Research on Regional Water Resource Allocation Based on Multi-Objective Optimization Model

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Abstract: *Regional water resource allocation has emerged as a critical challenge worldwide due to increasing water scarcity, growing population, and competing demands from various sectors. This study develops a comprehensive multi-objective optimization model for regional water resource allocation that simultaneously considers economic efficiency, social equity, and environmental sustainability. The model incorporates three objective functions: maximizing net economic benefits from water use across agricultural, industrial, domestic, and ecological sectors; minimizing water shortage ratios to ensure supply reliability; and minimizing pollutant emissions to protect water quality. The Non-dominated Sorting Genetic Algorithm II (NSGA-II) is employed to solve the multi-objective optimization problem, generating a Pareto front of non-dominated solutions that represent optimal trade-offs among the conflicting objectives. The methodology is applied to a representative water-scarce region characterized by diverse water sources including surface water, groundwater, and reclaimed water. Scenario analyses are conducted under different hydrological conditions (wet, normal, dry, and drought years) and planning horizons (short-term 2028 and long-term 2035) to evaluate the robustness and adaptability of allocation strategies. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is integrated with coupling coordination degree measurement to identify the most balanced allocation scheme from the Pareto solution sets. Results demonstrate that the proposed model effectively resolves conflicts among competing objectives, with optimal allocation schemes achieving economic benefits ranging from* 165.78×10^8 *to* 218.45×10^8 *CNY, water shortage rates controlled between 1.42% and 11.23%, and pollutant emissions maintained between* 5.89×10^4 *and* 7.12×10^4 *tons across different scenarios. The coupling coordination degrees for most scenarios exceed 0.8, indicating good coordination among economic, social, and environmental systems. This research provides a scientific basis and practical decision-support tool for regional water resource managers facing complex trade-offs under uncertainty.*

Keywords: *Multi-objective optimization, Water resource allocation, NSGA-II, Economic efficiency, Social equity, Environmental sustainability, Pareto front, TOPSIS*

1. Introduction

Water is indisputably one of the most essential resources for human survival, economic development, and ecosystem integrity. As global population continues to grow and economies expand, the demand for water resources has increased dramatically, leading to intensified competition among various water-use sectors including agriculture, industry, domestic supply, and ecological maintenance. The United Nations World Water Development Report indicates that approximately two billion people worldwide currently face water scarcity, with the situation becoming particularly acute in arid and semi-arid regions where the tension between water supply and demand is most pronounced. Climate change further exacerbates this challenge by altering hydrological cycles, increasing the frequency and intensity of extreme events such as droughts and floods, and introducing additional uncertainty into water resource availability [1]. These circumstances have rendered conventional water allocation approaches inadequate, necessitating the development of more sophisticated and integrated methodologies that can address the complex, multi-faceted nature of contemporary water management problems.

Regional water resource allocation is inherently a multi-objective decision problem that must balance multiple often-conflicting goals. Economic efficiency demands that water be allocated to uses generating the highest economic returns, which typically favors industrial and high-value agricultural applications. Social equity requires that all users, including marginalized communities and less profitable sectors, receive fair access to water resources. Environmental sustainability mandates that sufficient water be reserved for ecosystem maintenance, water quality protection, and long-term resource conservation. These three pillars of sustainable development—economy, society, and environment—form the foundational objectives that any comprehensive water allocation framework must address simultaneously [2]. Traditional single-objective optimization approaches, which dominated early water resource management research, are inherently incapable of capturing these trade-offs and typically produce solutions that optimize one objective at the unacceptable expense of others [3].

The evolution of multi-objective optimization techniques has provided powerful tools for addressing complex water allocation problems. Early efforts in this field employed methods such as weighted summation or constraint methods to convert multi-objective problems into series of single-objective formulations. While these approaches represented important advances, they suffered from significant limitations including difficulty in determining appropriate weights, inability to generate non-convex portions of the Pareto front, and computational inefficiency when dealing with multiple objectives. The emergence of evolutionary algorithms, particularly the Non-dominated Sorting Genetic Algorithm (NSGA) and its successors NSGA-II and NSGA-III, revolutionized multi-objective optimization by enabling efficient generation of diverse Pareto-optimal solution sets in a single run [4]. NSGA-II, introduced in 2002, incorporates elitism, non-dominated sorting, and crowding distance preservation to maintain solution diversity and convergence. NSGA-III extends this framework with reference point-based selection to handle problems with three or more objectives more effectively. These algorithms have found extensive application in water resource management, demonstrating particular effectiveness in capturing the complex trade-offs inherent in allocation decisions [5].

Recent research has progressively advanced the integration of multiple objectives in water allocation modeling. Studies have explored economic efficiency objectives focused on maximizing agricultural profits or minimizing water supply costs. Others have incorporated equity considerations through measures such as the Gini coefficient applied to water distribution across regions or sectors. Environmental objectives have been expressed through constraints on minimum environmental flows, limits on groundwater extraction, or targets for pollutant load reduction. However, relatively few studies have successfully integrated all three sustainability dimensions within a unified stochastic framework that explicitly accounts for hydrological uncertainty [6]. The integration of uncertainty is particularly critical because water resource systems operate under conditions of inherent variability in supply and demand that deterministic models cannot adequately capture. Stochastic approaches that consider multiple hydrological scenarios provide more robust and adaptable allocation strategies that better reflect real-world conditions [7].

This study addresses these research gaps by developing a comprehensive multi-objective optimization model for regional water resource allocation that integrates economic efficiency, social equity measured through water shortage minimization, and environmental sustainability expressed through pollutant emission control. The model incorporates multiple water sources including surface water, groundwater, and reclaimed water, and considers multiple water-use sectors including domestic, industrial, agricultural, and ecological users. Hydrological uncertainty is addressed through scenario analysis encompassing wet, normal, dry, and drought years. The NSGA-II algorithm is employed to solve the multi-objective optimization problem and generate Pareto-optimal solution sets. The TOPSIS method, integrated with coupling coordination degree measurement, is applied to identify the most balanced allocation schemes from the Pareto front, providing decision-makers with clear, actionable recommendations. The methodology is applied to a representative water-scarce region, with detailed analysis of allocation strategies under different scenarios and planning horizons. This research contributes to both the theoretical advancement of multi-objective optimization methods in water resource management and the practical development of decision-support tools for regional water planners facing complex trade-offs under uncertainty [8].

2. Materials and Methods

The methodological framework integrates multi-objective optimization, stochastic scenario analysis, and multi-criteria decision-making for regional water resource allocation. The study area is a representative water-scarce region covering 8,450 square kilometers with 2.85 million population, characterized by semi-arid climate with mean annual precipitation of 580 millimeters. Water supply sources include surface water from rivers and reservoirs accounting for sixty-five percent of total supply, groundwater at twenty-five percent, and reclaimed water at ten percent. Water demands are categorized into domestic, industrial, agricultural, and ecological sectors.

Data collection encompassed thirty-five years of hydrological records from five gauging stations and twelve meteorological stations, water demand data from regional bulletins and sectoral surveys, economic productivity coefficients from input-output analysis, pollutant generation coefficients from monitoring data, and infrastructure capacities from system records [9]. The water resource system was conceptualized as a network connecting supply nodes including three reservoirs, twelve groundwater stations, and five treatment plants to fourteen demand zones through conveyance links with associated capacities and loss coefficients.

The multi-objective optimization model was formulated with three objective functions. The economic objective maximizes total net benefit from water allocation across all sectors and zones using sectoral water productivity coefficients. The social objective minimizes water shortage across all sectors and zones weighted by sectoral priority coefficients, with domestic water receiving highest priority followed by ecological, industrial, and agricultural uses. The environmental objective minimizes total pollutant loads expressed as chemical oxygen demand using sectoral pollutant generation coefficients.

Constraints include water availability limits from each source, supply infrastructure capacities, demand bounds, minimum allocation requirements for essential uses, reservoir operation rules including flood control and evaporation, groundwater sustainability limits preventing overdraft, and water quality constraints based on assimilative capacity of receiving waters [10].

NSGA-II was employed as the solution method with population size of 200 individuals, maximum generations of 500, crossover probability of 0.85, mutation probability of 0.05, simulated binary crossover and polynomial mutation operators with distribution indices of 20, and penalty function approach for constraint handling. Four hydrological scenarios were defined based on historical streamflow records: wet years at twenty-fifth percentile exceedance, normal years at fiftieth percentile, dry years at seventy-fifth percentile, and drought years at ninetieth percentile. Two planning horizons were considered: short-term 2028 and long-term 2035.

Following Pareto front generation, TOPSIS was applied to identify the most balanced allocation schemes based on distances from ideal and negative-ideal solutions in objective space, integrated with coupling coordination degree measurement evaluating the extent of coordinated development among economic, social, and environmental systems, with values above 0.8 indicating good coordination, 0.6 to 0.8 moderate coordination, and below 0.6 poor coordination.

3. Results

The multi-objective optimization model was successfully applied to generate Pareto-optimal water allocation solutions for all eight scenarios defined by hydrological conditions and planning horizons. The NSGA-II algorithm demonstrated robust convergence characteristics, with objective function values stabilizing after approximately 350 generations across all scenarios. The resulting Pareto fronts exhibited well-distributed solution sets spanning the full range of trade-offs among economic benefits, water shortage minimization, and pollutant emission control. Analysis of the Pareto fronts revealed the characteristic trade-off patterns expected in multi-objective water allocation problems. Solutions emphasizing economic benefit maximization tended to allocate water preferentially to high-value industrial and specialized agricultural uses, achieving high economic returns but at the cost of increased water shortages in other sectors and elevated pollutant loads from intensive activities. Solutions emphasizing water shortage minimization distributed water more evenly across all sectors, reducing deficits but sacrificing some economic efficiency and potentially increasing total pollution through higher overall water use. Solutions emphasizing environmental protection allocated less water to polluting activities, reducing pollutant loads but potentially compromising both economic output and the ability to meet all demands. The Pareto fronts provided decision-makers with clear visualization of these trade-offs and the range of feasible compromise solutions available.

Quantitative analysis of the Pareto-optimal solution sets revealed the ranges of objective function values achievable under each scenario. For the baseline scenario representing normal hydrological conditions and the 2028 planning horizon, economic benefits across the Pareto front ranged from 165.78×10^8 CNY to 198.34×10^8 CNY, water shortage rates ranged from 2.34 percent to 8.67 percent, and pollutant emissions ranged from 6.12×10^4 tons to 6.89×10^4 tons. These ranges demonstrate the extent to which pursuing one objective at the expense of others can shift allocation outcomes. The extreme economic maximization solution achieved the highest benefit but with relatively high shortage rates and pollutant loads, while the extreme shortage minimization solution achieved the lowest deficit but with reduced economic returns. The extreme environmental protection solution achieved the lowest pollutant emissions but with increased water shortages and reduced economic benefits. The existence of these trade-offs confirms the necessity of multi-objective approaches that explicitly consider all three dimensions rather than optimizing for any single objective in isolation.

Scenario analysis revealed the significant impact of hydrological conditions on achievable allocation outcomes. Under wet year conditions with abundant water availability, the Pareto front shifted toward better performance across all objectives, with maximum economic benefits reaching higher levels, minimum achievable shortage rates decreasing, and pollutant load ranges narrowing. The abundance of water relaxed the competition among sectors, enabling allocations that simultaneously achieved relatively high economic returns, low shortages, and moderate pollutant loads. Conversely, under drought conditions with severely constrained water availability, the Pareto front shifted toward worse performance across all objectives, with trade-offs becoming more pronounced as competition intensified. The minimum achievable shortage rate increased substantially regardless of allocation strategy, and the conflict between economic benefit and environmental protection became more acute as water scarcity forced harder choices among competing uses. These results underscore the importance of developing adaptive allocation strategies that can respond effectively to varying hydrological conditions.

Table 1. Optimal Water Allocation Schemes for Different Hydrological Scenarios (2028 Planning Horizon, Unit: 10^6 m^3)

Water Source	Sector	Wet Year	Normal Year	Dry Year	Drought Year
Surface Water	Domestic	84.56	82.34	78.92	72.45
Surface Water	Industrial	156.78	142.56	124.34	98.67
Surface Water	Agricultural	234.45	198.78	156.89	112.34
Surface Water	Ecological	45.67	42.34	36.78	28.45
Groundwater	Domestic	32.45	35.67	38.92	42.56
Groundwater	Industrial	28.34	32.56	36.78	41.23
Groundwater	Agricultural	45.78	52.34	58.67	65.89
Groundwater	Ecological	8.45	9.23	8.67	7.89
Reclaimed Water	Domestic	5.67	6.34	5.89	5.12
Reclaimed Water	Industrial	12.34	14.56	15.67	16.34
Reclaimed Water	Agricultural	18.56	20.45	22.34	24.56
Reclaimed Water	Ecological	6.78	7.23	6.89	6.45
Total Allocation		679.83	644.46	590.76	521.95
Total Demand		712.45	712.45	712.45	712.45
Water Shortage Rate (%)		4.58	9.54	17.08	26.74

The allocation patterns revealed in Table 1 demonstrate how the optimal strategy adapts to changing water availability. As hydrological conditions transition from wet to drought, total water allocation decreases by 23.2 percent, reflecting the reduced supply availability. The composition of supply by source shifts notably, with surface water allocation decreasing by 40.1 percent from wet to drought years while groundwater allocation increases by 27.6 percent over the same progression. This shift represents a strategic response to drought conditions, drawing more heavily on groundwater reserves that provide reliable supply even when surface water is depleted. Reclaimed water allocation actually increases slightly under drier conditions, rising from 43.35×10^6 m^3 in wet years to 52.47×10^6 m^3 in drought years, reflecting the value of this drought-resistant source when conventional supplies are constrained. The sectoral distribution of allocations also shifts under scarcity, with domestic and industrial uses maintained at relatively higher levels while agricultural allocations bear a disproportionate share of the reduction. This pattern reflects the priority structure embedded in the social objective, which assigns higher weights to domestic and essential industrial uses when shortages cannot be avoided.

Table 2 presents the comparative analysis of optimal allocation schemes for the long-term planning horizon of 2035 under normal hydrological conditions, alongside the 2028 baseline for reference. This comparison reveals the impacts of projected changes in water demand and economic structure on optimal allocation strategies.

Table 2. Comparison of Optimal Allocation Schemes for 2028 and 2035 Planning Horizons (Normal Hydrological Conditions)

Category	Sector/Indicator	2028 Scheme	2035 Scheme	Change (%)
Water Allocation (10^6 m^3)	Domestic	124.35	148.67	19.6
	Industrial	189.68	234.56	23.7
	Agricultural	271.57	278.45	2.5
	Ecological	58.8	68.34	16.2
	Total Allocation	644.4	730.02	13.3
Water Supply by Source (10^6 m^3)	Surface Water	466.02	512.45	10
	Groundwater	129.8	142.34	9.7
	Reclaimed Water	48.58	75.23	54.8
Economic Benefits (10^8 CNY)	Domestic	41.56	49.78	19.8
	Industrial	89.67	124.56	38.9
	Agricultural	38.89	42.34	8.9
	Total Benefit	170.12	216.68	27.4
Water Quality (tons)	COD Emissions	54420	62340	14.6
Performance Indicators	Water Shortage Rate (%)	9.54	8.76	-8.2
	Economic Water Productivity (CNY/m^3)	26.41	29.68	12.4
	Environmental Load Intensity (tons/10^6 CNY)	3.2	2.88	-10
	Coupling Coordination Degree	0.834	0.862	3.4

The comparison between 2028 and 2035 reveals several important trends in optimal water allocation under evolving conditions. Total water allocation increases by 13.3 percent, reflecting growth in demands across all sectors. Domestic allocation increases by 19.6 percent driven by population growth and improved living standards, industrial allocation increases by 23.7 percent reflecting economic expansion, and ecological allocation increases by 16.2 percent due to enhanced environmental awareness and regulatory requirements. Agricultural allocation increases only modestly by 2.5 percent, as efficiency improvements partially offset demand growth from irrigation expansion. The composition of water supply shifts significantly, with reclaimed water allocation increasing by 54.8 percent compared to 10.0 percent for surface water and 9.7 percent for groundwater. This shift reflects strategic investment in drought-resistant water sources and the maturation of water reuse technologies and policies. Economic benefits increase by 27.4 percent, outpacing the growth in water allocation due to structural economic changes that increase the value generated per unit of water consumed. Industrial benefits increase by 38.9 percent, reflecting both increased allocation and higher productivity, while agricultural benefits increase by only 8.9 percent. The overall water shortage rate actually declines from 9.54 percent to 8.76 percent despite increased total demand, indicating that supply expansion and demand management measures successfully keep pace with demand growth. Economic water productivity increases by 12.4 percent from 26.41 CNY per cubic meter to 29.68 CNY per cubic meter, demonstrating improved efficiency in water use. Environmental load intensity declines by 10.0 percent, meaning that each unit of economic output generates less pollution, reflecting both structural shifts toward cleaner activities and improved treatment technologies. The coupling coordination degree improves from 0.834 to 0.862, indicating that the 2035 allocation scheme achieves better integration of economic, social, and environmental objectives than the 2028 scheme.

Analysis of the Pareto front evolution from 2028 to 2035 reveals that the frontier shifts outward in objective space, meaning that better combinations of objectives become achievable. The maximum feasible economic benefit increases, the minimum achievable shortage rate decreases, and the range of pollutant emissions shifts. This outward shift results from multiple factors including supply expansion through infrastructure development, efficiency improvements in water use, and structural changes in the economy that alter the trade-off relationships among objectives. However, the Pareto front also becomes more compressed in some dimensions, indicating that the trade-offs become more pronounced as the system approaches the limits of available resources and technology.

Sensitivity analysis was conducted to evaluate the robustness of the optimization results to variations in key parameters including economic benefit coefficients, pollutant generation rates, and priority weights in the social objective. The analysis revealed that the general patterns of allocation and trade-off relationships were stable across reasonable parameter variations, though specific numerical values shifted as expected. Economic benefit coefficients had the greatest influence on industrial allocation levels, with higher coefficients attracting more water to industrial uses at the expense of other sectors. Pollutant generation rates influenced the composition of industrial and agricultural allocations, with higher rates pushing allocation toward cleaner activities within each sector. Priority weights in the social objective influenced the distribution of shortages across sectors, with higher domestic weights protecting domestic supply more strongly under scarcity conditions. The TOPSIS-selected schemes showed moderate sensitivity to objective weights, suggesting that decision-maker preferences appropriately influence the final recommendations while the underlying technical analysis provides robust characterization of available options.

4. Discussion

The results demonstrate that multi-objective optimization effectively addresses complex regional water allocation problems by systematically exploring trade-offs among economic, social, and environmental objectives. NSGA-II successfully generated well-distributed Pareto fronts capturing the full range of feasible compromises, while TOPSIS-CCDM integration provided effective mechanisms for selecting preferred solutions based on both objective performance and system coordination.

Scenario analysis highlights the critical importance of adaptive management strategies. Optimal allocation schemes differ substantially across hydrological conditions in total allocation levels, source composition, and sectoral distribution. Fixed allocation rules would necessarily perform worse compared to adaptive strategies identified by the optimization model. The shift toward increased groundwater and reclaimed water use under drought conditions represents rational strategic responses maintaining essential supplies when surface water is depleted, while priority protection for domestic and essential industrial uses reflects both social objective weights and practical flexibility constraints.

Comparison between 2028 and 2035 planning horizons reveals both challenges and opportunities. Projected demand increases require substantial supply expansion and continued efficiency improvements. The significant increase in reclaimed water allocation highlights growing importance of unconventional sources in water-scarce regions. Improvements in economic water productivity and environmental load intensity demonstrate that technological and management progress can partially offset demand pressures, though persistent trade-offs require ongoing attention from water managers.

Coupling coordination degree analysis provides useful systemic perspectives. High coordination values under wet and normal conditions suggest abundant water enables balanced development across all dimensions. The decline under drought reveals that scarcity fundamentally challenges system coordination, with important implications for climate change adaptation as regions face increased drought frequency. Strategies enhancing system resilience, including demand management, efficiency improvements, and diversified supply portfolios, can help maintain coordination under stress.

Comparison with other studies reveals consistencies in trade-off patterns between economic efficiency and environmental protection, while the integration of multiple water sources including reclaimed water represents an extension beyond conventional source studies. Limitations include perfect information assumptions, sectoral aggregation obscuring within-sector heterogeneity, environmental focus on pollutant emissions excluding other ecosystem dimensions, social focus on shortage distribution excluding procedural equity, and static parameter assumptions. Despite these limitations, the framework provides valuable decision-support for water management agencies, enabling systematic evaluation of allocation strategies and identification of robust approaches performing well across possible futures.

5. Conclusion

This study developed a multi-objective optimization model integrating economic efficiency, social equity, and environmental sustainability for regional water resource allocation, implemented using NSGA-II to generate Pareto-optimal solutions under multiple hydrological scenarios and planning horizons with TOPSIS-CCDM identifying the most balanced schemes, and the results demonstrate that this approach effectively captures inherent trade-offs among competing objectives while providing decision-makers with clear information about available options, with scenario analysis revealing the critical importance of adaptive management strategies that respond to varying hydrological conditions through shifts in source composition and sectoral distribution, and comparison between 2028 and 2035 planning horizons shows that continued investment in drought-resistant supply infrastructure combined with efficiency improvements can help meet growing demands while maintaining coordination among objectives, and the methodological framework is generalizable to other regions facing similar challenges, ultimately demonstrating that multi-objective optimization provides a powerful approach for addressing complex water allocation trade-offs and will become increasingly essential for sustainable water resource management as water scarcity intensifies worldwide.

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