over the coming decades.

4.1.2. *Policies addressing water scarcity*

Water pricing reforms:

Water pricing is regarded as one of the most direct tools for managing demand, but its effectiveness is debated, especially in agriculture where demand is often price inelastic. Two main approaches are used to evaluate reform outcomes: estimating price elasticity of water demand and directly assessing water use changes after policy implementation. Studies on elasticity show mixed results. Some scholars find pricing effective: for example, Sun *et al.* (2017) demonstrated significant effects of agricultural water prices on irrigation demand; Hu *et al.* (2020) estimated an industrial elasticity of −3.423 and Zheng *et al.* (2012) reported urban residential elasticity of −2.43, suggesting strong conservation potential through price mechanisms.

However, others question the robustness of elasticity-based evidence. Wang *et al.* (2021b) showed that irrigation demand has a threshold of about 0.33 yuan/m^3, implying that current prices in areas such as Hebei Province (0.35 yuan/m^3) are too low to drive significant reductions. Similarly, Liao *et al.* (2016) emphasized that while raising prices can ease shortages, low elasticity constrains regulatory impact. Research also highlights possible non-linear effects, where demand is initially unresponsive, becomes more sensitive at intermediate levels and declines again at higher prices (Huang *et al.* 2006; Liu *et al.* 2015). This suggests that pricing reforms are context-dependent and their effectiveness hinges on surpassing perceived thresholds of water's economic value.

Beyond elasticity estimates, several studies have directly assessed water pricing reforms. Empirical evidence shows that comprehensive agricultural reforms reduce groundwater withdrawals and overall irrigation demand (Huang *et al.* 2010; Zhao *et al.* 2015a; Wang *et al.* 2016; Zhao *et al.* 2016; Shi *et al.* 2024), primarily through adoption of water-saving technologies (Yang and Wang 2021; Liu and Wang 2022; Zhang and Oki 2023) and changes in cropping patterns (Yi *et al.* 2019; Dong *et al.* 2024; Mu *et al.* 2024). In urban areas, tiered pricing schemes also prove effective; for instance, Jia and Huang (2013) found that a three-tier structure reduced annual per capita use by 16.87%. Nonetheless, concerns remain: Han and Zhao (2007) and Shi and Shen (2016) cautioned that price increases sometimes have minimal or even adverse impacts, such as heightened pollution linked to cost-driven behavioral shifts.

Water rights reforms:
The implementation of water rights trading policies in China has attracted considerable academic attention, particularly regarding their potential to improve water use efficiency, reduce overall consumption and enhance the effective allocation of water resources.

First, a growing body of research indicates that water rights reform can significantly enhance water use efficiency. Several studies have found that, following policy implementation, pilot regions increased investments in farmland water infrastructure, resulting in a notable expansion of irrigated land supported by improved facilities (Xu *et al.* 2023; Zhang and Li 2024). Governments also promoted the adoption of advanced irrigation technologies, encouraging farmers to invest in and implement water-saving methods (Fang and Zhang 2020; Ma *et al.* 2021 2022; Mu *et al.* 2022). These technological adoptions, in turn, contributed to measurable improvements in water use efficiency. Using various empirical methods — including difference-in-differences (DID), three-stage DEA models, the Malmquist productivity index, SBM models and the Global Non-Radial Directional Distance Function (GNDDF) — studies have confirmed that water rights reform has had a significant positive impact on provincial water use efficiency, particularly in the agricultural sector (Fang and Wu 2020; Tian *et al.* 2020; Qin *et al.* 2022; Wu *et al.* 2022; Yan *et al.* 2024).

Second, many studies have examined whether increased efficiency translates into actual water savings. The vast majority conclude that water rights reforms have yielded substantial conservation effects, largely due to improvements in irrigation efficiency. For instance, water rights trading has been shown to reduce agricultural water use by approximately 992.7 million cubic meters — an 8.04% reduction — across participating regions (Fang and Zhang 2020; Zhai *et al.* 2021; Yao and Li 2023). Industrial water use has also declined, resulting in a significant decrease in water consumption per unit of GDP, with total water use in pilot areas falling by 3.1% (Fang and Wu 2020; Tian *et al.* 2022; Mu *et al.* 2022; Jiang *et al.* 2025). However, some studies caution against potential rebound effects: increased irrigation efficiency may encourage farmers to expand their irrigated areas, thereby offsetting the gains in water savings (Xu *et al.* 2023). Nonetheless, Sheng *et al.* (2025) suggest that the establishment of water markets may also lead to improvements in water quality, which can help mitigate such rebound effects.

Finally, several studies highlight additional environmental benefits and improvements in water allocation resulting from water rights reform. On the environmental side, Jiang *et al.* (2025) report that reforms not only reduced industrial water use but also contributed to reductions in industrial wastewater discharge. Du *et al.* (2022) found that water rights trading has long-term positive effects on pollution control, particularly in reducing wastewater emissions in pilot regions. In terms of water allocation, Sheng *et al.* (2024) argue that a market-oriented water trading system can reduce water inequality and promote more equitable distribution across regions. Beyond spatial allocation, water rights trading also facilitates intersectoral reallocation by improving agricultural water use efficiency, thereby allowing water to be reallocated from agriculture to other sectors, easing sectoral competition over water resources (Fang and Wu 2020).

Adopting agricultural water saving technologies:
The adoption of agricultural water-saving technologies in China has produced significant outcomes in alleviating water scarcity and improving efficiency. Precision irrigation systems (PISs), such as drip and sprinkler irrigation, reduce evaporation and runoff, thereby increasing water-use efficiency (Deng *et al.* 2006;

Xuan *et al.* 2021; Lakhiar *et al.* 2024). Deficit irrigation further enhances crops' water uptake efficiency and reduces total consumption (Niu *et al.* 2024), while urban fringe farmers benefit from lower crop water use and improved productivity (Huang *et al.* 2017; Zhang *et al.* 2019). Nonetheless, rebound effects — where efficiency gains lead to expanded irrigated areas or higher cropping intensity — remain a concern (Liu *et al.* 2019; Wang *et al.* 2020c; Fang *et al.* 2020).

Beyond water conservation, these technologies strengthen food security and stabilize agricultural productivity. By enabling higher yields under constrained water supply, they help meet rising food demand (Wang *et al.* 2002; Lu *et al.* 2018; Li 2023). Integration into high-standard farmland projects has reduced inefficiencies and bolstered resilience against natural disasters (Li 2023). Drip irrigation has directly boosted productivity (Wang *et al.* 2020d), though trade-offs persist, as deficit irrigation may lower yields despite conserving water (Niu *et al.* 2024). Furthermore, advanced irrigation systems prevent soil salinization and land degradation by delivering water more precisely, maintaining soil health in regions vulnerable to salinity (Shi *et al.* 2023).

Finally, water-saving technologies support long-term sustainability by reducing waste and safeguarding resources. Their adoption underpins stable agricultural development for future generations (Lu *et al.* 2018), while government investment in research and promotion has been key to sustaining progress (Pu-te 2010). Compared with traditional flood irrigation, drip and sprinkler systems significantly reduce ineffective losses and maximize the productivity of each unit of water (Deng *et al.* 2006, 2017b; Liu *et al.* 2019; Lakhiar *et al.* 2024; Niu *et al.* 2024). Regional evidence shows notable gains: in Northwest China, irrigation efficiency has improved markedly (Mu *et al.* 2016), while on the Huang–Huai–Hai Plain, modern technologies raised composite water-use efficiency measured across eight indicators (Wang *et al.* 2020d). Together, these findings underscore their vital role in ensuring sustainable agricultural water management.

2010

Comprehensive control of groundwater overdraft:

Currently, there is limited research evaluating policies aimed at addressing groundwater overdraft, with most existing studies focusing on the Seasonal Land Fallowing Policy. Evaluating whether the Seasonal Land Fallowing Policy (SLFP) effectively achieves its goal of groundwater conservation has become a focal point of current research. On the micro level, several studies utilize household survey data to evaluate changes in water usage among participating farmers. One such study, based on 2019 survey data in Hebei, reported that SLFP led to a reduction of approximately 1,403 m^3/hectare/year in agricultural water usage, primarily due to decreased winter wheat planting area (Deng *et al.* 2021). Ti *et al.* (2021), using extensive household survey data from groundwater-overexploited areas of the North China Plain, found that winter wheat fallowing saved approximately 4,642, 3,325 and 1,906 m^3/hectare in semi-arid, dry sub-humid and humid regions, respectively. Other studies using descriptive comparison methods also supported the conclusion that SLFP helps reduce groundwater usage (Wu *et al.* 2017; Li 2019).

On the macro level, some studies use secondary data to assess impacts. For example, a study in Hengshui City, Hebei Province, calculated crop evapotranspiration using remote sensing and meteorological data, and compared agricultural water consumption before and after policy implementation. It found that total water usage for major crops declined from 2.98 billion cubic meters in 2013 to 2.83 billion cubic meters in 2015, a reduction of 146 million m^3, achieving 88.43% of the WWFP water reduction target (Lei *et al.* 2019). Other researchers, using object-oriented extraction methods and the SEBS model based on multi-source data, confirmed that SLFP effectively reduced evapotranspiration during winter wheat growth, contributing to sustainable water resource utilization (Zhai *et al.* 2021). It is worth noting, however, that while most research affirms SLFP's effectiveness in reducing water use, some studies suggest the policy may not have directly impacted groundwater table depth. This is because, despite the correlation between evapotranspiration and groundwater depth, decreasing precipitation has continued to drive groundwater levels lower (Lei *et al.* 2019).

4.1.3. *Policies resolving unequal water distribution*

The South-North Water Diversion Project (SNWDP) was designed not only to alleviate water scarcity and improve ecological conditions in recipient regions but also to restore agricultural productivity and promote local economic development. Accordingly, a growing number of scholars have sought to assess the effectiveness of the project from these perspectives.

A substantial body of research confirms that the SNWDP has mitigated water shortages and improved ecological conditions in recipient regions. Hydrological and numerical model studies show reduced groundwater depletion and recovery of water tables in cities such as Beijing (Yang *et al.* 2012; Zhang *et al.* 2018; Long *et al.* 2020). On the North China Plain, it has added about 0.3 km^3 of reserves annually and slowed groundwater decline, easing overextraction pressures (Ye *et al.* 2014; Zhang *et al.* 2020). Liu *et al.* (2020) found that the project significantly reduced water stress in Beijing and Tianjin. Econometric analyses further indicate that groundwater levels in receiving counties rose by an average of 4.4 meters, with water coverage expanding by 6.5% and groundwater growth rates increasing by 1.329 percentage points (Xie *et al.* 2023; Cui *et al.* 2025; Huang *et al.* 2025). Improvements in water conditions have also helped alleviate land subsidence and related environmental degradation (Du *et al.* 2021).

Findings on agricultural productivity remain mixed. Some studies suggest the project did not increase agricultural water use and even reduced the scale and share of agricultural water consumption, yielding slight negative effects on the primary sector (Xiao 2022; Xu *et al.* 2024). Others, however, emphasize positive outcomes through more efficient water allocation (Wang and Chen 2022). For example, Huang *et al.* (2025) reported that total grain output in recipient counties rose by 8.2%, with productivity up 4.7% due to expanded planting and greater mechanization, while Yang and Xu (2023) found higher agricultural value added, largely from cash crop cultivation.

The SNWDP has also been linked to broader economic benefits. In rural areas, it supports agricultural productivity, raises farmers' incomes and promotes rural development (Cui *et al.* 2025; Huang *et al.* 2025). In urban areas, it contributes to per capita income growth, industrial and service sector expansion, and urbanization (Huang *et al.* 2025). Li *et al.* (2024b) and Cui *et al.* (2025) documented post-policy increases of 6.9% in urban size, 4.2% in nighttime light intensity and 3.1% in population density. The project has also driven industrial upgrading, innovation, fiscal revenue growth, financial access and more equitable distribution of gains (Dai *et al.* 2024). Collectively, these outcomes demonstrate that the SNWDP promotes overall regional growth, raises per capita GDP, and helps narrow development gaps across China (Feng *et al.* 2007; Xie *et al.* 2023; Cui *et al.* 2025).

4.1.4. *Policies mitigating water pollution*

River and Lake Chief System (RLCS):
China's RLCS is an institutional innovation that assigns government officials responsibility for managing rivers and lakes, aiming to strengthen water resources management and environmental protection. Existing research generally affirms its effectiveness. Yang *et al.* (2024), using data from coastal rivers in Guangdong, found that the RLCS curbed environmental deterioration, while Song *et al.* (2024) confirmed improvements in Beijing's aquatic ecosystems. Mu *et al.* (2023) showed that the system reduced industrial wastewater pollution, and Li *et al.* (2021b) reported nationwide reductions in pollution based on monitoring station data. Regional variation is also evident: Chen (2024a) documented the diffusion of the RLCS from coastal to inland areas, highlighting its broader institutional reach.

Nonetheless, other studies reveal limitations in implementation. Li *et al.* (2020) emphasized persistent pollution in transboundary rivers due to weak coordination, and Yao and Cheng (2023) found that grassroots river chiefs' behaviors beyond routine patrols and "One River, One Policy" measures had little effect on pollution control. Case studies in Shaoxing, Fujian and Jiangsu identified deficiencies in standardized management, policy innovation, enforcement and public participation (Maosen *et al.* 2023). Even in Beijing, where the system has delivered notable ecological improvements, regional disparities and urban–rural gaps persist (Song *et al.* 2024).

Water Pollution Prevention and Control:
Existing research on water pollution control in China mainly focuses on the Water Pollution Prevention and Control Action Plan (WPPCAP) and ecological compensation for transboundary pollution. Most studies agree that WPPCAP has significantly reduced pollution, while also driving technological and institutional changes. For example, the policy spurred the adoption of low-energy, high-efficiency treatment systems, fostering green innovation (Du *et al.* 2018; Lai *et al.* 2025), and enhanced water-related information disclosure among sensitive enterprises (Li *et al.* 2021a). Together with industrial restructuring, these measures reduced the intensity of industrial water pollution (Lu *et al.* 2021; Zhou *et al.* 2021). WPPCAP also contributed to lower domestic water use, reducing urban pollution levels (Pan and Tang 2021; Chen 2024b).

However, some unintended consequences and uneven outcomes have been noted. Chen (2024b) found evidence of spatial spillovers, where pollution declined in strictly regulated cities but rose in nearby low-pressure ones within 60 km. Despite overall improvements, water quality challenges persist in certain regions, reflecting governance imbalances (Wang *et al.* 2021a). These findings suggest that while WPPCAP has been largely effective, its benefits are not uniformly distributed and may be undermined by regional disparities in enforcement.

A second stream of research evaluates ecological compensation as a mechanism for transboundary water pollution governance. Studies show that compensation incentivizes pollution reduction investments and transforms fiscal transfers into local development initiatives, improving water quality outcomes (Yi *et al.* 2021, 2024; Yu *et al.* 2024). Empirical evidence highlights reduced illegal discharges (Li and Lu 2022), improved river quality in Shenzhen (Sun *et al.* 2023), and significant declines in pollutants such as CODMn, BOD5, copper, zinc, chromium and arsenic (Liu and Mao 2020). Broader ecological benefits have also been observed: compensation improved overall urban water environments (Zhang *et al.* 2023; Yu *et al.* 2024) and raised the value of ecosystem services in the Yellow River Basin from 1.798 trillion yuan in 2010 to 1.838 trillion yuan in 2020 (Chen *et al.* 2021; Zhou *et al.* 2022a).

4.2. *Performance in terms of efficiency*

4.2.1. *The strictest water resources management policy (SWRM)*

The implementation efficiency of China's "most stringent water resources management system" lies in its ability to coordinate institutional mechanisms, prioritize regional needs and accelerate the adoption of water-saving practices through regulatory enforcement and incentive alignment. As Mu *et al.* (2016) observed in their analysis of agricultural water use efficiency in Northwest China, the improvements were not solely technical but institutional — driven by enhanced governance, policy coherence and fiscal mechanisms that targeted water-scarce regions. These reflect a high degree of technical and managerial efficiency in policy execution. Moreover, the integration of regional data monitoring, quota management and government-led coordination among agencies has reduced administrative fragmentation, promoting a more consistent and adaptive policy environment (Wang *et al.* 2020b).

However, evidence also points to certain implementation inefficiencies, particularly where policy incentives inadvertently misalign with sustainability goals. Liu *et al.* (2019) showed that although drip irrigation subsidy programs under the water-saving agenda increased adoption rates, they also led to an expansion of water-intensive crops, thereby increasing total regional water consumption. This suggests inefficiencies in demand-side management and unintended policy spillovers. Similarly, Fang *et al.* (2020) found that rebound effects offset much of the expected savings, implying that implementation efficiency was undermined by limited behavioral regulation and insufficient cross-sector monitoring. Therefore, while the overarching system demonstrates strong administrative reach and infrastructure deployment, true implementation efficiency remains contingent on better policy calibration, cross-level enforcement and dynamic evaluation mechanisms.

4.2.2. *Policies addressing water scarcity*

Water pricing reforms:
Scholars have sought to evaluate and compare the efficiency of different pricing models. For example, Dong *et al.* (2020) compared flat pricing, block tariffs and water rights trading mechanisms, concluding that water rights trading more effectively encourages farmers to adopt water-saving cropping strategies. Liao *et al.* (2016) found that a four-tier block pricing scheme yields greater water-saving efficiency than flat rates or three-tier pricing. Other researchers have focused on improving institutional design. Cai *et al.* (2020) argued that agricultural water pricing reforms should align with stakeholders' interests, suggesting that

institutional innovations should aim to reduce uncertainty and ensure stable, equitable and sustainable benefits for water users.

Several studies have proposed methods for setting more efficient water prices. Liu *et al.* (2017) developed a two-level dynamic game pricing model for water rights trading under quasi-market conditions. Pulido-Velazquez *et al.* (2013) constructed an integrated hydro-economic model at the basin level to design efficient water pricing policies that reflect the marginal value of water across the entire watershed. Other scholars have estimated farmers' willingness to pay (WTP) for water to identify appropriate price levels. For example, Yin and Cai (2016) found that the average WTP among farmers was 75.37 yuan per mu, while Mu *et al.* (2019) estimated an average WTP of 0.144 yuan/m^3 in their study region.

Water rights reforms:
Recent studies have shifted from evaluating outcomes of water rights reform to examining factors that enhance market efficiency. Jiang *et al.* (2025) emphasize that digital economy development improves industrial water-saving outcomes in pilot regions, while industrial upgrading and strict environmental regulation are also critical (Du *et al.* 2022). Rong *et al.* (2024) highlight that higher option fees, lower financial transaction costs, reduced credibility risks for regulators and expanded subsidies for intermediaries all increase participation in water rights option trading across farmers, industries and regulators. Yet, severe information asymmetry continues to hinder market activity, underscoring the importance of stronger oversight and corrective mechanisms such as transaction subsidies to improve efficiency (Xu and Yang 2019).

Pricing remains another key challenge for water rights trading. Using evolutionary game theory, Tian *et al.* (2023) show that transaction volume, buyer efficiency and market competition significantly influence prices. Wu *et al.* (2021b) argue that water's scarcity value exerts a moderating role, pushing prices upward as scarcity intensifies. Chen and Zhu (2021), applying the ELES model, proposed region-specific price bounds tailored to irrigation water rights, while Wu *et al.* (2018) introduced a two-step mechanism: first determining a base price through full-cost and shadow pricing models, then using bilateral auctions to finalize transfer prices. Together, these studies highlight the interplay between institutional design and pricing mechanisms in shaping the effectiveness of water rights reform.

Adopting agricultural water saving technologies:
The implementation efficiency of China's water-saving irrigation policies reflects a complex interplay of institutional coordination, policy incentives and behavioral responsiveness. Mu *et al.* (2016) highlighted that improvements in agricultural water use efficiency (AWUE) in Northwest China were not solely due to

technological adoption but closely linked to regionally compatible policy frameworks and strengthened inter-agency coordination. Localized allocation mechanisms and integrated governance structures enhanced responsiveness and reduced fragmentation. Moreover, as Wang *et al.* (2002) observed, the integration of agronomic and engineering measures into broader water-saving strategies — combined with top-down promotion and demonstration programs — facilitated the diffusion of best practices, especially in arid and semi-arid areas. These elements underscore how administrative and technical integration contributes to higher procedural and allocative efficiency during implementation.

However, several studies also point to critical inefficiencies in incentive design and policy coherence. Liu *et al.* (2019) found that subsidies promoting drip irrigation under plastic mulch (DIUF) significantly increased regional water use, as farmers shifted to more water-intensive, high-revenue crops — an unintended outcome of economic incentives misaligned with policy objectives. Similarly, Fang *et al.* (2020) identified a water rebound effect averaging 70.3%, indicating that technological gains were often offset by expanded irrigated areas or increased irrigation frequency. Blanke *et al.* (2007) further noted that while household-scale technologies spread rapidly under government support, collective-action technologies requiring institutional cooperation faced slow uptake due to implementation bottlenecks. These findings reveal that while China's water-saving technology policy framework exhibits strong administrative reach, its implementation efficiency depends critically on dynamic feedback mechanisms, incentive alignment and continuous behavioral regulation.

Comprehensive control of groundwater depletion:
Research on improving the efficiency of SLFP has centered on determinants of outcomes, optimal implementation scale and subsidy design. Key challenges include participant instability, limited incentives for shifting surplus labor, and underutilization of fallowed land (Deng *et al.* 2021). Farm size also matters, with larger farms more likely to participate due to operational advantages (Wang *et al.* 2023b). At the implementation scale, studies using models such as the IPLI, SGDCR and GM(1,1) suggest that the fallowing area should exceed official levels — Chen *et al.* (2023) estimate 4,089.288 hectares, while Ti *et al.* (2021) propose 3,100 hectares to maintain groundwater and 4,200 hectares to restore it.

Subsidy standards are equally critical. Based on household surveys, Zeng *et al.* (2018) estimated optimal compensation at RMB 7,677.60–9,962.40 per hectare, while Wang *et al.* (2024) argued for spatially differentiated subsidies ranging from RMB 218 to 689 per mu across sub-watersheds in the Haihe Basin. These findings suggest that differentiated incentives, combined with appropriate scale adjustments, are essential to maximize SLFP's water-saving potential while ensuring farmer income security.

4.2.3. *Policies resolving unequal water distribution*

As the world's largest water diversion project, the SNWDP has attracted massive state investment, making cost-effectiveness a crucial dimension of evaluation. Existing studies suggest that the project yields relatively high returns and sustainability compared to alternatives. Huang *et al.* (2025) estimate its internal rate of return (IRR) at 6.4%, higher than many large-scale Chinese infrastructure projects such as highways (4–6%) (Shirley and Winston 2004; Wu *et al.* 2021a). Similarly, Li *et al.* (2016), using a life cycle assessment (LCA), found that SNWDP is more sustainable than other water supply options.

At the same time, scholars emphasize strategies to further enhance its efficiency. Liu *et al.* (2018) recommend adjusting release volumes from the Danjiangkou Reservoir to reflect dynamic storage patterns, while Zhang *et al.* (2020) highlight reducing downstream demand and increasing the share of transferred water relative to groundwater extraction in the North China Plain. System-level optimization has also been proposed: Zhao *et al.* (2021) developed a priority-based multi-objective programming (MOP) model to optimize allocation, and Zhou *et al.* (2017) introduced an intelligent distribution method for inter-basin coordination. These studies underscore the need for adaptive operations and optimized allocation to maximize the SNWDP's long-term effectiveness.

4.2.4. *Policies mitigating water pollution*

River and Lake Chief System (RLCS):
Research on the efficiency of the RLCS mainly examines resource utilization and management costs, with findings suggesting that it can improve water governance and optimize allocation. Liu *et al.* (2023b), using 26 indicators across six dimensions, confirmed that strengthened governance under RLCS enhances resource use efficiency. Technological applications further support this, as Tian and Lin (2019) found that integrating GIS and UAVs improves inspection and monitoring. More broadly, the institutionalization of RLCS has streamlined responsibilities, enhanced responsiveness and embedded accountability into cadre evaluation, thereby reducing coordination failures among water agencies (Wang *et al.* 2019a; Maosen *et al.* 2023). Digital platforms and public participation also bolster transparency and real-time monitoring, enabling faster responses to pollution and encroachment (Wu *et al.* 2020).

Nonetheless, implementation efficiency is uneven due to disparities in resources, legal frameworks and basin coordination. County- and township-level offices often face staffing and expertise shortages that limit their effectiveness (Maosen *et al.* 2023). The absence of unified legislation weakens institutional authority, especially for cross-boundary water bodies, while inconsistent evaluation systems foster symbolic rather than substantive enforcement (Li *et al.* 2020). To strengthen long-term efficiency, scholars recommend stronger legal support, standardized performance metrics and better integration of ecological, social and economic dimensions into governance (Liu *et al.* 2023c).

Water Pollution Prevention and Control:
Research shows that the effectiveness of the Water Pollution Prevention and Control Action Plan (WPPCAP) depends on multiple factors, particularly the enforcement capacity of local governments and public participation, with weak supervision and low awareness often leading to suboptimal outcomes (Wang *et al.* 2021a; Li *et al.* 2023). To improve implementation efficiency, scholars have proposed technical and policy-level strategies, such as a zoning method that integrates administrative boundaries with watershed management to support control-unit design (Deng *et al.* 2017a), and stricter discharge standards and refined measures to enhance effectiveness (Zhou *et al.* 2021; Chen 2024b).

Similarly, the performance of transboundary ecological compensation mechanisms is shaped by compensation standards, local enforcement capacity, industrial structure and institutional arrangements, with political support being crucial (Liu and Yuan 2023; Sheng and Han 2022). Comparative analyses show that collaborative cooperation yields the highest system benefits among different cost-sharing models (Ding *et al.* 2022), while evaluations of Yangtze and Yellow River basin policies stress the importance of integrated mechanisms combining water quality, water quantity and dual-control compensation modules (Liu *et al.* 2023a). Joint governance is also critical: mechanisms promoting upstream–downstream coordination help resolve disputes and strengthen regional management (Jing *et al.* 2022), and dynamic game models indicate that central subsidies can incentivize local governments to improve pollution control (Jia *et al.* 2022).

4.3. *Performance in terms of welfare distribution*

4.3.1. *The strictest water resources management policy (SWRM)*

Regarding the welfare aspect, the effects of the SWRM policy are also characterized by both positive and negative outcomes. On the positive side, Feng *et al.* (2018) argued that the policy contributed to improving the Water Resources Carrying Status (WRCS), thus supporting regional sustainable development. Yang *et al.* (2022a) found that WRCS initially increased and then declined following policy implementation, indicating a phased impact on resource pressure regulation.

On the negative side, the policy has posed some constraints on welfare. Feng *et al.* (2018) pointed out that under the constraints of the "Three Red Lines" in water resource management, the upper threshold of the urbanization level in Zhangye City by 2030 would be limited to 48.05%, reflecting the potential restriction of urban development due to water policies. Shah *et al.* (2022) highlighted regional development imbalances, noting that the adoption rate of advanced water use technologies is higher in the eastern region than in the central and western regions. Guo and Wang (2022) criticized the policy for setting unreasonable red lines regarding water use and efficiency, which to some extent hindered the coordination between economic development and individual welfare.

4.3.2. *Policies addressing water scarcity*

Water pricing reforms:
Another important factor influencing the progress of water pricing reform is the potential for such policies to reduce agricultural output and farmers' income, thereby affecting overall household welfare. As a result, assessing the welfare implications of water pricing reform is essential.

Most existing studies emphasize the potential negative welfare impacts of water pricing policies. For instance, several studies report declines in agricultural output — particularly grain production — as a result of increased water prices (Huang *et al.* 2006, 2010; Liao *et al.* 2007). This reduction in output often translates into lower crop revenues and decreased household incomes (Huang *et al.* 2006, 2010; Liao *et al.* 2007; Liu *et al.* 2015). In turn, this can lead to reductions in real GDP, lower consumption levels and overall welfare losses in the agricultural sector (Zhao *et al.* 2015a, 2016; Yi *et al.* 2019). However, offering subsidies to farmers affected by water price reforms has been shown to effectively mitigate income losses and help achieve a win-win outcome (Liu *et al.* 2015; Wang *et al.* 2016).

At the same time, some studies suggest that water pricing reform may also generate positive effects. For example, Shi *et al.* (2024) found that the policy had a positive impact on economic output and rural household income. Tian *et al.* (2024) showed that comprehensive agricultural water pricing reform significantly increased farmer income by 31.9%, with even stronger effects in non-agricultural sectors. These benefits were primarily driven by improvements in Agricultural Green Total Factor Productivity (AGTFP). Additionally, Shi and Shen (2016) found that higher water prices in water-intensive industries had only a minor impact on the macroeconomy, resulting in a slight increase in GDP, modest reductions in household welfare and increased investment.

Water rights reforms:
Understanding how the implementation of water rights reform policies ultimately affects household welfare is a critical yet underexplored issue. Existing studies remain limited, with most analyses conducted at the macro level, and few addressing impacts at the individual or household level.

Among the available literature, most scholars emphasize that, unlike other water-saving management policies, water rights reform does not lead to reductions in agricultural output. In fact, it may even promote agricultural growth. The implementation of water rights reform has been shown to significantly enhance overall grain production capacity, increase agricultural yields and mitigate the economic losses associated with water scarcity in the agricultural sector (Xu *et al.* 2023; Zhang and Li 2024; Liu *et al.* 2025).

In addition, water rights reform can contribute to industrial water conservation without imposing substantial negative impacts on industrial economic performance. It can further stimulate corporate investment through two primary mechanisms: optimizing resource allocation and reducing business risk (Liu *et al.* 2022; Jiang *et al.* 2025). Ultimately, water rights reform is associated with broader economic benefits, with studies estimating that it can increase total economic value added by as much as 4.40% (Xu and Yang 2025).

Adopting agricultural water saving technologies:
The use of water-saving technologies has also yielded notable welfare benefits for farmers and society at large. For individual farmers, these technologies help reduce irrigation costs while enhancing both yield and crop quality, which directly translates into increased income (Chen and Li 2023). Drip irrigation systems, in particular, have shown considerable success in improving the economic returns of farming (Liu *et al.* 2019; Wang *et al.* 2020c).

On a broader societal level, the widespread promotion of agricultural water-saving technologies contributes to alleviating water supply-demand imbalances and improving the ecological environment. These improvements, in turn, enhance people's quality of life (Zhou *et al.* 2022b). Moreover, such technologies support the efficient allocation of water resources and promote the harmonious integration of economic, environmental and social development goals (Tang *et al.* 2015). Their use also plays a role in addressing regional disparities in water access, thus fostering more coordinated and balanced regional development (Blanke *et al.* 2007).

Comprehensive control of groundwater overdraft:
Research on the welfare impacts of the Seasonal Land Fallowing Policy (SLFP) remains limited. Existing studies primarily focus on agricultural output and household income.

On the one hand, SLFP aims to reduce groundwater usage by limiting winter wheat cultivation, which inevitably affects wheat production. Lei *et al.* (2019) found that winter wheat planting area declined from 35.71% (314,053 hectares) in 2013 to 32.98% (289,986 hectares) in 2015, achieving 84% of the WWFP's target of 26,000 hectares fallowed. As a result, wheat output is expected to decline. Ti *et al.* (2021) further suggested that expanding the fallowed area would lead to additional reductions in wheat yields.

On the other hand, SLFP also affects household income levels. Although agricultural income tends to decrease among participating households, overall household income tends to increase (Li and Li 2023). One key factor behind this increase is labor reallocation from agricultural to non-agricultural sectors (Wang *et al.* 2019b). The nature of this shift varies by household type: households without dependents are more likely to pursue off-farm employment in other regions, while those with caregiving responsibilities prefer local non-agricultural jobs (Li and Li 2023).

4.3.3. *Policies resolving unequal water distribution*

To date, several studies have examined the effects of the SNWDP on donor regions, though findings remain mixed. Some scholars argue that the project does not generate significant negative consequences for water source areas. For instance, by comparing counties providing water with those located within a 200-kilometer radius, researchers have found no substantial adverse effects in the source regions, suggesting that the benefits received by water-recipient counties do not come at the expense of donor regions. Cui *et al.* (2025) found that although the project led to a 5.6% decline in per capita agricultural GDP, this was offset by a 5.4% increase in per capita non-agricultural GDP, with no significant change in household consumption. Other studies even report positive economic effects for donor areas (Li *et al.* 2024b). Additionally, Chen and Xie (2010) found no significant impact of water transfers on local climate conditions in source areas. Conversely, other scholars highlight the potential negative impacts of the SNWDP on donor regions. Some studies suggest that the project may increase water scarcity risks in the supply areas, while others warn of elevated risks of saltwater intrusion, with harmful consequences for ecosystems and the environment in the source regions (Gu *et al.* 2012; Webber *et al.* 2015; Liu *et al.* 2020).

Research on the SNWDP's impact on human health remains limited. Zhang *et al.* (2022) found that the project has increased arsenic concentrations — a carcinogenic heavy metal — in surface water across the basin, posing heightened health risks. However, other studies report no significant change in water quality. According to these findings, the Water Quality Index (WQI) in the basin has remained consistently at the "excellent" level before and after the policy's implementation.

4.3.4. *Policies mitigating water pollution*

River and Lake Chief System (RLCS):
The RLCS has shown a positive impact on social welfare, particularly through improvements in living environments, public health and social harmony. By enhancing pollution control and ensuring clean drinking water supplies, the RLCS can directly improve public health outcomes (Wu *et al.* 2020). Moreover, improved river landscapes and water environments contribute to greater life satisfaction and a heightened sense of well-being among residents. Ju *et al.* (2022) introduced the concept of a "River Happiness Index" (RHI), arguing that a "happy" river should maintain ecological health, support high-quality socioeconomic development within its basin, and meet the well-being needs of the population. Public participation is another crucial factor in improving the social benefits of the RLCS. Wu *et al.* (2020) emphasized that encouraging and guiding public involvement in the RLCS helps enhance social governance. Citizen participation can effectively complement and supervise the performance of river chiefs.

However, the RLCS may also have negative welfare implications, particularly due to disparities in implementation outcomes across regions, which could exacerbate inequality. Maosen *et al.* (2023) found notable regional differences in RLCS effectiveness. Song *et al.* (2024) likewise reported that despite the significant achievements of the RLCS in Beijing, evident regional and urban–rural disparities persist in terms of ecological governance outcomes for rivers and lakes.

Water Pollution Prevention and Control:
Research on the welfare impacts of China's WPPCAP remains limited, though existing evidence suggests positive socio-economic effects. Studies indicate that WPPCAP stimulates growth in related industries, including pollution control equipment, environmental monitoring and consulting services, with direct contributions estimated at 1.4 trillion yuan and indirect effects of about 500 billion yuan (Wu *et al.* 2015). These developments are projected to boost GDP by 5.6964 trillion yuan and create 3.98 million non-agricultural jobs (Zhang *et al.* 2015). Additional findings suggest that the policy improves household income and supports population growth, further reinforcing its welfare benefits (Chen 2024b).

Similarly, studies on transboundary ecological compensation governance generally confirm positive welfare outcomes. In Zhejiang, Synthetic Control Method analysis found no adverse effects on the local economy (Chen *et al.* 2021), while a multi-stage DID model for the Xin'an River Basin (2009–2018) revealed that compensation pilots promoted industrial rationalization and upgrading, with dynamic effects across stages (Zheng *et al.* 2021). Broader assessments using ecological footprint and ecosystem service value methods also highlight contributions to environmental equity and sustainable urban development (Yang *et al.* 2022b).

4.4. *Comparative synthesis of policy performance across effectiveness, efficiency and welfare dimensions*

This section offers a comparative synthesis of China's recent water-related policy instruments by evaluating their performance across effectiveness, efficiency and welfare distribution. While earlier sections analyzed each reform individually, a cross-policy perspective helps identify governance patterns, trade-offs and complementarities. Such synthesis provides a more integrative understanding of how diverse instruments function under varying institutional and ecological contexts, offering insights for refining future water policy design.

To support this comparison, Table 2 summarizes the relative performance of the nine major reforms reviewed in this study. Each reform is qualitatively ranked across the three dimensions based on empirical evidence and theoretical reasoning presented in Sec. 4. Overall, most policies demonstrate strong effectiveness, though efficiency and equity outcomes vary considerably. Market-oriented tools like water pricing and water rights reforms achieve higher efficiency but uneven welfare distribution, while ecological compensation and agricultural water-saving technologies provide a more balanced combination of welfare and performance.

Table 2. Comparative Synthesis of Major Water Policies in China (Including Nine Key Instruments)

Policy Instruments	Effectiveness	Efficiency	Welfare Distribution
Strictest Water Resources Management Policy (SWRMP)	High	Medium	Medium
Water Pricing Reforms	Medium	High	Low to Medium
Water Rights Reforms	Medium	High	Medium
Agricultural Water-Saving Technologies	High	Medium	High
Comprehensive Control of Groundwater Overdraft Control	High	Medium	Medium
South–North Water Diversion Project (SNWDP)	High	Low	Mixed
River and Lake Chief System (RLCS)	Medium to High	Medium	Medium
Water Pollution Prevention and Control Action Plan (WPPCAP)	High	Medium	Medium to High
Interprovincial Ecological Compensation Mechanisms	Medium to High	Medium	High

These results highlight the importance of context-specific design and complementary policy mixes.

In terms of effectiveness, command-based measures such as SWRMP and SNWDP achieved notable success in curbing total water use and correcting regional imbalances through strong enforcement structures. Hybrid approaches, including the SLFP and WPPCAP, also performed well by combining regulatory mandates with incentives. Market-oriented reforms — particularly water pricing and rights trading — show potential in urban and industrial sectors, but their impacts in agriculture remain limited by low elasticity, institutional fragmentation and entrenched practices.

In terms of efficiency and welfare distribution, market-based and incentive-compatible mechanisms outperform purely administrative controls when enabling conditions exist, such as defined rights, metering infrastructure and user awareness. Tiered pricing, tradable rights and advanced irrigation technologies have improved allocation and technical efficiency, though rebound effects sometimes offset gains, underscoring the need for monitoring and land-use controls. Infrastructure-heavy projects like the SNWDP face rigid cost structures, while administrative quotas may achieve compliance but with high opportunity costs. Distributional outcomes remain uneven: flat-rate pricing and infrastructure transfers often favor wealthier or urban groups, whereas redistributive mechanisms such as SLFP compensation and WPPCAP's transboundary ecological payments improve equity. Participatory approaches, including localized water rights pilots and river chief initiatives, can enhance legitimacy, though inclusiveness varies. Overall, welfare distribution is most effective when equity is embedded in policy design rather than treated as an afterthought.

5. Concluding Remarks

China's recent water-related policy reforms reflect a bold and evolving effort to balance ecological sustainability, economic efficiency and social equity under complex hydrological and institutional constraints. This review has systematically examined major national initiatives — including the Strictest Water Resources Management Policy, water pricing and rights reforms, agricultural water-saving technologies, groundwater overdraft control, interregional water diversion and pollution control programs — through a unified evaluative framework centered on effectiveness, efficiency and welfare distribution. Evidence shows that many of these policies have yielded significant achievements in curbing water consumption, enhancing supply-demand coordination and reducing pollution intensity. Programs such as the Seasonal Land Fallowing Policy and tiered residential water pricing have demonstrated concrete conservation and governance gains. Meanwhile, institutional innovations such as the River Chief System and ecological compensation for transboundary pollution have improved accountability and fostered intergovernmental cooperation.

However, policy performance across regions and sectors remains uneven, and several unintended effects have emerged. Rebound effects from technological interventions, equity concerns linked to flat pricing mechanisms and implementation asymmetries between affluent and under-resourced regions illustrate the persistent challenges of integrated water governance. Moreover, while China's experience showcases the administrative capacity to scale complex interventions, policy effectiveness is often constrained by limited behavioral incentives, fragmented data infrastructures and varying local governance capabilities. These findings highlight the importance of aligning regulatory design with incentive mechanisms, strengthening policy feedback loops and fostering adaptive governance models that can accommodate regional diversity.

A comparative synthesis across policies reveals that no single governance model performs optimally across all three dimensions. Regulatory tools offer strong enforcement capacity but may lack flexibility or inclusiveness. Market-based instruments can enhance allocative efficiency but require institutional maturity to avoid unintended distributional consequences. Hybrid models — such as those integrating subsidies, pricing and command structures — demonstrate the most balanced performance when contextually adapted and well-resourced. These patterns underscore the importance of selective integration and calibration of instruments based on sectoral characteristics and regional implementation capacity. They also reinforce the theoretical proposition that the effectiveness of water governance hinges not only on the choice of instruments but on their institutional compatibility and coordination.

To advance the field, future research should prioritize interdisciplinary and multi-scalar approaches. First, more causal inference studies are needed to rigorously assess the long-term impacts of reforms on water use behavior, environmental outcomes and distributional equity. Second, comparative studies — both within China's diverse ecological and institutional contexts, and across countries — can help reveal structural conditions under which hybrid water governance models are most effective. Third, researchers should explore how digital technologies, such as real-time monitoring and smart irrigation systems, can be leveraged not only for efficiency gains but also for improving transparency and public engagement in water governance. Finally, further work is needed to evaluate the interactions between fiscal decentralization, bureaucratic incentives and policy implementation quality, particularly in rural and frontier areas.

Importantly, China's experience has broader implications for the Global South. As many developing countries confront similar challenges — limited water availability, institutional fragmentation and socio-economic disparities — China's hybrid approach of combining centralized mandates with localized experimentation and market mechanisms offers instructive lessons. Rather than promoting a one-size-fits-all solution, this review underscores the value of context-specific, evidence-based and politically feasible strategies for sustainable water governance. Strengthening international dialogues on water economics and policy — through South-South knowledge exchange and joint empirical frameworks — will be crucial to addressing the global water crisis in an equitable and efficient manner.

China's water reform experience offers valuable insights for other countries characterized by water stress, climate variability and centralized governance structures — particularly in the Global South. Nations such as India, Egypt, Iran and South Africa share similar challenges in managing limited freshwater resources under increasing climatic uncertainty and institutional complexity. China's pragmatic, trial-based policy style — marked by hybrid approaches that integrate market tools within a regulatory framework — can serve as a reference model. For example, the use of performance-based administrative accountability (as in the RLCS), and cross-regional compensation (as in ecological payment schemes), could inspire similar mechanisms elsewhere. Moreover, the evolution from rigid command-and-control to more adaptive and incentive-based reforms demonstrates the importance of policy flexibility. While China's experience cannot be transplanted wholesale due to contextual differences, its strategies illustrate how integrated, multi-scalar governance — blending state authority with market adaptation — can deliver measurable improvements in water outcomes under constrained conditions.

Acknowledgment

This research was supported by the Major Project of the National Social Science Foundation of China, titled "Research on the Modernization of Agriculture and Rural Areas in Countries with Large Populations" (Project No. 23&ZD108).

ORCID

Jinxia Wang https://orcid.org/0000-0002-8768-2707
Ruoying Mei https://orcid.org/0009-0001-8326-9376
Wei Chao https://orcid.org/0009-0004-9963-8297

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