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Scenario-Based Assessment and Regulatory Pathway Selection for Urban Water Metabolism Systems: A Case Study of Beijing

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Abstract

Regulating urban water metabolism systems requires not only comparing the effects of alternative regulatory scenarios, but also determining whether water environmental carrying-capacity constraints can be overcome while socioeconomic–water-environment coordination is maintained. Building on our previously developed and validated agent-based modeling–system dynamics (ABM–SD)-coupled model for Beijing, this study simulated a business-as-usual (BAU) scenario, a Planning scenario, and six sustainable development scenarios for 2024–2035. Total water use, COD and ammonia nitrogen emissions, the Nemerow index (PI), and coupling coordination degree (D) were evaluated. The D–PI method was extended from baseline diagnosis to multi-scenario comparison to identify regulatory pathways from their trajectories, threshold crossings, and final zones. Results show that the BAU scenario exhibits improving coordination but accumulating carrying-capacity risk. Under the Planning scenario, D increases to 0.912 and PI decreases to 1.732 by 2035, yet the system remains severely overloaded. Under SS1-2, SS2-2, and SS3-2, PI decreases to 0.881, 0.904, and 0.934, while D increases to 0.918, 0.923, and 0.927, respectively, enabling the system to enter the Coordination–Sustainability Zone. Under the recommended SS2-2 scenario, simulated total water use, COD emissions, and ammonia nitrogen emissions in 2035 are 35.49×10^8 m^3, 76,038 t, and 5900 t, respectively. Among the candidate pathways, SS1-2 achieves the highest mean D and lowest mean PI over 2024–2035, SS2-2 is conditionally recommended when retaining the specified planning-oriented development settings, and SS3-2 represents a high-growth constraint test.

Keywords: urban water metabolism; scenario simulation; regulatory pathway selection; coupling coordination degree; Beijing

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1. Introduction

Urban water systems provide essential support for population concentration, industrial activities, and ecological security [1]. With continuing urbanization and socioeconomic development, urban water demand, wastewater discharge intensity, and pressure on water environmental carrying capacity have continued to increase. Consequently, water scarcity and water pollution have evolved from isolated resource or environmental problems into interrelated systemic challenges. In water-scarce megacities, socioeconomic development depends on a stable water supply, whereas limited water resources and environmental capacity cannot sustainably accommodate high-intensity human activities [2,3]. Reducing water consumption and pollutant emissions while maintaining reasonable urban development and improving coordination among water resource utilization, environmental

protection, and socioeconomic growth has therefore become a major concern in urban water governance and urban water metabolism research [4–6]. From the perspective of urban water metabolism, urban water problems are not limited to insufficient supply or excessive pollutant concentrations. Rather, they result from persistent imbalances across multiple processes, including water input, socioeconomic use, pollutant generation, wastewater treatment, reclaimed water utilization, and final discharge. An urban water metabolism system is a complex system shaped jointly by the natural water cycle and socioeconomic activities [7–9]. Its operation is influenced not only by water supply, environmental capacity, wastewater treatment capacity, and water reuse infrastructure, but also by population size, industrial structure, residential water-use behavior, industrial production, water prices, wastewater treatment fees, and the intensity of environmental regulation. Because different agents interact through behavioral responses and feedback mechanisms, simply expanding water supply or strengthening end-of-pipe pollution control is often insufficient to achieve system-wide improvement [9–11]. Regulation of urban water metabolism systems must therefore address two objectives simultaneously: reducing the metabolic pressure imposed by socioeconomic activities and improving wastewater treatment, water reuse, and water environmental carrying capacity.

Previous studies have extensively investigated the structural identification, process simulation, state assessment, and regulation of urban water metabolism systems [12]. Urban metabolism analysis, material flow analysis, ecological network analysis, grey water footprint assessment, system dynamics, and scenario-based simulation have been widely used to examine urban water consumption, pollutant generation and transfer, water-use efficiency, and water-system sustainability [4,6–9]. System dynamics models can represent the feedback relationships among population, economy, water resources, and the environment and are therefore suitable for analyzing the long-term evolution of urban water systems [13,14]. Scenario simulation can compare multiple potential system states by defining alternative development modes, technological levels, and policy intensities [15–17]. In recent years, some studies have further integrated agent-based simulation, system dynamics [18], and comprehensive assessment methods to improve the representation of complex socioeconomic behavior and policy responses in urban water-system modeling [19–21].

However, existing studies remain largely focused on comparing how individual indicators change under different scenarios, with relatively limited attention paid to selecting suitable regulatory pathways from multi-scenario simulation results. Conventional scenario analyses typically compare water use, pollutant emissions, resource-use efficiency, or composite assessment scores across alternatives, but rarely determine whether a scenario can effectively overcome water environmental carrying-capacity constraints or whether its improvement is achieved at the expense of socioeconomic development [22]. For urban water metabolism systems, improvement in a single indicator does not necessarily mean that the system has entered a sustainable state [8,9]. For example, lower water use may result from restricted development, whereas a higher coupling coordination degree may conceal the continued accumulation of water environmental carrying pressure. Conversely, a scenario that achieves substantial emission reductions may lack practical feasibility if it requires excessively stringent environmental protection or an unrealistically low development rate. Regulatory pathway selection should therefore not be reduced to minimizing a single indicator or maximizing a composite score [23,24]. Instead, it should jointly consider system coordination, environmental carrying safety, development compatibility, and policy implementation conditions.

To support the comprehensive evaluation of multi-scenario results, previous studies have applied the analytic hierarchy process, entropy weighting, fuzzy comprehensive evaluation, projection pursuit, TOPSIS, and multi-objective optimization to rank alternative

schemes [25–27]. Related agricultural studies have examined irrigation allocation under uncertainty [28], collaborative water–energy–food–carbon optimization [29], and two-stage multiobjective decision-making for water–energy–food systems [30]. These methods can integrate multiple indicators into a comprehensive assessment, but their results are generally presented as a composite score or ranking and provide limited insight into the system state represented by each scenario and its direction of evolution [31]. For cities subject to stringent resource and environmental constraints, a scenario cannot be considered genuinely sustainable if water environmental carrying pressure remains in an overloaded state, even when it receives a high composite score. The identification of regulatory pathways for urban water metabolism systems should therefore move beyond simple alternative ranking toward system-state identification and dynamic pathway interpretation.

Against this background, combining socioeconomic–water environmental coordination with water environmental carrying pressure can provide a more interpretable framework for evaluating multiple regulatory scenarios [32]. The coupling coordination degree (D) reflects the level of coordinated development between the socioeconomic system and the water environment system, whereas the Nemerow index (PI) measures the combined pressure exerted by water use and pollutant loads entering receiving waters on water environmental carrying capacity. These two indicators are complementary because they represent internal system coordination and environmental carrying constraints, respectively. Considering D alone may lead to the misinterpretation of improved coordination despite accumulating carrying-capacity risks, whereas considering PI alone may overlook the level of socioeconomic development and the system's coordination capacity [33–35]. Identifying scenario trajectories, state zones, and threshold crossings in a two-dimensional D–PI state space can therefore help determine whether a regulatory alternative simultaneously meets the requirements of coordinated development and environmental safety [21].

Beijing is a typical water-scarce megacity with limited local water resources. It has long faced multiple constraints, including insufficient local water availability, substantial dependence on transferred water [36], a high concentration of population and economic activities, and considerable pressure on water environmental carrying capacity [37–39]. In recent years, measures such as the South-to-North Water Diversion Project, reclaimed water utilization, groundwater withdrawal control, wastewater treatment capacity expansion, and water-saving city development have improved water allocation and environmental governance to some extent [38,39]. Nevertheless, the conflicts among urban development, resource consumption, and environmental protection remain systemic and persistent. The potential water metabolism pathways resulting from different combinations of development modes and water environmental protection intensities, as well as whether existing planning measures can enable the system to overcome its carrying-capacity constraints before 2035, require systematic investigation through dynamic simulation and integrated state assessment [40].

The present study inherits three elements from [21]: (i) the Beijing water-metabolism system boundary and the coupled architecture comprising six agent types and four SD subsystems; (ii) the core equations, agent behavioral rules, bidirectional information exchange, and historical calibration and validation basis for 2017–2023; and (iii) the definitions of D and PI and the D–PI state-classification framework. The original contributions of this manuscript are (i) designing and comparing a Planning scenario and six sustainable development scenarios against a common BAU baseline; (ii) applying annual D–PI trajectories and threshold-crossing times to screen candidate regulatory pathways; and (iii) interpreting and selecting these pathways according to their environmental performance and prescribed socioeconomic development objectives. The preferred pathway is identified conditional on retaining the planning-oriented development setting. The extension therefore concerns sce-

nario design and comparative pathway interpretation, while the underlying model structure and assessment framework are retained.

Using the previously developed model, this study compares BAU, Planning, and six sustainable development scenarios combining socioeconomic development modes with water environmental protection intensities for Beijing during 2024–2035. It tracks total water use, COD and ammonia nitrogen emissions, PI, and D, and extends the D–PI assessment to compare scenario trajectories, state transitions, and threshold crossings. The pathways are then screened for development compatibility and policy feasibility.

This study makes three contributions. First, it combines socioeconomic development modes and water environmental protection intensities to compare multiple regulatory pathways against a common baseline. Second, it extends D–PI diagnosis to compare scenario trajectories and state transitions, identifying whether and when scenarios move beyond overload. Third, it considers environmental performance, development compatibility, and policy implementation conditions to distinguish ecological-safety-priority, planning-compatible balanced, and high-growth constraint-testing pathways. These findings provide a reference for differentiated water governance and sustainable development decisions in cities facing stringent resource and environmental constraints.

2. Materials and Methods

2.1. Study Area, System Boundary, and Data Sources

This study focuses on Beijing's urban water metabolism system. Beijing is located on the northwestern edge of the North China Plain and is a typical water-scarce megacity in China. The location of the study area and its river-system divisions are shown in Figure 1a. Beijing's water system consists mainly of five major river systems: the Yongding River, Chaobai River, North Canal, Jiyun River, and Daqing River systems. With continued population concentration, economic development, and the expansion of urban functions, Beijing has long faced insufficient local water supply, increasing dependence on transferred water, growing domestic and ecological water demand, and substantial pressure on water environmental carrying capacity. In recent years, measures including the South-to-North Water Diversion Project, groundwater withdrawal control, water-saving management, and improvements in wastewater treatment and reclaimed water utilization have enhanced the city's water resource allocation to some extent. Nevertheless, conflicts between socioeconomic development and the carrying capacities of water resources and the water environment remain [37–39].

The urban water metabolism system of Beijing was divided into six major processes: water supply, water use, wastewater and runoff generation, wastewater collection and treatment, reclaimed water reuse, and discharge into receiving water bodies. The system structure and scenario control targets are shown in Figure 1b. Water supply sources include local surface water, groundwater, transferred water, and harvested rainwater. Water-use sectors comprise residential use, primary industry, secondary industry, tertiary industry, and ecological and environmental use. Domestic sewage, industrial wastewater, service-sector wastewater, and urban non-point-source runoff generated within the system enter the wastewater collection and treatment process. Part of the treated effluent is reused as reclaimed water for production, ecological purposes, and miscellaneous municipal uses, whereas the remaining effluent and runoff are discharged into receiving water bodies. These water flows, together with the transport of pollutants such as chemical oxygen demand (COD) and ammonia nitrogen (NH_3–N), constitute the basic structure of Beijing's urban water metabolism system.

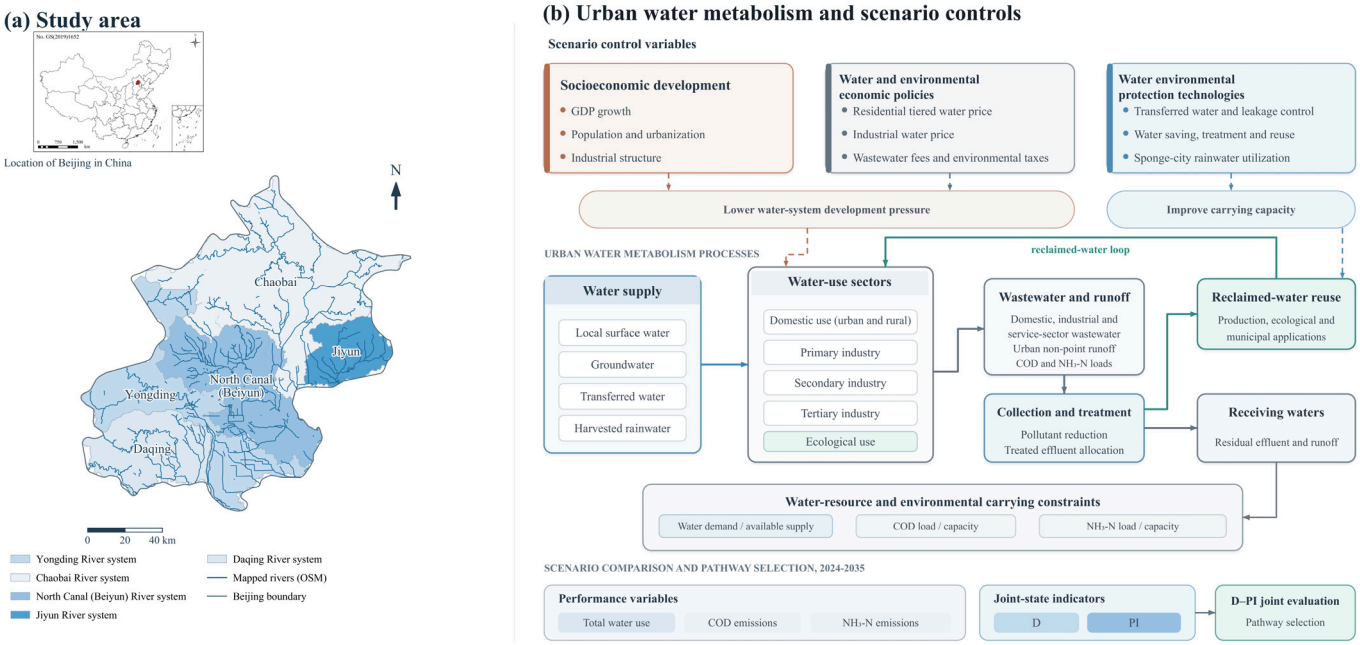


Figure 1. Study area and scenario-control framework for Beijing's urban water metabolism system: (**a**) location and major river systems; (**b**) system boundary, metabolic processes, and principal scenario-control variables.

Within this system boundary, scenario control variables were established along three dimensions: socioeconomic development, water and environmental economic policies, and water environmental protection technologies. Socioeconomic development primarily includes population size, industrial structure, and GDP growth. Water and environmental economic policies regulate water-use and pollutant-discharge behavior through instruments such as water prices, wastewater treatment fees, and environmental taxes. Water environmental protection technologies improve system performance through water conservation, leakage control in water supply networks, wastewater treatment, reclaimed water utilization, and rainwater utilization. The specific scenario combinations and parameter settings are described in the following sections, while the behavioral relationships connecting these variables are documented in the previous model study [21].

The historical data underpinning the model were obtained mainly from the *Beijing Statistical Yearbook (2013–2023)*, Beijing Statistical Communiqué on National Economic and Social Development (2012–2023), *Beijing Water Affairs Statistical Yearbook (2016–2023)*, Beijing Water Resources Bulletin (2012–2023), Beijing Environmental Statistics Annual Report (2012–2019), Beijing Statistical Annual Report on Emission Sources (2020–2023), and *China Urban Construction Statistical Yearbook (2012–2023)*. The data and parameters used in the model and scenario analysis included population, GDP and industrial structure, sectoral water use, wastewater treatment rates, reclaimed-water utilization rates, leakage rates of water-supply networks, COD and ammonia nitrogen emissions, available water resources, and water environmental capacity. Historical-data processing, baseline calibration, and the associated assumptions are documented in our previous urban water metabolism simulation study [21].

Scenario parameters were specified with reference to the Beijing Urban Master Plan (2016–2035) [41], the Beijing 14th Five-Year Plan for Wastewater Treatment and Resource Utilization [42], and the Beijing 14th Five-Year Plan for Water-Saving Society Development [43]. Sponge-city-related parameters additionally drew on the Beijing Sponge City Special Plan, as documented in the previous study [21], and the Beijing Design Standard for Sponge City Stormwater Control and Utilization Engineering (DB11/685–2021) [44]. Where the

planning documents did not provide direct numerical targets, the scenario inputs reported in Section 2.4 were determined from historical trends and the stated scenario-design rules.

2.2. Research Framework

This study uses the previously developed and validated ABM–SD coupled model of Beijing's urban water metabolism system as the simulation platform [21]. Rather than repeating model structure development and validation, the present study focuses on the dynamic responses of the system under different development modes and regulation intensities and subsequently identifies regulatory pathways with different policy implications. As shown in Figure 2, the research framework comprises four stages: study basis and boundary definition, regulatory scenario design, dynamic simulation and results comparison, and integrated assessment and pathway screening.

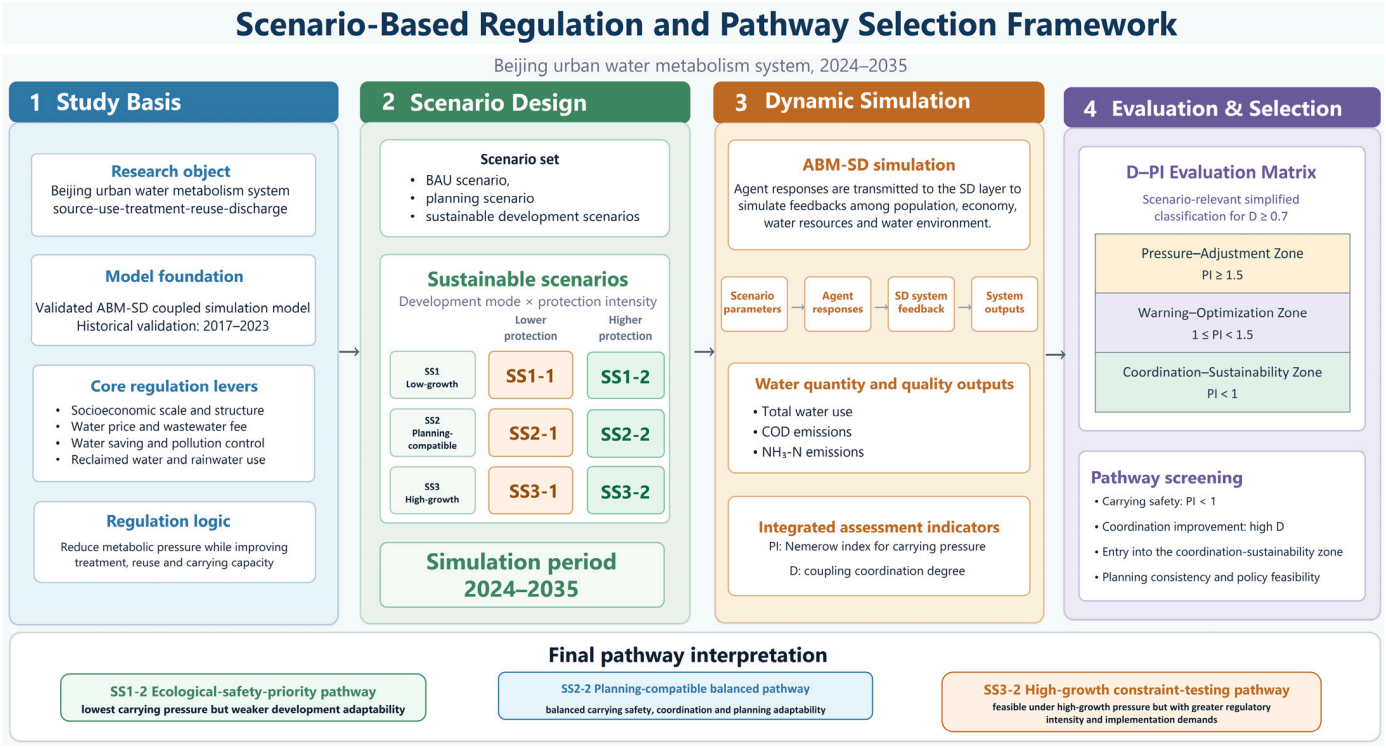


Figure 2. Framework for scenario-based regulation and pathway selection of the urban water metabolism system.

The first stage involves defining the study basis and system boundary. Beijing's administrative area was adopted as the spatial boundary, and 2024–2035 was selected as the simulation period. The model structure, behavioral rules, and baseline parameters that were historically validated in the previous study were retained [21]. In accordance with the regulatory objectives of the present study, population, economic development, industrial structure, water resource utilization, pollution control, reclaimed water utilization, and water and environmental economic policies were selected as the main scenario inputs. Total water use, COD emissions, ammonia nitrogen emissions, the Nemerow index (PI), and the coupling coordination degree (D) were selected as the main simulation outputs.

The second stage involves regulatory scenario design. A business-as-usual (BAU) scenario and a Planning scenario were established to represent system evolution under the continuation of existing development trends and the implementation of current planning targets, respectively. Six sustainable development scenarios were further constructed according to the combined framework of "socioeconomic development mode × water environmen-

tal protection intensity." The socioeconomic development dimension comprised three modes: low-growth development, planning-compatible development, and high-growth development. Water environmental protection was divided into lower- and higher-intensity levels. Together with the BAU and Planning scenarios, these combinations produced eight simulation pathways with different development and governance characteristics.

The third stage involves dynamic simulation and results comparison. Scenario-specific parameters related to population, economic growth, industrial structure, water conservation, pollution control, reclaimed water utilization, and tax and fee policies were entered into the ABM–SD model to simulate the annual operation of Beijing's urban water metabolism system from 2024 to 2035 [21]. Changes in water consumption, COD emissions, ammonia nitrogen emissions, PI, and D were compared across scenarios to identify the direction and magnitude of regulatory effects and differences in long-term system evolution.

The fourth stage involves integrated assessment and pathway screening. The D–PI state-diagnosis method used in the previous study was extended to dynamic multi-scenario comparison. A PI value below 1 was used to determine whether water environmental carrying pressure had been substantially alleviated, whereas the level and stability of D were used to assess whether coordinated development between the socioeconomic system and the water environment system was maintained. Candidate scenarios satisfying both environmental safety and system coordination requirements were first identified according to their D–PI state zones and threshold crossings. These candidate pathways were then classified and comprehensively screened by considering their development modes, compatibility with planning objectives, and policy feasibility. This process ultimately identified differentiated regulatory pathways, including an ecological-safety-priority pathway, a planning-compatible balanced pathway, and a high-growth constraint-testing pathway.

2.3. Previous Model Basis

The scenario simulations in this study were conducted using the ABM–SD coupled model of Beijing's urban water metabolism system developed in our previous study [21]. Based on complex adaptive systems theory and system dynamics, the model couples micro-level agent behavior with macro-level system feedback to simulate the dynamic relationships among population and economic development, water resource utilization, wastewater generation and treatment, reclaimed water reuse, pollutant emissions, and water environmental carrying status. The previous study provided detailed descriptions of the model boundary, structural equations, agent behavioral rules, variable-transfer mechanisms, and parameter calibration. Therefore, the present study only summarizes the model components directly relevant to scenario design and result interpretation. The model components and the interlayer information exchange relevant to the present scenario analysis are summarized in Figure 3.

The model consists of an ABM agent-behavior layer and an SD system-feedback layer. The ABM layer contains six types of agents: government, residents, enterprises, industries, wastewater treatment plants, and the environment. It mainly simulates their behavioral responses to water prices, wastewater treatment fees, environmental taxes, and water resource and environmental constraints [21]. The SD layer comprises the population–resources–environment subsystem, economy–resources–environment subsystem, rainwater collection and utilization subsystem, and water resource supply–demand and water environmental carrying-capacity balance subsystem. It aggregates micro-level agent behavior and calculates urban-scale water consumption, wastewater generation, pollutant reduction, reclaimed water reuse, and environmental pressure. Water-use and pollutant-discharge behavior generated in the ABM layer is transferred to the SD layer to form the macro-level system state. The resource and environmental constraints calculated by the SD layer are then

fed back to government, resident, and enterprise agents, forming a closed-loop mechanism of "agent behavior–system response–policy adjustment."

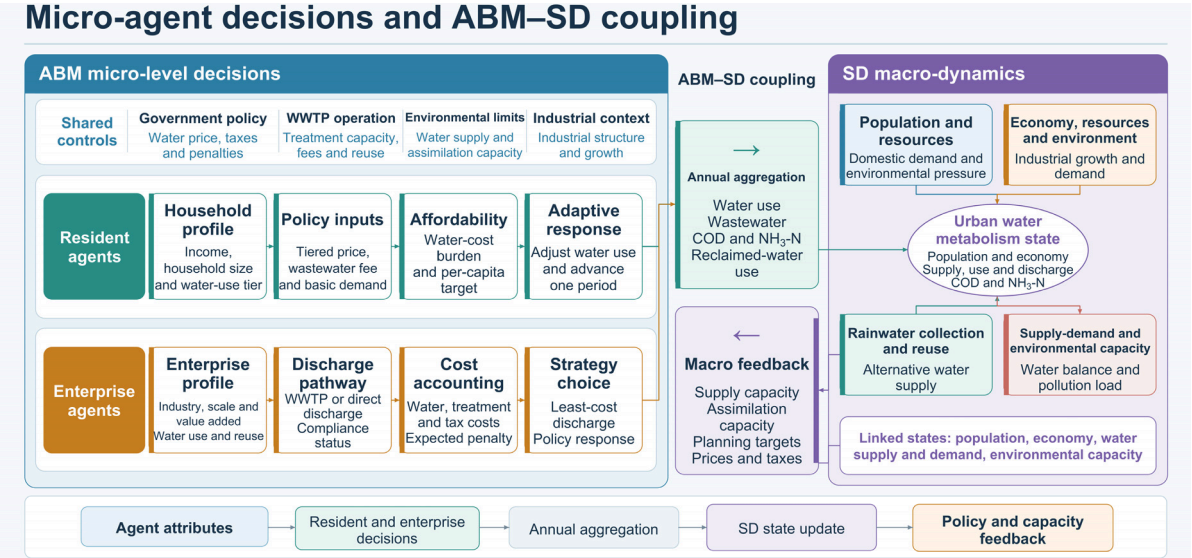


Figure 3. Micro-level agent behavior modules and interlayer information exchange in the ABM–SD coupled model of the urban water metabolism system.

The ABM–SD model was initialized in 2017, and its historical reproduction was evaluated annually for 2017–2023 using total population, GDP, total water use, COD emissions, and ammonia nitrogen emissions [21]. Simulated and historical values were compared for each variable and year, giving 35 comparisons. Population, GDP, and water-use data were compiled from the statistical sources listed in Section 2.1. Pollutant emission histories were harmonized to the revised 2023 reporting basis using population- and sector-output-based emission-intensity trends. The relative error was calculated as $RE = 100 \times (S - H)/H$, where S and H denote the simulated and historical values for the same variable and year. The adopted historical check required $|RE| < 10\%$. The maximum absolute relative errors were 0.15% for population, 6.80% for GDP, 5.34% for total water use, 8.42% for COD emissions, and 8.40% for ammonia nitrogen emissions. These results support reproduction of the selected historical trajectories but do not independently validate future projections. The annual time step and core calibrated model were retained for the 2024–2035 scenario comparison, with only the designated scenario inputs varied as described below.

Based on the previous model, an input interface was established between the scenario parameters and model variables. The scenario inputs were divided into two categories. The first category comprised socioeconomic development parameters, including population, GDP growth, industrial structure, and the development levels of different water-use sectors, which were used to represent alternative socioeconomic development modes. The second category comprised water environmental protection and management parameters, including water conservation levels, wastewater treatment capacity, pollutant removal efficiency, reclaimed water utilization rates, leakage rates of water supply networks, water prices, wastewater treatment fees, and environmental taxes. These parameters were used to represent different environmental protection technologies and policy regulation intensities. Only the corresponding exogenous parameters and policy variables were adjusted across scenarios, while the model's fundamental causal relationships remained unchanged [21].

The model outputs include total water use and annual city-level COD and ammonia nitrogen emissions. The Nemerow index (PI) and socioeconomic–water environmental coupling coordination degree (D) were subsequently calculated from the corresponding

model variables. PI was used to measure water environmental carrying pressure and determine whether it fell below the safety threshold, whereas D was used to assess the coordination between socioeconomic development and the water environment system. The annual positions and evolutionary directions of the different scenarios in the two-dimensional D–PI state space were further tracked. This approach transforms the model outputs from individual-indicator comparisons into system-state identification and provides the basis for subsequent candidate pathway screening.

The reported COD and ammonia nitrogen emissions are annual city-level discharged loads, comprising untreated releases, residual loads after treatment, and urban non-point-source contributions, rather than gross pollutant generation. The model separately calculates loads entering receiving waters using source-specific transfer coefficients; these river-entry loads are used in the pollutant carrying ratios for PI. Reclaimed-water reuse is represented in the water-flow balance and is not treated as pollutant removal by itself.

The ABM–SD coupled model was implemented and run using AnyLogic 8.9.3. Microsoft Excel 2021 was used for data organization and processing. Study-area maps were prepared using ArcGIS 10.8.2, and charts were generated using Origin 2023.

2.4. Scenario Design

Three scenario categories—BAU, Planning, and sustainable development—were established to compare regulatory pathways for Beijing's urban water metabolism system. The dual-regulation strategy enhances carrying capacity by improving water environmental protection technologies, reclaimed water utilization, and wastewater treatment capacity, while reducing anthropogenic pressure by controlling socioeconomic development intensity, optimizing industrial structure, and regulating water prices and pollutant-discharge costs. The scenario categories, development modes, protection and policy intensities, and regulatory implications are summarized in Table 1.

Table 1. Scenario settings and their regulatory implications.

Category	Code	Development Mode	Protection and Policy Intensity	Regulatory Implication
Business-as-usual scenario	BAU	Continuation of current trends	Existing governance intensity	Natural evolution without additional regulatory measures
Planning scenario	Planning	Development constrained by planning targets	Planned governance intensity	Improvement achieved through implementation of existing plans and policies
Sustainable scenario	SS1-1	Low-growth development	Lower-intensity protection	Basic protection pathway under low development pressure
Sustainable scenario	SS1-2	Low-growth development	Higher-intensity protection	Pathway prioritizing composite pressure reduction
Sustainable scenario	SS2-1	Planning-compatible development	Lower-intensity protection	Basic protection pathway under planning-compatible development
Sustainable scenario	SS2-2	Planning-compatible development	Higher-intensity protection	Planning-compatible balanced pathway
Sustainable scenario	SS3-1	High-growth development	Lower-intensity protection	Basic protection pathway under high development pressure
Sustainable scenario	SS3-2	High-growth development	Higher-intensity protection	High-growth constraint-testing pathway

2.4.1. Business-As-Usual Scenario

The business-as-usual (BAU) scenario assumes that Beijing's existing development patterns and governance levels continue during 2024–2035, without additional improvements in water environmental protection technologies or policy regulation intensity. It serves as the baseline for assessing whether planned and additional optimization measures improve the urban water metabolism system.

2.4.2. Planning Scenario

The Planning scenario was established according to Beijing's existing planning targets and policy orientations, mainly referring to the Beijing Urban Master Plan, relevant plans for the 14th Five-Year Plan period, and the city's water resource management and water environmental governance objectives. This scenario incorporates planned measures such as population control, industrial structure optimization, wastewater treatment capacity expansion, increased reclaimed water utilization, reduced leakage from water supply networks, and guaranteed ecological water use.

Compared with BAU, the Planning scenario assesses improvements achievable under existing policies and targets. It does not represent an optimal pathway with stronger water environmental protection technologies and tax and fee policies. Its purpose is to test whether current planning measures can support coordinated and sustainable development of Beijing's urban water metabolism system before 2035.The parameter settings for the Planning scenario at the 2025, 2030, and 2035 milestones are presented in Table 2.

2.4.3. Sustainable Development Scenarios

The six sustainable development scenarios combine three socioeconomic development modes with two integrated regulatory intensities. The development modes are low-growth, planning-oriented moderate-growth, and high-growth development. Technological measures and economic policy settings are grouped into lower- and higher-intensity packages rather than varied as two independent factors. The resulting 3 × 2 design comprises SS1-1, SS1-2, SS2-1, SS2-2, SS3-1, and SS3-2. The suffixes "−1" and "−2" identify the lower- and higher-intensity packages specified in Table 3. The term "sustainable development scenarios" denotes the sustainability-oriented objective of scenario design, not an outcome assumed for all six alternatives. Whether a scenario attains the adopted composite non-overload criterion is evaluated from its simulated PI trajectory; SS1-1, SS2-1, and SS3-1 remain above PI = 1 in 2035.

The SS1 series represents lower development pressure, whereas the SS3 series tests the prescribed regulatory packages under higher growth. The SS2 series is termed planning-compatible because its GDP growth rate, industrial structure, and urbanization rate follow the planning-oriented 2035 settings reported in Table 2. Specifically, SS2 uses a GDP growth rate of 4%, industrial shares of 0.10:10.5:89.4, and an urbanization rate of 89.6%. This does not reproduce the full annual trajectory of the Planning scenario. The SS2 population growth rate is a separate scenario assumption of 1.5‰, compared with 4.25‰ in the Planning scenario in 2035. These distinctions define the scope of planning compatibility used in the present comparison.

The three higher-intensity scenarios are retained as representative candidate pathways: SS1-2 for prioritizing composite pressure reduction under low growth, SS2-2 for maintaining planning-oriented development, and SS3-2 for testing high-growth conditions. Their eligibility and relative merits are evaluated from their PI and D trajectories rather than assumed from these labels. All parameter settings remain those reported in Table 3.

The lower- and higher-intensity labels refer to regulatory packages and do not imply identical values for every protection parameter. Within the higher-intensity group, SS1-2

assumes a 50% reduction in industrial freshwater-use intensity relative to the 2023 baseline, compared with 45% in SS2-2 and SS3-2. This stronger industrial water-saving assumption is part of the SS1-2 package and must be considered when comparing outcomes across development modes.

All scenarios were initialized from the validated 2023 system state, and scenario-specific interventions were applied from 2024. Annual parameter values between the 2025, 2030, and 2035 milestones were generated by linear interpolation. Parameters specified by a single scenario value were held constant throughout 2024–2035.

Table 2. Parameter settings for the Planning scenario of Beijing's urban water metabolism system.

(a) Socioeconomic development parameters				
Regulatory measure	**Related parameter**	**Planning scenario**		
		2025	**2030**	**2035**
Adjust economic growth	GDP growth rate	5.00%	4.50%	4.00%
Adjust industrial structure	Shares of primary, secondary, and tertiary industries	0.20:14.0:85.8	0.15:12.5:87.35	0.10:10.5:89.4
Adjust population size	Population growth rate	1.30‰	2.80‰	4.25‰
Adjust population structure	Urbanization rate	88.1%	88.9%	89.6%
(b) Water environmental protection technology parameters				
Regulatory measure	**Related parameter**	**Planning scenario**		
		2025	**2030**	**2035**
Inter-basin water transfer (South-to-North Water Diversion + Yellow River diversion)	Total transferred water	12.3	16.7	21
Local reserve water	Total strategic surface-water and groundwater reserves	40	55	70
Improve water supply networks and reduce leakage	Leakage rate of water supply networks	8.0%	7.3%	6.6%
Rainwater reuse	Rainwater collection and utilization rate	5%	7%	9%
Increase wastewater reclamation and reuse	Wastewater reclamation and reuse rate	57.91%	63.95%	70%
Ecological water demand	Ecological and environmental water use	17.35	19.15	20.13
Water-saving measures for production and domestic use and increased water reuse	Primary-industry water-use intensity	−10%	−20%	−30%
	Freshwater consumption per CNY 10,000 of industrial value added	−7.7%	−22.6%	−40.12%
	Tertiary-industry water-use intensity	−8%	−15%	−25%
	Urban residential water-use intensity	−8.7%	−17.4%	−26.1%
	Rural residential water-use intensity	−5%	−11.8%	−18.7%

Table 2. *Cont.*

Cleaner production and reduced pollutant emissions	Primary-industry pollutant-generation intensity	−6%	−12%	−18%
	Secondary-industry pollutant-emission intensity (enterprise level)	−10%	−25%	−40%
	Tertiary-industry pollutant-generation intensity	−10%	−20%	−30%
Reduce domestic pollutant generation	Urban residential COD-generation intensity	−8%	−15%	−25%
	Urban residential ammonia nitrogen-generation intensity	−8%	−15%	−30%
	Rural residential COD-generation intensity	−5%	−12%	−20%
	Rural residential ammonia nitrogen-generation intensity	−5%	−12%	−25%
Improve sewer networks and wastewater treatment	Urban wastewater treatment rate	98.5%	99.2%	100%
	Rural wastewater treatment rate	90%	94%	98%

Note: Water-volume variables are expressed in 10^8 m^3. Negative percentage values indicate reductions relative to the corresponding 2023 baseline values unless otherwise specified. Pollutant-generation intensity refers to pollutant production before treatment per unit of sectoral value added or per resident, as applicable. Secondary-industry pollutant-emission intensity refers to enterprise-level pollutant discharge per unit of industrial value added. These input intensities are distinct from the city-level emission totals and river-entry loads defined in Section 2.3.

Table 3. Parameter settings for sustainable development regulatory scenarios of Beijing's urban water metabolism system.

a. Socioeconomic development scale and structure regulation scenarios

Regulatory measure	**Specific indicator**	**Socioeconomic development scale and structure regulation scenarios**					
		SS1-1	**SS1-2**	**SS2-1**	**SS2-2**	**SS3-1**	**SS3-2**
Adjust economic growth	GDP growth rate	3.00%	3.00%	4.00%	4.00%	5.00%	5.00%
Adjust industrial structure	Shares of primary, secondary, and tertiary industries (%)	0.12:11: 88.88	0.12:11: 88.88	0.10:10.5: 89.4	0.10:10.5: 89.4	0.08:10: 89.92	0.08:10: 89.92
Adjust population size	Population growth rate	1‰	1‰	1.5‰	1.5‰	2‰	2‰
Adjust population structure	Urbanization rate	88.10%	88.10%	89.60%	89.60%	91.10%	91.10%

b. Water environmental protection technologies and tax and fee policy scenarios

Regulatory measure	**Specific indicator**	**Water environmental protection technologies and tax and fee policy scenarios**					
		SS1-1	**SS1-2**	**SS2-1**	**SS2-2**	**SS3-1**	**SS3-2**
Adjust water environmental tax and fee policies	First-tier residential water price (CNY m^{-3})	6	9	6	9	6	9
	Industrial water price (CNY m^{-3})	10	13	10	13	10	13

Table 3. *Cont.*

Water conservation for production and domestic use and increased water reuse	Primary-industry water-use intensity	−35%	−40%	−35%	−40%	−35%	−40%
	Freshwater consumption per CNY 10,000 of industrial value added	−45%	−50%	−45%	−45%	−45%	−45%
	Tertiary-industry water-use intensity	−30%	−35%	−30%	−35%	−30%	−35%
	Urban residential water-use intensity	−30%	−35%	−30%	−35%	−30%	−35%
	Rural residential water-use intensity	−25%	−30%	−25%	−30%	−25%	−30%
Cleaner production and reduced pollutant emissions	Primary-industry pollutant-generation intensity	−25%	−30%	−25%	−30%	−25%	−30%
	Secondary-industry pollutant-emission intensity (enterprise level)	−45%	−50%	−45%	−50%	−45%	−50%
	Tertiary-industry pollutant-generation intensity	−40%	−45%	−40%	−45%	−40%	−45%
Reduce domestic pollutant generation	Urban residential COD-generation intensity	−35%	−40%	−35%	−40%	−35%	−40%
	Urban residential ammonia nitrogen-generation intensity	−40%	−45%	−40%	−45%	−40%	−45%
	Rural residential COD-generation intensity	−30%	−35%	−30%	−35%	−30%	−35%
	Rural residential ammonia nitrogen-generation intensity	−35%	−40%	−35%	−40%	−35%	−40%
Sponge city development	Proportion of runoff routed through stormwater wetlands	0.8	0.9	0.8	0.9	0.8	0.9
	Permeable pavement coverage rate	85%	90%	85%	90%	85%	90%
	Green roof coverage rate	10%	15%	10%	15%	10%	15%

Note: Negative percentages indicate reductions relative to the corresponding 2023 baseline intensity values, rather than negative water use or pollutant loads. Industrial structure entries are percentage shares of the primary, secondary, and tertiary industries, respectively, and sum to 100%. Population growth rates are expressed in ‰. The runoff proportion is dimensionless; values of 0.8 and 0.9 correspond to 80% and 90%, respectively. The "−1" and "−2" suffixes identify the lower- and higher-intensity integrated packages reported in this table.

2.5. Integrated Scenario Assessment and Pathway Selection

This study applies the D–PI assessment method developed in our previous work [21]. Here, water environmental carrying status denotes the integrated pressure state under water resource and pollutant assimilation constraints. PI quantifies this state by combining the maximum and mean of three carrying ratios: water demand relative to available water supply, and modeled COD and ammonia nitrogen loads entering receiving waters relative to their respective environmental capacities. Carrying-status categories are assigned using PI thresholds; they are not a third independently calculated numerical indicator.

D is calculated from the standardized integrated efficacy values of the socioeconomic and water environment subsystems, following the procedure in [21]. It evaluates their coordinated development, whereas PI evaluates pressure relative to physical resource and environmental capacities. D is therefore not an inverse transformation of PI. The two indicators are complementary, and an increase in D can coexist with an increase in PI.

According to the adopted classification, $0.6 < D \leq 0.7$, $0.7 < D \leq 0.8$, and $0.8 < D \leq 1$ represent primary, moderate, and well-coordinated development, respectively. $PI < 1$ denotes a non-overloaded state under the composite classification, whereas $1 \leq PI < 1.5$ and $PI \geq 1.5$ indicate slight and severe overload, respectively. Because PI combines the maximum and mean carrying ratios, $PI < 1$ does not by itself establish that every constituent ratio is below 1; individual constraints require separate examination.

Pathway selection comprises three steps. First, annual D and PI trajectories are compared across scenarios. $D \geq 0.7$ is retained as a reference within the adopted coordination classification. However, all 96 annual D values across the eight scenarios exceed 0.7 during 2024–2035, with a minimum of 0.7647 for SS3-2 in 2024. This cut-off therefore has no discriminatory power within the present scenario set. Second, $PI < 1$ determines candidate eligibility within the observed D range. Third, the eligible candidates are compared using continuous D values, PI levels, PI threshold-crossing years, and their prescribed socioeconomic settings. Preference remains conditional on the stated development objectives and does not constitute a cost-optimization or implementation-feasibility assessment. To make the temporal comparison explicit, we summarize each candidate trajectory using the arithmetic means of its 12 annual D and PI values for 2024–2035, assigning a weight of 1/12 to every year. D and PI are averaged separately and are not combined into a weighted score. The year-by-year values and PI threshold-crossing years are also examined, so the averages do not replace annual carrying-status checks. The 2035 values are reported separately as end-of-horizon states; they receive no additional weight in the annual means. Attainment of $PI < 1$ by 2035 remains an eligibility condition within the observed D range. Preference based on the full-period indicators is distinguished from a conditional recommendation that retains the planning-oriented development settings in Section 2.4.3.

To strengthen the link between scenario outcomes and regulatory recommendations, descriptive Spearman rank correlations were calculated between 21 selected control parameters in Table 3 and the 2035 PI values in Table 4 across the six sustainable development scenarios ($n = 6$). Tied control values were assigned average ranks, and intensity reductions were coded as positive reduction magnitudes. The parameter values and coefficients are reported in Table S1, and the results are interpreted in Section 3.5. The added rank analysis uses the parameter settings and endpoint values reported in Tables 3 and 4. Because several controls vary together in the designed scenarios, the coefficients describe associations within this scenario set rather than independent causal effects. Paired regulatory-package comparisons within each development mode were also evaluated using absolute changes in endpoint PI.

Table 4. Simulated PI and D values and scenario eligibility in 2035.

Scenario	PI in 2035	D in 2035	PI < 1?	Eligible for the Coordination–Sustainability Zone?	Preliminary Judgment
BAU	2.768	0.845	No	No	Unsustainable; severe overload remains
Planning	1.732	0.912	No	No	Improved, but still severely overloaded
SS1-1	1.019	0.914	No	No	Close to PI = 1, but the criterion is not met
SS1-2	0.881	0.918	Yes	Yes	Eligible candidate prioritizing composite pressure reduction

Table 4. *Cont.*

Scenario	PI in 2035	D in 2035	PI < 1?	Eligible for the Coordination–Sustainability Zone?	Preliminary Judgment
SS2-1	1.046	0.919	No	No	Close to PI = 1, but the criterion is not met
SS2-2	0.904	0.923	Yes	Yes	Eligible planning-compatible candidate
SS3-1	1.080	0.923	No	No	Coordination improves, but PI remains above 1
SS3-2	0.934	0.927	Yes	Yes	Eligible candidate under high-growth conditions

3. Scenario Simulation Results

The ABM–SD simulations compare BAU, Planning, and six sustainable development scenarios for Beijing during 2024–2035 in terms of water use, pollutant emissions, carrying status, and socioeconomic–water environment coordination. BAU and Planning serve as common references. The integrated comparison then examines whether individual indicator improvements achieve joint attainment of the carrying-safety and coordination criteria, supporting the pathway assessment in Section 4.

3.1. Changes in Water Use and Pollutant Emissions Across Scenarios

Figure 4 compares total water use, COD emissions, and ammonia nitrogen emissions across the eight scenarios. The SS1, SS2, and SS3 series represent low-growth, planning-compatible, and high-growth development, respectively, while the suffixes "−1" and "−2" denote the lower- and higher-intensity integrated regulatory packages specified in Section 2.4. This arrangement supports paired comparisons between the lower- and higher-intensity regulatory packages within each development mode. Comparisons across development modes reflect the combined socioeconomic and regulatory settings, because individual protection parameters are not identical across all scenarios in the same intensity group.

Under BAU, all three indicators increase over the simulation period, reflecting the continued accumulation of water-use and pollution pressures under the existing development trajectory and governance intensity. In the model, socioeconomic activities generate sectoral water demand and associated pollution loads; consequently, continued growth without additional regulation increases aggregate metabolic pressure. Domestic and service-sector demand are among the ongoing sources of pressure represented in these modeled processes. The aggregate curves show their overall outcome, rather than separately quantifying each sector's contribution.

The Planning scenario produces substantial improvements relative to BAU. By 2035, total water use reaches 39.62×10^8 m^3, COD emissions reach 102,844 t, and ammonia nitrogen emissions reach 8033 t, representing reductions of 9.9%, 37.0%, and 37.8%, respectively, relative to BAU in the same year. The planned population control, industrial restructuring, wastewater treatment expansion, greater reclaimed-water use, and leakage reduction act through demand management, pollution control, and water reuse in the model. These combined adjustments improve the simulated outcomes, although their individual contributions cannot be separated from this scenario comparison.

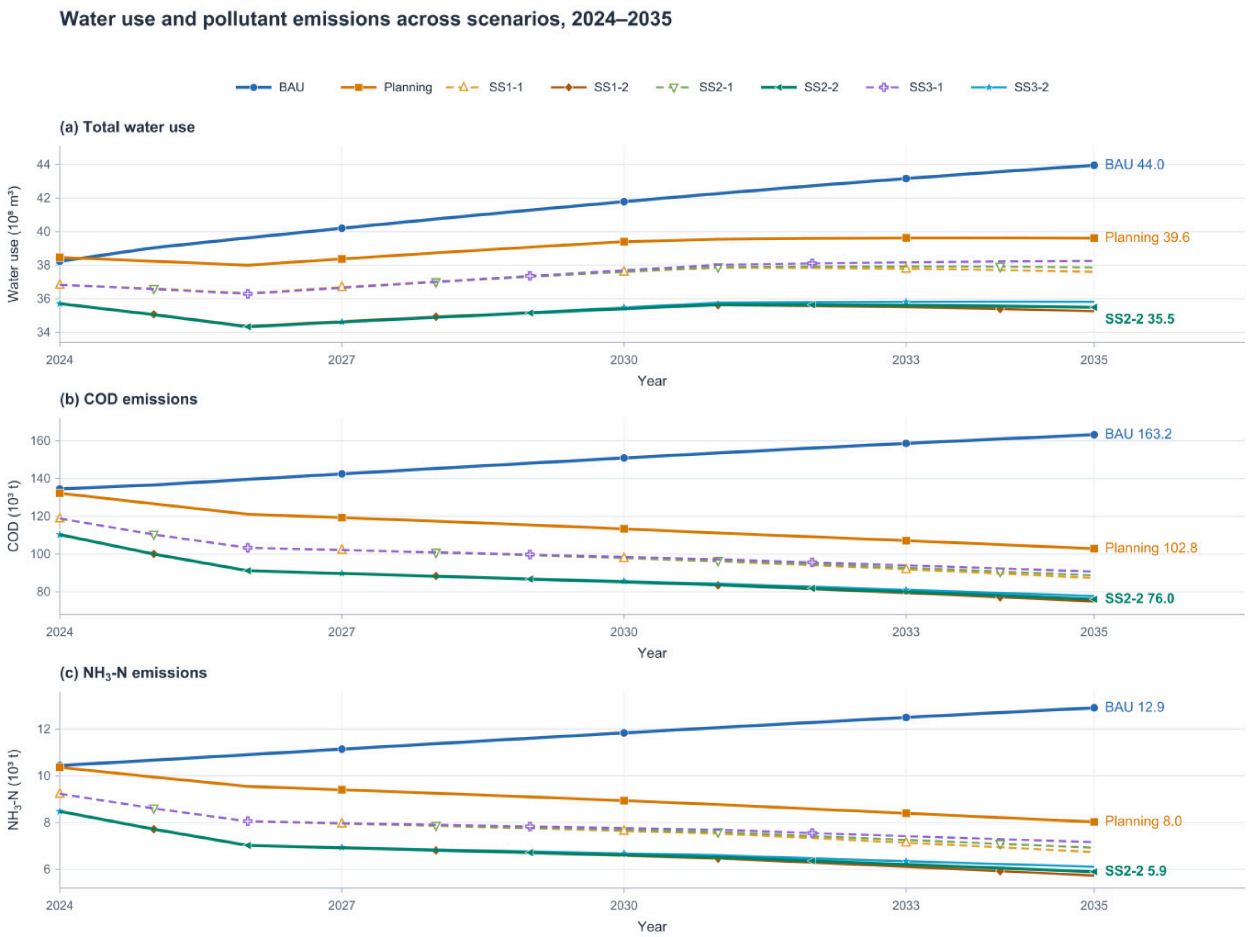


Figure 4. Changes in total water use, COD emissions, and ammonia nitrogen emissions across scenarios from 2024 to 2035. Pollutant emissions denote annual city-level discharged loads, as defined in Section 2.3.

Planning-scenario water use initially declines and then rebounds modestly, while COD and ammonia nitrogen emissions continue to decrease. Water use under the sustainable development scenarios follows a similar pattern but remains below BAU throughout the simulation period. In the model, demand growth can partly offset water savings while treatment and other pollution-control measures continue to reduce discharged loads. These differing responses mean that the water-use rebound does not imply that the integrated regulatory package has ceased to provide benefits.

All six sustainable development scenarios reduce total water use relative to BAU. Their differences reflect both development mode and regulation intensity. At the start of the simulation, scenarios within each regulatory-intensity group have identical water-use values; their trajectories subsequently diverge under their respective socioeconomic and regulatory settings. By 2035, water use in the lower-intensity group is 37.60, 37.87, and 38.26 × 10^8 m^3 under SS1-1, SS2-1, and SS3-1, respectively. In the higher-intensity group, the corresponding values are 35.26, 35.49, and 35.82 × 10^8 m^3. Thus, SS1-1 and SS1-2 have the lowest 2035 water use within the lower- and higher-intensity groups, respectively. The lower water use under SS1-2 cannot be attributed solely to its lower development intensity, because this scenario also assumes a larger reduction in industrial freshwater-use intensity. Within each development mode, the higher-intensity package lowers water use relative to its lower-intensity counterpart. These results indicate that development control and water environmental protection must be considered together.

COD and ammonia nitrogen emissions decline under all six sustainable development scenarios, with lower emissions under SS1-2, SS2-2, and SS3-2 than under their lower-intensity counterparts. For example, within the planning-compatible development mode, total water use in 2035 is 37.87 × 10^8 m^3 under SS2-1 and 35.49 × 10^8 m^3 under SS2-2, corresponding to a reduction of 2.38 × 10^8 m^3 (6.3%). COD emissions decrease from 88,715 to 76,038 t, a reduction of 12,677 t (14.3%), while ammonia nitrogen emissions decrease from 6926 to 5900 t, a reduction of 1026 t (14.8%). The larger proportional response of the pollutant indicators shows that the additional benefits of the higher-intensity package extend beyond water savings. Because water prices and several conservation and pollutant-intensity parameters vary together in Table 3, these differences represent the combined response to the prescribed regulatory package and do not identify the marginal effect of a single technology or policy instrument.

SS2-2 further illustrates the additional improvement beyond existing planning measures. By 2035, its total water use, COD emissions, and ammonia nitrogen emissions reach 35.49 × 10^8 m^3, 76,038 t, and 5900 t, respectively. These values are 19.3%, 53.4%, and 54.3% below BAU and 10.4%, 26.1%, and 26.5% below Planning in the same year. The comparison shows that strengthening the integrated regulatory package under planning-compatible development can deliver additional reductions in water use and pollutant loads. Whether these reductions are sufficient to meet the composite PI-based non-overload criterion is examined in Section 3.2.

3.2. Changes in Water Environmental Carrying Status Across Scenarios

The Nemerow index (PI) expresses the combined pressure of total water use and modeled COD and ammonia nitrogen loads entering receiving waters, each relative to its corresponding resource or environmental capacity. A lower PI indicates lower composite pressure. PI < 1 denotes a non-overloaded state under the adopted composite classification, whereas 1 ≤ PI < 1.5 and PI ≥ 1.5 indicate slight and severe overload, respectively [21]. As explained in Section 2.5, PI < 1 does not establish that every constituent carrying ratio is below 1. Figure 5 examines whether the output reductions described in Section 3.1 change the composite carrying-status category.

Under BAU, PI increases from 2.249 in 2024 to 2.768 in 2035, remaining above the severe-overload threshold throughout the simulation period. Under Planning, PI decreases from 2.229 to 1.732. This improvement is consistent with the combined demand-management and pollution-control measures described above, but the endpoint remains in the severe-overload range. The distinction between a reduction in pressure and a change in carrying status is consequential: improvements relative to BAU do not, by themselves, establish attainment of the absolute composite PI criterion. Existing planning measures alleviate pressure but remain insufficient to remove severe overload by 2035 under the modeled conditions.

PI decreases under all six sustainable development scenarios, with greater reductions under the higher-intensity packages. By 2035, PI reaches 1.019, 1.046, and 1.080 under SS1-1, SS2-1, and SS3-1, respectively. Although close to 1, all three values remain above the threshold. They therefore indicate substantial pressure relief without full elimination of overload within the simulation period. In particular, even low-growth development under SS1-1 does not meet the PI < 1 criterion, showing that reducing development intensity alone is insufficient under the lower-intensity regulatory settings examined here.

Under SS1-2, SS2-2, and SS3-2, PI falls to 0.881, 0.904, and 0.934, respectively. Among the eight scenarios examined, only SS1-2, SS2-2, and SS3-2 attain PI < 1 by 2035. This result is specific to the tested scenario set and does not establish that high-intensity protection is necessary under other regulatory combinations. The paired changes are quantified in

Section 3.5. Attainment of this composite criterion does not establish compliance with every constituent carrying constraint.

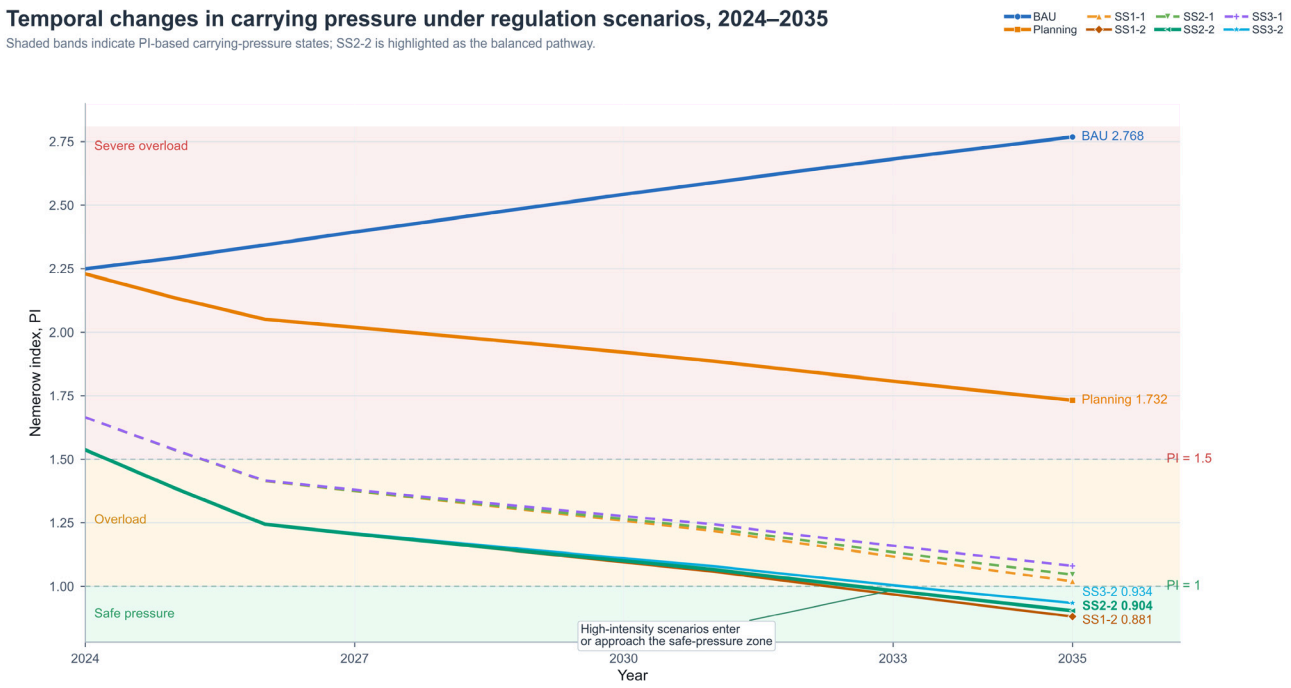


Figure 5. Temporal changes in the Nemerow index (PI) across scenarios from 2024 to 2035.

The trajectories differ in the timing and extent of threshold attainment. SS1-2 and SS2-2 first reach PI < 1 in 2033 and remain below it through 2035, covering three annual simulation points; SS3-2 first reaches this range in 2034, covering two annual points. SS3-2 therefore enters the composite non-overloaded range one simulated year later than the other two higher-intensity pathways. This difference characterizes the prescribed integrated pathways rather than an isolated effect of GDP growth. The numerical distances below PI = 1 in 2035 are 0.119, 0.096, and 0.066 for SS1-2, SS2-2, and SS3-2, respectively. These are index distances, not quantities of unused environmental capacity. SS3-2 combines later threshold attainment with an endpoint closer to the overload boundary, whereas SS1-2 has the lowest endpoint composite pressure. These trajectory features complement the endpoint comparison in pathway selection.

3.3. Changes in Socioeconomic–Water Environment Coupling Coordination Across Scenarios

The coupling coordination degree (D) measures coordination between the socioeconomic and water environmental systems. A higher D indicates better coordination, but does not directly determine whether the water environmental carrying constraint is exceeded [21]. Figure 6 focuses on the level and temporal evolution of coordination, complementing the carrying-status analysis in Section 3.2.

D increases under all scenarios. Under BAU, it rises from 0.787 in 2024 to 0.845 in 2035; under Planning, it rises from 0.773 to 0.912. Although Planning begins with a lower D than BAU, it achieves a higher endpoint, indicating that the planned regulatory adjustments produce a more favorable coordination trajectory over the simulation horizon. However, the positive BAU trend also demonstrates why coordination improvement must be interpreted separately from the absolute carrying status: a system can become more coordinated while remaining subject to increasing environmental pressure.

All six sustainable development scenarios achieve D > 0.9 by 2035. Within the lower-intensity group, the endpoint values are 0.914, 0.919, and 0.923 for SS1-1, SS2-1, and SS3-1;

the corresponding higher-intensity values are 0.918, 0.923, and 0.927 for SS1-2, SS2-2, and SS3-2. Higher-intensity regulation improves the endpoint D within each development mode. SS3-2 achieves the highest endpoint value, indicating that strong coordination can be maintained under high-growth development when accompanied by the specified higher-intensity protection measures.

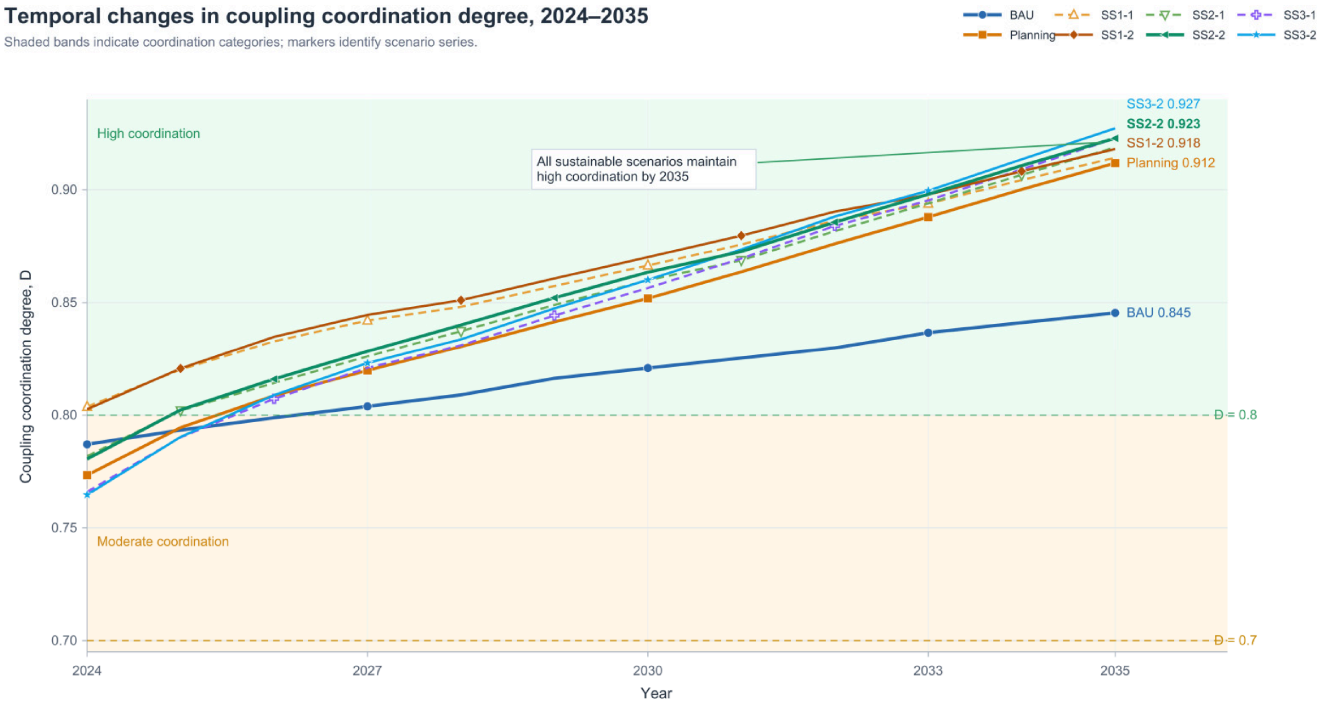


Figure 6. Temporal changes in the coupling coordination degree (D) across scenarios from 2024 to 2035.

The ordering of the higher-intensity scenarios changes over time. In 2024, D is 0.803, 0.781, and 0.765 under SS1-2, SS2-2, and SS3-2, respectively, whereas the endpoint ordering in 2035 is reversed. Thus, the highest endpoint D under SS3-2 does not imply that this scenario has the highest coordination throughout the simulation period. The curves describe different rates and stages of coordination improvement, and their comparison depends on the time horizon as well as the final state. The initial differences reflect scenario-specific interventions applied from 2024 to the common validated 2023 system state, rather than different calibration baselines.

The coordination comparison consequently shows that maximizing D alone does not identify the preferred pathway. A higher-growth scenario may achieve a higher coordination score while imposing greater carrying pressure, whereas a low-growth scenario may reduce pressure more strongly without maximizing D. The two indicators address different aspects of system performance and need to be interpreted jointly. The integrated comparison below examines this relationship, while Section 4 evaluates development compatibility and the applicability of the candidate pathways.

3.4. Integrated Comparison of Scenario Simulation Results

Table 4 summarizes the 2035 PI and D values and joint eligibility under the adopted matrix. Reductions in metabolic outputs, improvements in coordination, and attainment of the composite non-overloaded state are related but distinct outcomes. Under BAU, D improves while PI rises; under Planning, both indicators improve, but severe composite overload remains. Thus, improvements relative to a reference scenario do not by themselves demonstrate attainment of the absolute PI criterion.

All eight scenarios exceed D = 0.7 throughout 2024–2035, rather than only at the endpoint. This coordination cut-off does not screen out any scenario. Within the observed D range, candidate eligibility is therefore determined by PI < 1, which is attained by SS1-2, SS2-2, and SS3-2 by 2035. Continuous D values remain informative for comparing coordination among these candidates.

Eligibility does not establish an overall preference among the three candidates. SS1-2 has the lowest PI, SS3-2 has the highest D, and SS2-2 occupies an intermediate position on both indicators. Their descriptive parameter associations are examined in Section 3.5, and their trajectory characteristics and development settings are compared in Section 4. The preference among them is evaluated within the stated scenario objectives rather than treated as a global optimum.

3.5. Descriptive Associations Between Scenario Parameters and Carrying Pressure

The cross-scenario Spearman analysis is reported in Table S1. GDP growth, population growth, urbanization, and the tertiary-industry share each have a positive association with the 2035 PI ($\rho = 0.478$). Residential and industrial water prices, most intensity-reduction parameters, and the sponge-city parameters share a negative association with PI ($\rho = -0.878$). The industrial freshwater-intensity reduction has $\rho = -0.655$ under the scenario-specific values currently reported in Table 3. These coefficients summarize the parameter and PI rank patterns across the six designed scenarios.

Repeated coefficients reflect shared input patterns rather than equal independent effects. For example, water prices and several technological settings increase together between the lower- and higher-intensity packages, while the socioeconomic variables follow the same ordering across development modes. Consequently, the correlations cannot identify which individual control causes the PI change or establish a ranking of independent parameter sensitivities. No inferential significance claim is made from these six designed scenarios.

The paired comparisons provide a more direct assessment of the integrated packages within each development mode. Moving from "−1" to "−2" reduces the 2035 PI by 0.138, 0.142, and 0.146 in the SS1, SS2, and SS3 series, respectively, and changes all three endpoints from composite overload to PI < 1. These results support strengthening the integrated regulatory package under the modeled conditions. They do not separate the contributions of pricing, conservation, pollution reduction, treatment, or reuse. Section 4.5 therefore relates the policy recommendations to package-level results and model mechanisms rather than attributing the observed improvements to individual measures. For SS2-2, individual ±10% input changes yielded a 2035 PI of 0.8378–0.9778, remaining below 1. Joint ±5% changes produced a 2035 PI interval of 0.8176–0.9988 and a sustained PI < 1 entry year between 2030 and 2035. Under joint ±10% changes, the 2035 upper bound rose to 1.1045, so the terminal PI < 1 condition was not guaranteed. The simultaneous adverse change in each input at which the 2035 PI reached 1 was 5.06% for SS2-2, compared with 6.35% for SS1-2 and 3.41% for SS3-2. These results qualify the planning-compatible recommendation for SS2-2 and show the greater terminal carrying-safety margin of SS1-2 (Tables S2 and S3; Figure S1).

4. Scenario Screening and Preferred Regulatory Pathway Identification

Building on Sections 3.1–3.5, this section applies the D–PI matrix to classify the simulated states and compare the three eligible pathways. The assessment uses composite carrying pressure, coordination, threshold-crossing time, and the prescribed socioeconomic development settings to identify a preferred pathway within the modeled alternatives. Costs and implementation feasibility are considered limitations rather than quantified selection criteria.

4.1. Scenario Classification Based on the D–PI Matrix

The D–PI matrix combines subsystem coordination with composite water environmental carrying status. Because D remains above 0.7 throughout all simulated trajectories, the relevant state space comprises the Pressure–Adjustment Zone for PI ≥ 1.5, the Warning–Optimization Zone for 1 ≤ PI < 1.5, and the Coordination–Sustainability Zone for PI < 1. This simplification applies to the D range observed here; the complete matrix is reported in [21]. Figure 7 shows the trajectories and endpoint classifications. The dashed line at D = 0.8 separates moderate from well-coordinated development and does not define entry into the Coordination–Sustainability Zone.

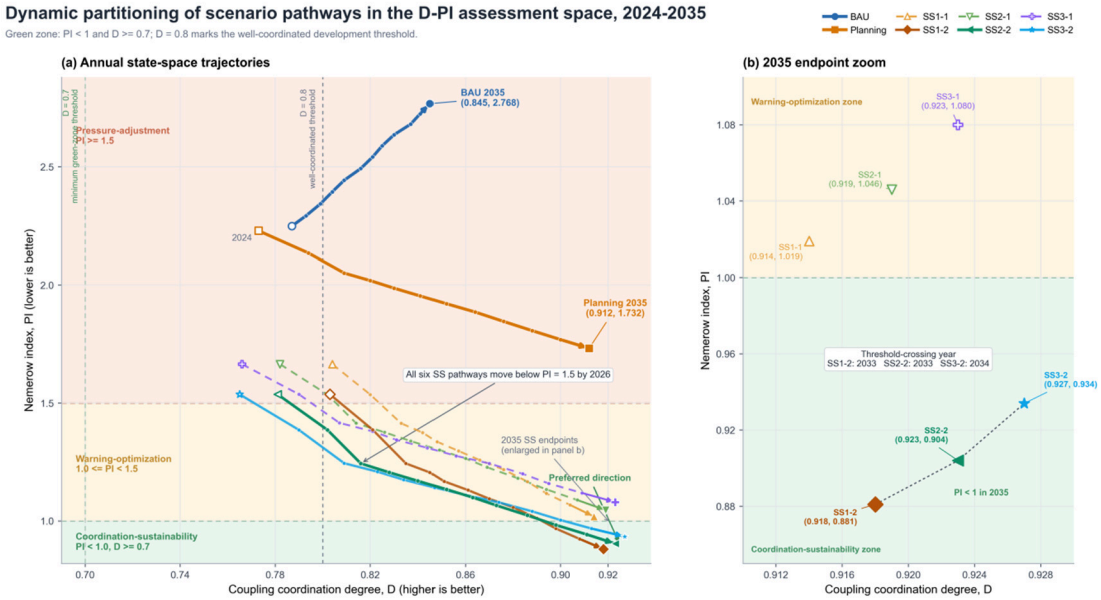


Figure 7. Dynamic evolution and zone classification of alternative regulation scenarios in the D–PI assessment space: (**a**) scenario state-space trajectories from 2024 to 2035; (**b**) enlarged view of scenario endpoints in 2035. The dashed line at D = 0.8 distinguishes moderate from well-coordinated development under the adopted classification. The criteria for entry into the Coordination–Sustainability Zone are D ≥ 0.7 and PI < 1; D = 0.8 is not an eligibility threshold.

As summarized in Table 4, BAU and Planning remain severely overloaded in 2035, and the three lower-intensity scenarios do not meet PI < 1. Only SS1-2, SS2-2, and SS3-2 satisfy the joint criteria and are retained for pathway comparison. SS1-2 and SS2-2 first meet PI < 1 in 2033, and SS3-2 does so in 2034. Table 5 compares these candidates without repeating the full endpoint inventory.

Neither the BAU nor the Planning scenario enters the Coordination–Sustainability Zone. Under the BAU scenario, PI increases from 2.249 in 2024 to 2.768 in 2035, indicating mounting water environmental carrying pressure. Under the Planning scenario, PI decreases from 2.229 to 1.732. Despite this improvement, the system remains severely overloaded.

Under the low-intensity protection scenarios SS1-1, SS2-1, and SS3-1, PI reaches 1.019, 1.046, and 1.080 in 2035, respectively. All three values remain above 1, indicating that low-intensity measures are insufficient to eliminate overload.

Under the high-intensity scenarios SS1-2, SS2-2, and SS3-2, PI declines to 0.881, 0.904, and 0.934 by 2035, while D increases to 0.918, 0.923, and 0.927, respectively. All three scenarios therefore meet the criteria of PI < 1 and D ≥ 0.7. SS1-2 and SS2-2 enter the non-overloaded range in 2033, whereas SS3-2 enters it in 2034. These scenarios are thus retained for further comparison.

Table 5. Threshold-crossing years and interpretation of candidate regulatory pathways.

Scenario	First Year with PI < 1	Development Setting	Pathway Interpretation
SS1-2	2033	Low growth	Preferred when selection is based solely on the 2024–2035 mean D and PI
SS2-2	2033	Planning-oriented development	Conditionally preferred when retaining the specified planning-oriented development settings
SS3-2	2034	High growth	High-growth constraint test with later attainment of PI < 1

Note: Threshold-crossing years refer to the first annual simulation point with PI < 1. All three candidates remain below this threshold through 2035 after first attaining it. Endpoint PI and D values are reported in Table 4.

In summary, SS1-2, SS2-2, and SS3-2 are candidate pathways that satisfy the criteria for the Coordination–Sustainability Zone. The following section compares their environmental safety, development compatibility, and regulatory requirements.

4.2. Comparison of Candidate Regulatory Pathways

Table 4 reports the 2035 PI and D values and scenario eligibility. Table 5 compares the three eligible pathways in terms of their first year with PI < 1, development settings, and pathway interpretation. The higher-intensity designation identifies the packages in Table 3; it does not imply that every protection parameter is identical across development modes.

Figures 5 and 6 show the full annual trajectories, and Table S4 reports the corresponding values for the three candidates. SS1-2 has a higher D than SS2-2 in 2024–2032, whereas SS2-2 has a higher D only in 2033–2035. Their PI values are equal in 2024 and nearly equal in 2025–2026, with SS2-2 marginally lower in those two years; SS1-2 has the lower PI in 2027–2035. The equal-year mean D is 0.8649 for SS1-2 and 0.8560 for SS2-2, while the corresponding mean PI is 1.1341 and 1.1413. Both maintain PI < 1 from 2033 onward. Thus, SS1-2 performs better on both full-period averages, and the late D crossover does not establish consistent superiority of SS2-2.

SS1-2 prioritizes composite pressure reduction under low growth. It has the lowest endpoint PI and the largest distance below PI = 1, and it first reaches the composite non-overloaded range in 2033. These results make it a suitable candidate when reducing composite carrying pressure is the dominant objective. However, its prescribed GDP growth rate of 3% is lower than the planning-oriented 4% setting used in SS2. Its preference therefore depends on the development objective rather than PI alone.

SS2-2 combines planning-oriented development with a higher-intensity regulatory package. It reaches PI < 1 in 2033 and has a distance of 0.096 below the threshold in 2035. Its GDP growth, industrial shares, and urbanization setting follow the planning-oriented endpoint settings in Table 2, while its population growth rate remains the separate assumption stated in Section 2.4.3. This combination provides the basis for preferring SS2-2 when retaining the prescribed planning orientation is part of the selection objective.

SS3-2 tests the regulatory package under high growth. It has the highest endpoint D, but a higher PI and a smaller distance below PI = 1 than the other two candidates. It first reaches the composite non-overloaded range in 2034, one year later. These results show that maximizing D does not identify the earliest transition out of composite overload. SS3-2 is therefore retained as a high-growth constraint-testing pathway. The simulations do not quantify additional implementation costs or establish that this scenario uses a stronger protection package than the other higher-intensity candidates.

4.3. Selection of the Preferred Regulatory Pathway

Candidate eligibility and pathway preference are evaluated separately. Within the observed D range, SS1-2, SS2-2, and SS3-2 meet PI < 1 by 2035. Under the equal-year comparison defined in Section 2.5, SS1-2 has the highest mean D and lowest mean PI among these candidates. It would therefore be preferred if selection were based solely on these two full-period indicators. The higher terminal D of SS2-2 relative to SS1-2 does not establish an overall advantage over the planning horizon.

SS2-2 is conditionally recommended when retaining the planning-oriented GDP growth, industrial structure, and urbanization settings specified in Section 2.4.3 is an explicit selection objective. Its prescribed GDP growth rate is 4%, compared with 3% under SS1-2, while its population growth remains the separate scenario assumption described there. This recommendation reflects the stated development conditions rather than superiority under the full-period D and PI averages. The 2035 values describe the end-of-horizon state and are not given extra weight in those averages. This is a conditional choice within the predefined scenario set, not a global optimum established by a cost function or a quantified implementation-feasibility assessment. If the stated development conditions are not required, the two full-period indicators favor SS1-2.

4.4. Interpretation of Scenario Responses and Comparison with Previous Studies

The divergence between D and PI under BAU reflects their different evaluation references. D depends on the standardized integrated efficacy of the socioeconomic and water environment subsystems, whereas PI compares water demand and pollutant loads entering receiving waters with their corresponding capacities. Improvements in standardized subsystem performance can therefore coexist with rising physical carrying pressure. The present comparison extends the baseline diagnosis in [21] by examining whether the prescribed development and regulation combinations can reverse this divergence and cross the composite overload threshold.

The lower PI values under the higher-intensity packages are consistent with interacting pathways represented in the coupled model. Conservation and leakage control affect water demand and supply losses; reclaimed-water and rainwater utilization affect water circulation and available supply. Cleaner production and lower domestic pollutant-generation intensities reduce source loads, while wastewater collection and treatment affect discharged loads. Modeled agent responses to economic instruments, including water prices, feed into the SD balances. These mechanisms explain how the integrated packages can change the constituent carrying ratios. Their separate contributions were not identified by the present scenario comparisons.

The development scenarios jointly vary GDP growth, population, urbanization, and industrial structure. Their effects are therefore interpreted at the pathway level. SS3-2 reaches PI < 1 later and has a higher endpoint PI than SS1-2 and SS2-2, while achieving a higher D. This combination is consistent with higher development pressure coexisting with stronger standardized subsystem performance. The associations in Section 3.5 support this interpretation of the designed pathways, but do not isolate the effects of individual socioeconomic or regulatory parameters.

The findings connect with complementary urban water assessments. Renouf et al. [8] derived water-mass-balance indicators for resource efficiency and supply internalization. Li et al. [3] showed that water-quality constraints expose scarcity and economic risks omitted by quantity-only assessment, while Baccour et al. [2] examined the role and cost-effectiveness of water-quality management in future scarcity reduction in the Pearl River Basin. In Beijing, SS2-2 reduces total water use, COD emissions, and ammonia nitrogen emissions relative to BAU by 19.3%, 53.4%, and 54.3%, respectively, showing why water-use

change alone is insufficient to describe the modeled response. Coupling-coordination assessment in the Nansi Lake catchment [45] and VPOSR-based carrying-capacity assessment in Beijing [46] also examine socioeconomic and water environmental conditions. Their indicator systems and evaluation periods differ from ours, so the numerical scores are not directly comparable. The present contribution is the joint interpretation of carrying-pressure trajectories and coordination under the prescribed scenarios; it does not establish the cost-effectiveness assessed in [2].

Several limitations qualify the pathway interpretation. The rank analysis contains only six designed scenarios with controls that vary together, and therefore cannot establish independent causal effects or a whole-system sensitivity ranking. Threshold-crossing years are annual deterministic outputs. The supplementary sensitivity analysis examines changes in carrying-assessment inputs and PI entry years, but does not test uncertainty in socioeconomic, policy, or behavioral parameters through ABM–SD feedback, or recalculate D. PI < 1 denotes the adopted composite state and does not establish that every constituent constraint is satisfied. Future work should examine model-parameter uncertainty, individual regulatory effects, constituent carrying ratios, and implementation costs before treating the preferred modeled pathway as an operationally validated plan.

The reported D and PI are city-level indicators for Beijing. Improvements in these aggregate indicators do not establish that water-use or pollution pressure has been relieved in every district or river system. Application of the ABM–SD model and D–PI assessment framework to other cities requires local parameterization of water supply, water environmental capacity, and socioeconomic conditions. Beijing's scenario settings and preferred pathway should therefore not be transferred directly.

4.5. Recommended Regulatory Strategies

The recommendations are based on the paired package comparisons, the descriptive associations in Section 3.5, and the mechanisms represented in the ABM–SD model. They prioritize integrated regulation under the planning-oriented SS2-2 setting rather than rank the independent effectiveness of individual measures.

First, development scale and sectoral structure should be managed together with water environmental protection. SS2-2 reaches the composite non-overloaded range earlier than SS3-2 while retaining the planning-oriented development assumptions specified in Section 2.4.3. This supports the use of coordinated development and environmental objectives in pathway selection, rather than maximizing growth or D alone.

Second, water conservation should be combined with improved water circulation. Within each development mode, the higher-intensity package lowers endpoint PI and changes the composite carrying-status category. Conservation across residential, industrial, and service sectors, leakage control, and appropriate reclaimed-water and rainwater use should therefore be considered as an integrated package. Reuse can reduce dependence on conventional water sources, subject to the suitability of treatment and end uses [47,48]. The present simulations do not determine the separate contribution of each measure.

Third, pollution control should accompany water-demand management. Under SS2-2, the proportional reductions in COD and ammonia nitrogen emissions relative to BAU exceed the reduction in total water use. This supports joint attention to water quantity and pollutant loads. Source reduction, wastewater collection and treatment, and stormwater management should be coordinated, including appropriate sponge-city measures [49–51]. Sector-specific priorities should be evaluated using disaggregated loads rather than inferred solely from aggregate emission curves.

Fourth, water pricing should be assessed as part of the integrated package. Its negative association with PI in Section 3.5 reflects the shared ordering of water prices and technologi-

cal controls across the designed scenarios. It does not identify an independent pricing effect. Tariff design should therefore be evaluated with user characteristics, affordability, and price elasticity, rather than justified solely by the observed scenario correlation [52,53]. Additional targeted analysis is needed before attributing package-level benefits to a particular price change.

Fifth, monitoring should combine D, PI, and the constituent water, COD, and ammonia nitrogen carrying ratios. An increase in D with PI remaining above 1 signals that coordination gains have not resolved composite overload. A decline in PI should be assessed alongside coordination and the individual carrying constraints. This joint monitoring can guide adjustments while avoiding the assumption that PI < 1 guarantees compliance with every constituent capacity limit.

SS2-2 is preferred within the modeled alternatives because it combines the stated development orientation with attainment of the composite PI criterion and a high D. Its practical implementation, costs, and performance under uncertainty require further assessment. The recommendations therefore provide a basis for evaluating an integrated pathway rather than a claim that its individual measures or operational feasibility have already been independently validated.

5. Conclusions

This study used the previously validated ABM–SD model and established D–PI assessment framework to compare eight scenarios for Beijing during 2024–2035. Its contribution is to link multi-scenario simulation to the selection of a planning-compatible regulatory pathway that jointly considers system coordination and water environmental carrying safety.

Coordination improves under both the BAU and Planning scenarios, but neither eliminates severe overload by 2035. Among the eight scenarios examined, only the three higher-intensity sustainable development scenarios reach PI < 1 by 2035. Under the baseline inputs and stated development objectives, SS2-2 is conditionally preferred because it combines planning-compatible development with high-intensity protection. It reaches PI < 1 in 2033 and achieves PI = 0.904 and D = 0.923 in 2035.

Practically, the study provides a scenario-based basis for comparing development and protection packages and identifying situations in which coordination improves while composite overload persists. Under explicitly stated development objectives, Beijing should integrate water conservation, reclaimed-water reuse, and pollution control with water pricing and wastewater fees. Joint monitoring of D, PI, and the constituent water, COD, and ammonia nitrogen carrying ratios can inform policy adjustments. Future research should assess uncertainty in the full ABM–SD model, isolate the effects of individual measures, and evaluate implementation costs before operational application.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su182110722/s1, Supplementary Text S1: Assessment input sensitivity analysis; Figure S1: Sensitivity of carrying pressure to assessment inputs; Table S1: Scenario control values and their Spearman rank correlations with PI in 2035 (n = 6); Table S2: SS2-2 terminal PI and sustained entry years under one-at-a-time ±10% input changes; Table S3: Terminal PI bounds and simultaneous adverse-change margins for the three high-intensity candidate pathways; Table S4: Annual D and PI values and equal-year means for the three candidate pathways.

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