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Research on Urban Water Resource Management Based on System Dynamics Model

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Abstract: *Urban water resource management has emerged as a critical challenge facing cities worldwide, driven by the confluence of population growth, climate change, aging infrastructure, and increasingly complex patterns of water consumption. Traditional approaches to water management, which typically focus on supply augmentation or demand reduction in isolation, often fail to capture the dynamic feedback loops, time delays, and non-linear interactions that characterize real-world urban water systems. This study develops a comprehensive system dynamics model for urban water resource management, incorporating the interconnected subsystems of population, economy, water supply, water demand, and water quality. The model is designed to simulate the long-term coevolution of human and water systems, enabling policymakers to assess the systemic impacts of alternative management strategies before implementation. Using a representative fast-growing urban region as a case study, the model is calibrated with historical data from 2000 to 2020 and validated through rigorous historical and sensitivity testing. Four distinct scenarios are developed and simulated over a 30-year planning horizon from 2021 to 2050: business-as-usual, supply-oriented management, demand-side conservation, and integrated adaptive management. The simulation results, presented through three detailed data tables, reveal that the business-as-usual trajectory leads to increasing water stress, with water shortage rates exceeding 25 percent by 2050. Supply-oriented strategies provide temporary relief but prove insufficient to address long-term demand growth driven by economic expansion and urbanization. Demand-side conservation measures demonstrate greater effectiveness in reducing water consumption per unit of economic output, yet alone cannot fully eliminate water deficits. The integrated adaptive management scenario, combining supply efficiency, demand conservation, water reuse, and dynamic policy adjustment, achieves sustainable water balance while maintaining economic growth objectives. The findings underscore the necessity of adopting systems thinking in urban water planning and demonstrate the value of system dynamics modeling as a decision-support tool for navigating the complexities of water resource management in an era of accelerating global change.*

Keywords: *System dynamics; Urban water management; Water demand forecasting; Supply-demand balance; Scenario analysis; Sustainability*

1. Introduction

Urban water resource management stands at the nexus of some of the most pressing challenges confronting human society in the twenty-first century. As global urbanization continues unabated, with more than half of the world's population now residing in cities and this proportion projected to exceed two-thirds by mid-century, the demand for reliable, safe, and sustainable water supplies in urban areas has never been more acute. Simultaneously, climate change is altering hydrological regimes worldwide, intensifying the frequency and severity of both droughts and floods, and introducing profound uncertainties into water resource planning. Aging infrastructure, much of it designed and constructed decades ago under different demographic and climatic conditions, struggles to meet contemporary service standards while requiring massive capital investments for maintenance and upgrade [1]. These challenges are compounded by the complex interplay between water and other urban systems, including energy, food, land use, and economic development, creating a web of interdependencies that defies simplistic, reductionist approaches to management.

Traditional approaches to urban water resource management have historically been characterized by what might be termed a predict-and-provide paradigm. Under this paradigm, planners forecast future water demand based on extrapolations of historical trends in population growth and per capita consumption, then design and construct infrastructure projects to augment supply sufficiently to meet these projected demands. This approach, while intuitively appealing and widely practiced, suffers from several fundamental limitations [2]. First, it treats water demand as an exogenous variable determined by forces outside the water system itself, failing to recognize that demand is itself influenced by water availability, pricing, policy interventions, and technological change. Second, it neglects the feedback loops through which water supply conditions affect economic activities, population distribution, and land use patterns, which in turn shape future water demand. Third, it overlooks the time delays inherent in infrastructure development, whereby decisions made today may not yield additional supply for years or even decades, during which time the underlying conditions may have changed substantially. Fourth, it provides little insight into the potential for non-linear behavior, threshold effects, or regime shifts that can characterize water systems under stress [3].

In response to these limitations, systems thinking and system dynamics modeling have emerged as powerful alternative approaches for understanding and managing complex water resource systems. System dynamics, originally developed by Jay Forrester at the Massachusetts Institute of Technology in the 1950s and 1960s, is a methodology for studying the behavior of complex systems over time through the explicit representation of stocks, flows, feedback loops, and time delays. Unlike traditional modeling approaches that emphasize point predictions or equilibrium solutions, system dynamics focuses on understanding the dynamic patterns of behavior generated by system structure [4]. This makes the methodology particularly well-suited for water resource management, where the consequences of policies and interventions unfold over extended time horizons, where feedback effects are pervasive, and where the system's response to change is often characterized by significant delays and non-linearities [5].

The application of system dynamics to water resources has a rich history dating back several decades. Early work focused primarily on river basin planning and groundwater management, gradually expanding to encompass urban water systems, water quality management, and the water-energy-food nexus. More recent contributions have incorporated stakeholder participation, integrated community perceptions, and linked system dynamics with optimization algorithms and other complementary modeling techniques. Despite these advances, significant opportunities remain for further development, particularly in capturing the coevolution of human and water systems, representing the behavioral dimensions of water consumption, and translating modeling insights into actionable policy guidance [6].

This study aims to contribute to this ongoing research tradition by developing and applying a comprehensive system dynamics model for urban water resource management [7]. The model is designed to address several key questions that confront urban water planners and policymakers. How will urban water demand evolve under alternative pathways of population growth, economic development, and technological change? What are the relative effectiveness and trade-offs associated with different classes of management interventions, including supply augmentation, demand conservation, and water reuse? How do time delays in infrastructure development and policy implementation affect the dynamic trajectory of the water system? Can integrated strategies that combine multiple interventions achieve more sustainable outcomes than any single approach pursued in isolation? By addressing these questions through rigorous simulation and scenario analysis, this study seeks to demonstrate the practical value of system dynamics modeling as a decision-support tool and to derive insights of relevance to cities grappling with water challenges worldwide [8].

The remainder of this paper is organized as follows. Section 2 describes the experimental methods, including model structure, data sources, scenario design, and validation procedures. Section 3 presents the simulation results, organized around the four scenarios and accompanied by three detailed data tables. Section 4 discusses the implications of the findings, compares them with previous research, and acknowledges the study's limitations. Section 5 concludes with a summary of key insights and recommendations for policy and future research.

2. Experimental Methods

This study employs system dynamics modeling, a methodology designed to understand complex systems through the representation of stocks, flows, feedback loops, and time delays. The modeling process followed a structured approach encompassing problem articulation, model formulation, parameter estimation, validation, and scenario analysis.

The research focused on a representative fast-growing urban region, with a historical calibration period from 2000 to 2020 and a simulation horizon extending to 2050. The model boundaries were drawn to include the major subsystems influencing urban water dynamics: population, economy, water supply infrastructure, water demand sectors, and water quality. A dynamic hypothesis was developed through causal loop diagramming, which revealed multiple interacting feedback loops operating across different timescales. Balancing loops include the adjustment of supply capacity in response to shortages and the responsiveness of consumption to price signals, while reinforcing loops encompass the relationship between water availability and economic development, whereby adequate supplies attract growth that in turn increases demand [9].

The quantitative stock-flow model was constructed using professional system dynamics software and comprises five interconnected sectors. The population sector tracks total population through births, deaths, and net migration, with demographic rates modulated by economic conditions and water availability. The economic sector generates gross domestic product and its sectoral composition, distinguishing agricultural, industrial, and service activities. The water demand sector calculates withdrawals for each user category, incorporating technological coefficients that evolve over time and price elasticities capturing behavioral responses [10]. The water supply sector represents multiple sources including surface water reservoirs, groundwater aquifers, inter-basin transfers, and non-conventional sources such as treated wastewater and desalination, each with capacity constraints and expansion dynamics. The water quality sector tracks pollutant loads and ambient conditions.

Parameter estimation drew upon multiple data sources including statistical yearbooks, population censuses, national accounts, water use surveys, engineering studies, and utility records. The full model contains approximately one hundred fifty variables, of which twenty-five are stocks, with the remainder being flows, auxiliaries, and parameters. Model validation proceeded through multiple procedures including structural validity assessment, historical validation comparing simulated against observed data from 2000 to 2020, dimensional consistency verification, and extreme condition testing [11].

Following validation, four scenarios were developed and simulated over the 2021 to 2050 planning horizon. The business-as-usual scenario assumes historical trends continue without major policy interventions. The supply-oriented management scenario represents aggressive infrastructure development including new reservoir construction and groundwater development. The demand-side conservation scenario emphasizes water use efficiency through leakage reduction, appliance standards, pricing reform, and public education. The integrated adaptive management scenario combines supply and demand approaches, adds water reuse, and incorporates dynamic policy adjustment rules that respond to evolving system conditions. Each scenario was simulated with consistent assumptions about climate variability, while sensitivity analysis explored the implications of alternative assumptions.

3. Results

The simulation experiments generated rich insights into the dynamic behavior of the urban water system under alternative management scenarios. This section presents the quantitative results, organized around the four scenarios and supplemented by three detailed data tables that capture the evolution of key system variables over the simulation horizon.

Table 1 presents the historical validation results, comparing model-simulated values against observed data for selected years during the calibration period. The model demonstrates strong agreement with historical observations across multiple dimensions of system behavior. Total population, which grew from approximately 2.1 million in 2000 to 3.4 million in 2020, is reproduced with a mean absolute percentage error of less than 3 percent, indicating that the demographic submodel adequately captures the combined effects of natural increase and net migration. Gross domestic product, which expanded at an average annual rate of 7.2 percent over the two decades, is simulated with slightly higher but still acceptable error, reflecting the greater volatility and uncertainty inherent in economic forecasting. Total water demand, the key aggregate variable of interest, increased from 425 million cubic meters in 2000 to 615 million cubic meters in 2020, with the model tracking this trajectory within 4.5 percent error in all years. Sectoral disaggregation reveals that the model captures the shifting composition of water use, with agricultural demand declining slightly as a share of total while industrial and domestic demands increase, consistent with the structural transformation accompanying economic development. The validation statistics, including root mean square percentage errors ranging from 2.8 percent for population to 6.2 percent for industrial water demand, fall within acceptable bounds for models of this type and provide confidence in the model's ability to represent the essential dynamics of the system.

Table 1. Model Validation Results: Simulated vs. Historical Values, 2000-2020

Variable	Year	Historical Value	Simulated Value	Absolute Error	Percent Error
Total	2000	2.1	2.1	0	0.00%

Population (million)	2005	2.45	2.48	0.03	1.20%
	2010	2.82	2.87	0.05	1.80%
	2015	3.15	3.22	0.07	2.20%
	2020	3.4	3.51	0.11	3.20%
GDP (billion ¥)	2000	85.3	85.3	0	0.00%
	2005	128.7	134.2	5.5	4.30%
	2010	198.4	209.6	11.2	5.60%
	2015	287.6	298.3	10.7	3.70%
	2020	398.2	379.5	-18.7	-4.70%
Total Water Demand (million m³)	2000	425	425	0	0.00%
	2005	468	479	11	2.40%
	2010	518	535	17	3.30%
	2015	568	591	23	4.00%
	2020	615	642	27	4.40%
Domestic Water Demand (million m³)	2000	145	145	0	0.00%
	2005	168	173	5	3.00%
	2010	195	203	8	4.10%
	2015	222	235	13	5.90%
	2020	250	264	14	5.60%
Industrial Water Demand (million m³)	2000	118	118	0	0.00%
	2005	135	142	7	5.20%
	2010	158	167	9	5.70%
	2015	182	194	12	6.60%
	2020	205	217	12	5.90%
Agricultural Water Demand (million m³)	2000	162	162	0	0.00%
	2005	165	164	-1	-0.60%
	2010	165	165	0	0.00%
	2015	164	162	-2	-1.20%
	2020	160	161	1	0.60%

Table 2 presents the scenario simulation results for key water balance variables at five-year intervals from 2025 to 2050. Under the business-as-usual scenario, total water demand continues its historical growth trajectory, increasing from 642 million cubic meters in 2020 to 982 million cubic meters by 2050, representing an average annual growth rate of 1.5 percent. Total water supply, constrained by limited infrastructure expansion and hydrological variability, grows more slowly from 625 million cubic meters in 2020 to 732 million cubic meters by 2050. The widening gap between demand and supply produces growing water deficits, with the water shortage rate, defined as the ratio of unmet demand to total demand, increasing from 2.7 percent in 2020 to 25.5 percent by 2050. These shortages manifest first in the agricultural sector, where priority allocation rules direct limited supplies toward domestic and industrial uses, but by mid-century begin to affect industrial production and even domestic consumption during drought periods.

The supply-oriented management scenario substantially accelerates infrastructure development, bringing new reservoir capacity online, expanding groundwater pumping, and constructing inter-basin transfer facilities. Under this scenario, total water supply reaches 868 million cubic meters by 2050, significantly exceeding the business-as-usual trajectory. The additional supply temporarily alleviates water stress, with the water shortage rate peaking at 8.7 percent in 2035 before declining slightly as new projects come online. However, the demand-supply gap persists and even widens in later years as the stimulus to economic activity provided by reliable water supplies generates additional demand growth, partially offsetting the supply expansions. By 2050, water shortage remains at 6.2 percent, and the system remains vulnerable to drought events that could temporarily reduce available supplies below average levels.

The demand-side conservation scenario takes a fundamentally different approach, focusing on reducing water requirements through efficiency improvements rather than expanding supply. Under this scenario, per capita domestic water consumption declines gradually through appliance standards, pricing reforms, and public education, while industrial water use intensity falls through technological upgrading and water recycling. Total water demand in 2050 reaches 748 million cubic meters, nearly 24 percent lower than under business-as-usual and 14 percent lower than under supply-oriented management. Water supply expands modestly but remains well below the supply-oriented scenario. The combination of reduced demand and moderate supply growth yields water shortage rates that peak at 4.8 percent in 2030 then decline to 2.1 percent by 2050. These results demonstrate that demand-side measures can be highly effective in managing water stress, though they require sustained policy commitment and may encounter diminishing returns as the most cost-effective efficiency opportunities are exhausted.

The integrated adaptive management scenario combines supply efficiency, demand conservation, and water reuse while incorporating dynamic policy rules that adjust interventions based on system conditions. Under this scenario, treated wastewater becomes a significant supply source, contributing 85 million cubic meters annually by 2050, while desalination provides drought-proof supply during dry periods. Total water demand is managed to 715 million cubic meters by 2050, slightly below the demand-side scenario, while total water supply reaches 742 million cubic meters, creating a modest surplus that builds system resilience. The water shortage rate remains below 1 percent throughout the simulation horizon, effectively eliminating involuntary water use restrictions even under drought conditions. This scenario demonstrates the synergistic benefits of integrated approaches, where multiple interventions reinforce one another and dynamic adjustment prevents the emergence of imbalances that could otherwise destabilize the system.

Table 2. Scenario Simulation Results for Key Water Balance Variables, 2025-2050

Business-as-Usual	Total Water Demand (million m³)	698	758	818	875	930	982
	Total Water Supply (million m³)	652	679	704	723	732	732
	Water Deficit (million m³)	46	79	114	152	198	250
	Water Shortage Rate (%)	6.6	10.4	13.9	17.4	21.3	25.5
Supply-Oriented	Total Water Demand (million m³)	712	782	852	912	958	992
	Total Water Supply (million m³)	685	735	778	812	842	868
	Water Deficit (million m³)	27	47	74	100	116	124
	Water Shortage Rate (%)	3.8	6	8.7	11	12.1	12.5
Demand-Side Conservation	Total Water Demand (million m³)	662	692	714	728	739	748
	Total Water Supply (million m³)	658	682	698	710	720	732
	Water Deficit (million m³)	4	10	16	18	19	16
	Water Shortage Rate (%)	0.6	1.4	2.2	2.5	2.6	2.1
Integrated Adaptive	Total Water Demand (million m³)	658	685	702	712	715	715
	Total Water Supply (million m³)	672	698	715	728	735	742
	Water Surplus (million m³)	14	13	13	16	20	27
	Water Shortage Rate (%)	0	0				

Table 3 provides a more detailed breakdown of sectoral water demand and supply composition for selected scenario years, offering insight into the structural changes underlying the aggregate results. Under business-as-usual, domestic demand increases from 284 million cubic meters in 2030 to 392 million cubic meters in 2050, driven by population growth and modest increases in per capita consumption. Industrial demand grows even more rapidly, from 238 million to 353 million cubic meters, reflecting continued economic expansion partially offset by efficiency gains. Agricultural demand remains relatively stable, declining slightly as a share of total. Supply composition remains heavily dependent on surface water, which contributes 62 percent of total supply in 2050, with groundwater providing an additional 28 percent and non-conventional sources only 10 percent.

The integrated adaptive scenario reveals a dramatically different structure. Domestic demand in 2050 reaches only 328 million cubic meters, 16 percent below the business-as-usual level, achieved through comprehensive conservation programs and pricing reforms. Industrial demand is similarly reduced to 268 million cubic meters, a 24 percent reduction achieved through recycling and efficiency. Agricultural demand declines more substantially as some marginally productive irrigated land transitions to dryland farming or alternative uses. Supply composition shifts toward greater diversity and resilience, with surface water contributing 48 percent, groundwater 22 percent, treated wastewater 18 percent, and desalination 12 percent. This diversified portfolio reduces vulnerability to any single supply disruption and provides flexibility to adapt to changing conditions.

Table 3. Detailed Sectoral Water Demand and Supply Composition for Selected Scenarios

Scenario	Category	Subcategory	2030	2040	2050
Business-as-Usual	Demand (million m³)	Domestic	284	338	392
		Industrial	238	295	353
		Agricultural	202	210	205
		Ecological	34	32	32
		Total	758	875	982
	Supply (million m³)	Surface Water	421	434	454
		Groundwater	190	198	205
		Wastewater Reuse	45	65	45
		Desalination	23	26	28
		Total	679	723	732
Integrated Adaptive	Demand (million m³)	Domestic	256	295	328
		Industrial	215	245	268
		Agricultural	185	148	95
		Ecological	29	24	24
		Total	685	712	715
	Supply (million m³)	Surface Water	405	392	356
		Groundwater	175	168	163
		Wastewater Reuse	82	112	134
		Desalination	36	56	89
		Total	698	728	

Sensitivity analysis revealed that the qualitative ranking of scenarios is robust across a wide range of assumptions about population growth, economic development, climate variability, and policy effectiveness. The integrated adaptive scenario consistently outperforms the other scenarios in terms of water balance sustainability, though the quantitative magnitude of the advantage varies with assumptions. Under high population growth assumptions, for example, the water shortage rate in the integrated scenario increases to 2.3 percent by 2050, still far below the 31 percent shortage experienced under business-as-usual. Under more severe climate change scenarios, characterized by reduced precipitation and increased evapotranspiration, all scenarios show increased stress, but the integrated scenario maintains water shortage below 5 percent while business-as-usual exceeds 35 percent. These sensitivity results reinforce the main findings and demonstrate the robustness of the integrated approach across a range of plausible futures.

4. Discussion

The simulation results carry significant implications for urban water management theory and practice. The finding that business-as-usual trajectories lead to growing water stress, with shortage rates exceeding 25 percent by mid-century, aligns with research documenting the vulnerability of urban water systems under current paradigms. The specific rate is context-dependent, but the pattern of widening demand-supply gaps appears robust across diverse settings.

The comparison between supply-oriented and demand-oriented strategies reveals important insights about policy resistance. Supply-oriented approaches exhibit induced demand effects, whereby expanded supply stimulates additional economic activity and population growth that generate new water demands, partially offsetting initial gains. This finding does not imply supply expansion is never warranted, but rather that it must be accompanied by demand management to prevent induced growth effects from undermining benefits.

Demand-side conservation measures demonstrate greater effectiveness, reducing water requirements by 24 percent in 2050 relative to business-as-usual. However, the simulations reveal that demand-side measures alone cannot fully eliminate water stress, particularly under severe drought or higher-than-expected population growth. This suggests demand management should form the cornerstone of sustainable water policy but must be complemented by strategic supply investments.

The superior performance of the integrated adaptive management scenario carries several lessons. First, combining multiple interventions produces synergistic benefits beyond individual effects. Second, diversifying supply sources reduces portfolio risk and enhances resilience. Third, dynamic adjustment rules prevent accumulation of imbalances. The scenario's ability to maintain water shortage below 1 percent while supporting economic growth demonstrates sustainable water management is technically feasible.

Several limitations should be acknowledged. The model omits some factors including detailed water quality dynamics, political economy considerations, and behavioral heterogeneity. Parameter uncertainty remains significant despite empirical estimation efforts. The case study focus limits generalizability of numerical findings, though qualitative insights about feedback structures and integrated approaches are likely transferable.

Future research should extend the framework to incorporate agent-based representations of user behavior, integrate optimization algorithms, apply the model across multiple case studies, and employ participatory approaches engaging stakeholders throughout the modeling process to enhance relevance and translation of insights into action.

5. Conclusion

This study developed and applied a comprehensive system dynamics model to investigate urban water resource management, with the results demonstrating that continuation of historical trends leads to growing water stress with shortage rates exceeding 25 percent by 2050, while supply-oriented strategies provide only temporary relief due to induced demand effects and demand-side conservation measures alone cannot eliminate water stress under all conditions. The integrated adaptive management scenario, combining supply efficiency, demand conservation, water reuse, and dynamic policy adjustment, achieves sustainable water balance with shortage rates below 1 percent throughout the simulation horizon, demonstrating that sustainable urban water management is technically achievable through coordinated application of multiple interventions, sustained policy commitment, and adaptive governance. The research contributes both specific findings for the case study region and a demonstration of the system dynamics methodology as a tool for urban water analysis, revealing that water systems must be understood as complex dynamic systems where feedback loops and time delays can produce counterintuitive behaviors, that no single intervention is sufficient and portfolios of measures are required, that adaptive approaches outperform fixed strategies under uncertainty, and that planning horizons must extend to decades rather than years to match the timescales of system dynamics, ultimately providing a template that can be tailored to local conditions as cities worldwide confront growing water challenges in an era of climate change and continued urbanization.

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