Check for updates

Enhancing Urban Water Supply System Resilience: A Configurational Analysis Based on the PSR Framework

Jinfeng Li

School of Business Administration, Liaoning Technical University, Huludao 125105, China

Corresponding author. Email: 1186391488@qq.com

Abstract. In response to climate change and urbanization challenges, promoting the transformation of urban water supply systems toward a resilience paradigm is critical. Based on the Pressure-State-Response (PSR) framework, this study employs dynamic fuzzy-set Qualitative Comparative Analysis (fsQCA) to investigate the driving pathways of water supply system resilience using panel data from 18 cities in Sichuan Province (2013–2022). The results show that overall resilience has improved, yet high-resilience cities remain scarce. No single necessary condition exists, confirming the complexity of resilience formation. Four equivalent configuration models are identified: resource-infrastructure redundancy, infrastructure-governance synergy, resource-governance synergy, and strategic investment-driven. This study reveals the complex causal mechanisms underlying resilience and provides a theoretical basis for differentiated enhancement strategies during the 15th Five-Year Plan period.

Keywords: Water Supply System Resilience; PSR Model; Dynamic fsQCA; Configuration Pathways

1 Introduction

Urban water supply systems, as critical urban lifelines, face mounting pressures from climate change, rapid urbanization, aging infrastructure, and water quality challenges. The traditional safety paradigm centered on robustness is no longer sufficient, necessitating a transition toward a resilience paradigm that emphasizes adaptability, recoverability, and learning capacity. Existing research has made progress in identifying influencing factors[1], assessment methods[2], and enhancement strategies[3]. However, three gaps remain: firstly, assessment indicators often remain static, failing to capture dynamic adaptive processes; secondly, systematic empirical research at the meso-level urban scale is limited; thirdly, most studies adopt single-factor or static perspectives, overlooking the configurational effects among multiple factors and their temporal evolution. To this end, this paper introduces the PSR framework to construct a dynamic analysis model. It employs the CRITIC-TOPSIS method and dynamic fsQCA to identify the configuration pathways for achieving high resilience across different periods. This provides theoretical support for the formulation of differentiated resilience strategies.

© The Author(s) 2026
L. W. Koon et al. (eds.), *Proceedings of the 2026 7th International Conference on Management Science and Engineering Management (ICMSEM 2026)*, Advances in Economics, Business and Management Research 399,
https://doi.org/10.2991/978-94-6239-758-3_77

2 Theoretical Framework

The Pressure-State-Response (PSR) model is employed to construct a dynamic analytical framework for water supply system resilience. This framework conceptualizes the system as a dynamically adaptive complex entity, where pressure drives changes in state, state triggers responses, and response reshapes state and mitigates pressure through feedback loops, forming a continuous optimization cycle. Variables at different levels interact synergistically to constitute multiple driving pathways. The framework includes:

Pressure Layer (P): External disturbances driving changes in system state. Core variables are social development pressure (P1) and water demand intensity(P2).

State Layer (S): Resource conditions and infrastructure status under pressure. Core conditions include water resource endowment(S1) and water supply infrastructure level(S2).

Response Layer (R): Proactive management strategies and regulatory measures to enhance resilience. This primarily involves sewage treatment level (R1) and infrastructure investment intensity(R2).

3 Research Design

3.1 Methods, Sample, and Variables

A mixed-method approach is adopted: first, the CRITIC-TOPSIS method is used to measure the comprehensive resilience level, avoiding weight distortion; then, dynamic fsQCA is applied to analyze panel data from 18 prefecture-level cities in Sichuan Province. Following the principle of combining data-driven analysis with policy context, the study period is divided into two stages: 2013–2017 (T1) and 2018–2022 (T2). Data are sourced from statistical yearbooks and water resources bulletins, and individual missing values are filled using linear interpolation. The outcome variable is the continuous resilience score (Y) of urban water supply systems, calculated using the CRITIC-TOPSIS method. Proxy indicators for Y include pipeline leakage rate, water supply coverage rate, comprehensive water supply capacity, number of water plants, total water supply volume, reclaimed water utilization rate, and water resource utilization efficiency[4]. The condition variables are defined in Table 1. All variables are treated as fuzzy sets.

Table 1. Criteria for Condition Variable Values and Set Membership Direction.

Dimension	Variable	Description	Indicator Property
Pressure (P)	P1	Urbanization rate	Inverse
	P2	Per capita water consumption	Inverse
State (S)	S1	Per capita water resources	Direct
	S2	Pipeline density in built-up area	Direct
Response (R)	R1	Sewage treatment rate	Direct
	R2	Fixed asset investment in water supply	Direct

3.2 Calibration

Fuzzy set membership scores are derived from raw data through direct percentile calibration. Specifically, the sample's 75th, 50th, and 25th percentiles are designated as thresholds for full membership (0.75), crossover (0.50), and full non-membership (0.25) [5]. For resilience-inhibiting inverse indicators (P1, P2), fuzzy negation is utilized to adjust preliminary calibration scores, with calibration anchors for both stages detailed in Table 2.

Table 2. Calibration Anchors.

Variable		T1 Stage Calibration Anchors			T2 Stage Calibration Anchors		
		Full Membership	Crossover Point	Full Non-membership	Full Membership	Crossover Point	Full Non-membership
Condition	P1	41.239	43.916	46.751	49.446	50.516	53.376
	P2	77.232	81.879	93.157	82.321	98.382	107.891
	S1	2124.914	1582.200	650.494	3014.726	1789.175	1023.554
	S2	13.184	10.273	8.554	16.384	11.361	8.389
	R1	92.798	88.625	84.961	96.826	95.828	95.366
	R2	7743.300	3801.500	2665.025	16324.456	9348.903	5076.864
Outcome	Y	0.519	0.488	0.447	0.550	0.518	0.495

4 Empirical Results

4.1 Resilience Level Analysis

The resilience level of sample cities has steadily increased. The regional mean rose from 0.48 to 0.52 in T1, with a stage average of 0.49; the mean further fluctuated upward to 0.54 in T2, a 10.2% increase over T1. Significant intercity disparities persist: Chengdu consistently maintained a leading position, while Zigong recorded the largest increase, rising from 0.24 to 0.45. In contrast, cities such as Luzhou, Deyang, and Guang'an experienced relatively slow growth. By the end of T2, according to the grading standards for water supply system resilience[2], among the 18 prefecture-level cities, only Chengdu attained high resilience; Mianyang, Panzhihua, Leshan, and Suining were classified as "relatively high resilience"; the remaining 13 cities were at the "medium resilience" level. This indicates that most cities' water supply systems possess only basic functionality, with deficiencies in system completeness and stability. Elevating the region from medium to relatively high resilience thus represents a core governance challenge.

4.2 Necessity Analysis

Prior to configuration analysis, necessity tests were conducted using fsQCA 3.0 to examine whether any single condition variable constitutes a necessary condition for high resilience across the two periods. The consistency levels for all six condition variables are below the 0.9 threshold[5], indicating that no single condition is necessary for high resilience. This finding underscores the complexity of the mechanisms underlying high resilience in urban water supply systems, where achieving a high level depends on the synergistic configurational effects of multiple factors.

4.3 Sufficiency Analysis

To identify multiple driving pathways for high resilience in urban water supply systems, this study sets the consistency threshold at 0.8, case frequency at 1, and PRI consistency at 0.75[6]. All six conditions are coded as "present or absent" for configurational analysis across T1 and T2[5]. As is shown in table 3, overall solution consistency exceeds 0.85 in both stages, with overall coverage of 0.429 and 0.451, respectively. Based on core condition combinations, six effective pathways are summarized into four higher-order driving models.

Resource-Infrastructure Redundancy Model (A1, A2): Relies on S1 and S2 as core conditions. Ya'an, a typical city, achieves high resilience through abundant water resources (S1) and dense pipeline infrastructure (S2), where natural endowments and engineered redundancy jointly enhance system robustness.

Infrastructure-Governance Synergy Model (A3, B1): Relies on S2 and R1 as core conditions. Chengdu serves as a representative city, relying on dense pipeline infrastructure (S2) and a high sewage treatment rate (R1), demonstrating that strong infrastructure combined with effective governance can compensate for other limitations.

Resource-Governance Synergy Model (A4): Relies on S1 and R1 as core conditions. Guangyuan exemplifies this pathway, leveraging abundant water resources (S1) alongside a high sewage treatment rate (R1), where natural availability is reinforced by strong treatment capacity.

Strategic Investment-Driven Model (B2): Relies on R2 as core condition. Meishan achieves high resilience primarily through sustained fixed asset investment in water supply (R2), where strategic capital input drives system upgrading and capacity building.

Table 3. Configuration Analysis Results for High Resilience in Water Supply Systems.

Condition Variable	T1 Stage				T2 Stage	
	A1	A2	A3	A4	B1	B2
P1	●	⊗	⊗	●	⊗	•
P2	⊗	•	⊗	⊗	⊗	⊗
S1	●	●	⊗	●		•
S2	●	●	●	⊗	●	⊗
R1	⊗	⊗	●	●	●	⊗
R2	●	⊗	●	⊗		●

Condition Variable	T1 Stage				T2 Stage	
	A1	A2	A3	A4	B1	B2
Consistency	0.854	0.899	0.968	0.911	0.988	0.987
Raw Coverage	0.088	0.105	0.129	0.154	0.383	0.088
Unique Coverage	0.061	0.096	0.108	0.135	0.363	0.068
Overall Coverage	0.429				0.451	
Overall Consistency	0.939				0.988	

Note: ● = core condition present; ⊗= core condition absent; • = peripheral condition present; ⊗ = peripheral condition absent; blank = condition does not affect.

4.4 Robustness Test

To ensure the reliability of research conclusions, a robustness test was conducted on the configuration results as follows: (1) Cases with a calibrated membership score of exactly 0.5 in Phase T2 were adjusted to 0.501 to assess the sensitivity of results to minor changes in the calibration threshold; (2) While keeping the case frequency threshold unchanged, the sample consistency threshold was raised from 0.80 to 0.85 to verify the stability of core configurations under stricter criteria. The consistency, coverage, corresponding cases and other parameters of the two phases remained consistent with the original results after testing, which indicates that the configuration results are robust [5] .

5 Conclusion

This study empirically analyzed the driving pathways of urban water supply system resilience in 18 Sichuan cities from 2013 to 2022 using the PSR framework and dynamic fsQCA. Three main conclusions are drawn:

(1)Resilience levels have improved overall, yet highly resilient cities remain scarce, resulting in an imbalanced hierarchical structure. During the study period, urban resilience rose steadily. By the end of the period, only Chengdu reached the high resilience level, while the majority of cities stayed at the moderate resilience stage. Thus, realizing the leap from moderate to relatively high resilience has become the core challenge at present.

(2)High resilience is driven by multiple conditional configurations, and no single necessary condition exists. Necessity test results indicate that none of the individual antecedent conditions serve as a necessary condition for high resilience, which verifies the complexity of the formation mechanism of urban water supply system resilience.

(3)Configuration analysis further identifies four equivalent high-level modes: resource-facility redundancy, facility-governance coordination, resource-governance coordination and strategic investment-driven type. It reveals that cities with different endowments can achieve high resilience through diverse combinations of conditions, providing a theoretical basis for the formulation of differentiated strategies.

For management practice, differentiated strategies should be implemented according to each city's dominant pathway. Synergistic development of hard infrastructure and soft governance capabilities should be prioritized, alongside the establishment of normalized resilience-building mechanisms integrated into daily operations.

Limitations include the regional focus on Sichuan Province; future research could extend to other regions, incorporate additional dynamic variables such as extreme climate events, and employ system dynamics or machine learning for simulation and prediction.

References

1. Helmrich A, Markolf S, Li R, et al. (2021) Centralization and decentralization for resilient infrastructure and complexity[J]. Environmental Research: Infrastructure and Sustainability, 1(2): 021001. DOI 10.1088/2634-4505/ac0a4f
2. Wang Y R , Chen H Z . (2025) Resilience Evaluation of Zhengzhou Water Supply System Based on DPSIR Dynamic Framework. Yellow River, 47(05): 80-86.
3. Khedun C P, Lewis A C, Kaiser R A, et al. (2025) Building resilience into the public water supply system through targeted data-driven conservation strategies[J].Journal of Irrigation and Drainage Engineering,151(3),04025011. DOI 10.1061/jidedh.ireng-10453
4. Li Z T, Li T F, Liu S N. (2025) Research on Leakage Control and Consumption Reduction Strategies for Water Supply Networks Based on Pressure-Demand Model. Water & Wastewater Engineering, 61(07): 144-149. DOI:10.13789/j.cnki.wwe1964.2024.11.29.0002.
5. Wang D, Wu F. Research on Configuration Paths of Urban Infrastructure Resilience Under the Extended TOE Framework. Journal of Safety Science and Technology, 2025, 21(02): 208-216.
6. Schneider C Q, Wagemann C. (2010) Standards of good practice in qualitative comparative analysis (QCA) and fuzzy-sets[J]. Comparative sociology, 9(3): 397-418. DOI 10.1163/156913210x12493538729793

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (http://creativecommons.org/licenses/by-nc/4.0/), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.