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Water treatment chemical supply chain disruption risk assessment and mitigation strategy ranking using BWM–VIKOR

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Abstract

Chemical supply disruptions can compromise compliance with water treatment regulations and service continuity. This study proposes an integrated multi-criteria decision-making framework that combines the Best–Worst Method (BWM) and VIKOR to prioritize mitigation strategies for water treatment chemical supply chain disruptions. A case application at Shanghai's Yangshupu Water Plant demonstrates the approach. BWM-based weighting shows that compliance/public health (0.26) and service continuity (0.18) dominate decision priorities (44% combined), followed by recoverability/flexibility (0.16) and supply vulnerability (0.14). Using these weights, VIKOR ranks mitigation alternatives and identifies a compromise set. Under baseline conditions ($v = 0.5$), dual sourcing and supplier prequalification achieve the best compromise performance ($Q = 0.083$, $S = 0.563$), while safety stock and reorder redesign minimize worst-case regret ($R = 0.140$); the acceptable advantage condition is not satisfied ($0.135 < 0.167$), leading to a compromise set $\{A1,A2\}$. Sensitivity and scenario tests confirm that the shortlist is robust, with safety stock becoming top-ranked under prolonged logistics disruption and QA/QC strengthening rising under quality failures. The proposed framework provides transparent, defensible support for utility resilience planning.

Keywords: water treatment; chemical supply chain; disruption risk; BWM; VIKOR

1. Introduction

Reliable access to water treatment chemicals—including coagulants, disinfectants, pH/alkalinity reagents, and process aids, underpins day-to-day compliance and operational stability in drinking-water production[1, 2]. Disruptions in these inputs can quickly propagate into higher noncompliance risk, reduced treatment capacity, and constrained operational control during raw-water shocks[3, 4]. Evidence from the sector over the past few years has made this vulnerability visible: utilities have reported recurring difficulties securing key disinfectants, such as liquid chlorine and sodium hypochlorite, alongside broader procurement and delivery challenges[5, 6].

A growing body of authoritative guidance frames treatment chemicals as an explicit supply-chain resilience problem. The U.S. EPA documents that disruption risks vary by chemical and emphasizes that local risk profiles can differ substantially from national-level patterns, thereby encouraging utilities to incorporate chemical supply risks into formal resilience and risk assessment processes[7, 8]. EPA’s companion products provide chemical-by-chemical supply chain profiles (46 chemicals), including competing uses, manufacturing routes, trade exposure, and disruption history, information intended to support practical mitigation planning rather than merely descriptive risk awareness [9-11]. Together, these resources establish (i) the breadth of chemical dependencies and (ii) the multi-tier pathways through which disruptions occur (feedstocks → production capacity → transport constraints → receiving/quality failures). However, guidance documents typically fall short of providing a formal, auditable method for prioritizing mitigation options when utilities face competing objectives (risk reduction, feasibility, implementation time, cost, and safety constraints).

Recent literature on the water sector also recognizes supply-chain fragility, often highlighting the pandemic-era period as a catalyst for renewed attention to cascading effects[12, 13]. Systems-oriented work has shown how supply disruptions can ripple into water services and societal coping capacity, underscoring that “critical service” performance depends on upstream supply availability and logistics as much as on on-site treatment assets. Yet much of this water-focused disruption literature remains qualitative or descriptive. In contrast, quantitative prioritization and decision optimization are more commonly developed in general supply-chain research than tailored to utility chemical continuity decisions[14, 15].

In parallel, water management research has increasingly adopted multi-criteria decision-making (MCDM) to handle complex trade-offs under uncertainty. Recent studies illustrate the direction: multi-scenario and multi-model decision frameworks are used to stress-test choices under uncertain futures in urban water management, explicitly acknowledging that rankings can change with scenario assumptions and stakeholder preferences[16, 17]. VIKOR-based applications continue to expand across water-related planning and assessment problems, including integrated VIKOR models for water-quality monitoring evaluation and modified VIKOR variants for water-related selection and assessment tasks, typically accompanied by sensitivity analyses to test robustness [18, 19]. These studies demonstrate that compromise-based ranking is widely accepted in water research—but they usually focus on technology selection, monitoring design, or planning, rather than on chemical supply-disruption mitigation, which links upstream supply fragility directly to treatment performance outcomes.

For criteria weighting, the Best–Worst Method (BWM) has gained traction because it reduces the burden of pairwise comparisons while offering an explicit consistency structure[20, 21]. BWM is increasingly used in water-resilience contexts where stakeholder preferences must be incorporated systematically, as in recent work developing multi-criteria resilience indicators for water and wastewater utilities. This is important for chemical continuity decisions because the “right” mitigation choice depends on how decision-makers prioritize outcomes (compliance margin, continuity, recoverability) relative to constraints (cost, feasibility, safety/environment). A weighting method that is efficient, transparent, and defensible is therefore a practical requirement, not just a methodological preference[22].

VIKOR is particularly suitable for selecting mitigation strategies because it explicitly balances group utility and individual regret, yielding either a single compromise solution or a compromise set when alternatives are close[23]. This aligns with real utility governance, in which decision-makers often prefer a shortlist of “near-best” options that remain credible across different risk attitudes and scenarios. Moreover, water literature increasingly expects robustness checks, varying weights, varying method parameters, and testing plausible disruption scenarios, rather than reporting a single static ranking.

Against this background, the key gap is not the absence of mitigation ideas (e.g., supplier diversification, safety stock, strengthened QA/QC, substitution protocols, mutual aid). Still, the lack of a sector-tailored, reproducible prioritization logic that:

(i) reflects water-specific risk consequences (public health/compliance and continuity), (ii) uses expert judgment efficiently with consistency screening, (iii) ranks strategies under conflicting objectives using a compromise model, and (iv) demonstrates stability via sensitivity and scenario testing. The integrated BWM–VIKOR approach directly addresses this gap by coupling a preference-efficient weighting method with a compromise ranking method, then verifying whether the resulting priorities remain stable under realistic uncertainty—an evidence structure that utility managers and regulators can audit and act upon.

2. Methodological frameworks

2.1. Study framework and decision problem definition

An integrated decision-support framework links upstream water-treatment chemical supply-chain disruptions to downstream treatment performance and compliance risks. Then it prioritizes mitigation actions using a two-stage MCDM workflow (Figure 1). The decision problem is defined as: which mitigation strategies should be prioritized to maintain safe, continuous treatment when critical chemicals become unavailable, delayed, or nonconforming, while balancing regulatory compliance, service continuity, recoverability, cost, and implementability. The system boundary covers the utility’s chemical-dependent treatment processes (e.g., disinfection, coagulation/flocculation, pH/alkalinity adjustment, adsorption) and the associated supply network (suppliers, transport routes, storage, quality assurance). Disruption scenarios include production outages, logistics delays (port/trucking), import restrictions, supplier failure, quality deviations, and demand shocks that propagate into operational instability (dose limitations, process upsets, throughput reduction, or elevated noncompliance probability). Mitigation alternatives are defined as actionable measures, such as dual sourcing, safety stock policies, supplier prequalification, approved substitutions, process flexibility plans, on-site generation where feasible, and mutual aid/sharing arrangements. They are evaluated against a structured set of criteria. BWM is used to elicit consistent expert-derived criteria weights reflecting the relative importance of compliance and resilience objectives, and VIKOR is applied to rank mitigation alternatives by identifying compromise solutions that balance overall utility and worst-case regret under the defined criteria (Figure 1).

Figure 1. Overview of the integrated BWM–VIKOR decision-support framework for water treatment chemical supply chain resilience, linking (i) chemical supply network and disruption scenario identification, (ii) criteria structuring and BWM-based weighting, and (iii) VIKOR-based compromise ranking of mitigation strategies to produce prioritized actions and an implementation roadmap. The diagram was created by the authors using Microsoft PowerPoint (Version 365, Microsoft Corporation, https://www.microsoft.com).

2.2. System boundary: water treatment chemicals and supply network mapping

The system boundary is defined to capture how upstream chemical-supply disruptions propagate to downstream treatment performance and compliance outcomes by explicitly mapping the end-to-end water-treatment chemical-supply network from production to point of use (Figure 2). The boundary begins with chemical manufacturers and formulators (primary production and blending), includes distributors/wholesalers and logistics nodes (ports, border crossings, trucking corridors, local depots), and extends to the utility's receiving, quality verification, storage, and dosing systems, where chemicals directly affect process units. The chemical set is scoped to "critical inputs" that can constrain treatment capacity or compliance when unavailable or nonconforming, typically including disinfectants (chlorine gas, sodium hypochlorite, chloramines precursors), coagulants/flocculants (alum, ferric salts, polymers), pH/alkalinity adjustment chemicals (lime, caustic soda, acids, sodium bicarbonate), adsorbents (powdered/granular activated carbon), and selected specialty reagents used for taste/odour control or advanced treatment (as applicable to the plant). Supply network mapping is conducted by (i) identifying each chemical's approved suppliers and sourcing modes (single vs. multiple sourcing, local vs. imported), (ii) recording lead times, transportation routes, minimum order quantities, and storage constraints, (iii) documenting receiving/QA-QC steps (certificate-of-analysis checks, acceptance testing, rejection/return pathways), and (iv) linking chemical availability and quality to specific treatment "use-points" (coagulation, disinfection, pH control, adsorption) and associated service outcomes (treated-water quality compliance, throughput, and recovery time). The resulting map provides the structured input for subsequent risk identification and criteria formulation by making dependencies, bottlenecks, and feasible substitution pathways explicit (Figure 2).

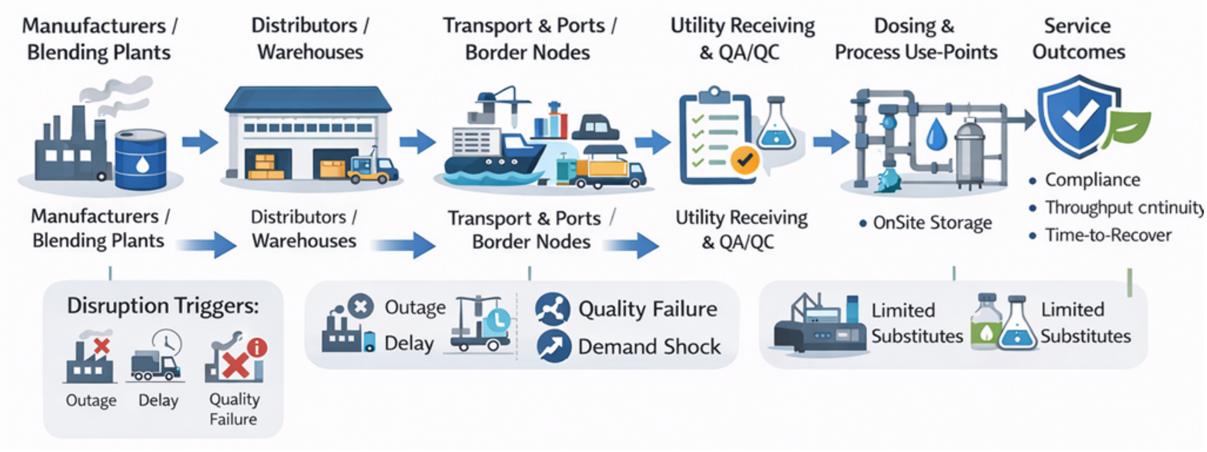

Figure 2. System boundary and end-to-end chemical supply network mapping for a water treatment utility, linking upstream production and distribution nodes, logistics pathways, and on-site receiving/QA-QC and storage to treatment process use-points and service outcomes, with key disruption triggers and vulnerability factors highlighted. The diagram was created by the authors using Microsoft PowerPoint (Version 365, Microsoft Corporation, https://www.microsoft.com).

2.3. Disruption risk identification and structuring (risk taxonomy)

Disruption risks are identified and structured into a water-utility–specific taxonomy that reflects how failures emerge across the chemical supply network and how they translate into treatment constraints. The risk identification process begins by compiling an initial long list of disruption events across the whole boundary defined in Figure 2 (upstream production → distribution → logistics nodes → utility receiving/QA-QC → storage → dosing/use-points). Sources for this long list include utility procurement and operations records (purchase orders, delivery performance logs, emergency sourcing events), supplier communications (allocation notices, lead-time changes, quality nonconformance reports), and structured expert elicitation with staff from treatment operations, laboratory/QA-QC, procurement, safety, and maintenance. Risks are captured in an "event–mechanism–impact" format to avoid generic labels: event (what occurred), mechanism (why it caused a shortage or rendered the chemical unusable), and impact pathway (which process-use point is affected and what operational outcome is threatened).

To enable consistent assessment, risks are organized into a three-level hierarchical taxonomy. Level 1 (risk domains) groups risk by where they originate: (R1) upstream supply/production, (R2) procurement and supplier relationship, (R3) logistics and transportation, (R4) receiving and quality conformance, (R5) on-site storage and handling, and (R6) process dependency and substitution constraints.

Level 2 (risk categories) breaks each domain into operationally meaningful categories. For example, upstream supply/production includes plant outages, raw-material shortages, energy curtailments, and regulatory shutdowns; logistics includes port congestion, customs/border delays, trucking shortages, route disruption, and hazardous-material transport restrictions; receiving/quality includes certificate-of-analysis mismatch, concentration deviations, contamination, packaging integrity failure, and mislabelling; storage/handling includes tank capacity limits, incompatibility/segregation issues, shelf-life decay, temperature sensitivity, and safety incidents that restrict use; and process dependency includes tight dose windows, limited substitute chemicals, operator readiness for alternative dosing, and permit/standard constraints on process changes.

Level 3 (specific risk events) provides the assessable items used later in BWM–VIKOR. Each risk event is written as a measurable statement, such as: “Delay of sodium hypochlorite deliveries beyond safety-stock coverage due to port congestion,” “Alum shipment rejected due to off-spec concentration leading to immediate coagulant shortfall,” or “Chlorine supplier allocation during regional demand surge causing reduced delivered quantities.” For each event, a concise data sheet is prepared including: affected chemical(s), node of origin (mapped to Figure 2), primary triggers, early-warning indicators, typical lead time to detect, expected duration, and the direct link to treatment functions (coagulation, disinfection, pH/alkalinity control, adsorption). Where multiple chemicals can play similar roles (e.g., alternative coagulants), substitution relationships are explicitly noted so the taxonomy reflects real operational flexibility rather than assuming fixed dependencies.

Finally, the taxonomy is checked for completeness and non-overlap through an expert review cycle. Duplicate or nested risks are consolidated, ambiguous risks are rewritten into event-based statements, and rare but high-consequence events are retained even if historical frequency is low (e.g., abrupt import restriction or major supplier insolvency). The output of this subsection is a validated, decision-ready set of disruption risks, each clearly mapped to the chemical supply network and to treatment-process consequences, ensuring that subsequent weighting (BWM) and mitigation ranking (VIKOR) are grounded in operational reality rather than in generic supply-chain descriptors.

2.4. Expert panel design and data collection protocol

A structured expert-elicitation protocol is used to obtain defensible inputs for both BWM (criteria weights) and VIKOR (mitigation performance ratings), while minimizing bias and ensuring traceability from raw questionnaires to final rankings. Baise University in China confirmed that all questionnaires and the online protocol were completed, and that the obtained data are confidentially retained to preserve the anonymity of the respondents. A panel of 100 experts is recruited to represent the complete decision ecosystem of water treatment chemical supply and utility operations, combining (i) industry practitioners (water utilities, treatment plant operations, laboratory/QA-QC, procurement and contracting, safety/EHS, and logistics/supply management within chemical distribution), (ii) chemical supply-side professionals (manufacturers/formulators, distributors/wholesalers, hazmat transport and port/border logistics coordinators), and (iii) university experts (faculty/researchers in water treatment, water quality engineering, industrial engineering/operations research, and supply chain risk). Panel selection follows purposeful sampling with minimum eligibility thresholds to ensure domain competence: verified involvement in water treatment or chemical supply decision-making, demonstrated familiarity with treatment process constraints and chemical specifications, and sufficient experience to judge disruption likelihood and mitigation feasibility (e.g., senior operational roles, procurement leads, QA/QC managers, or researchers with sustained publication/consulting in the area). To improve response quality, participation is anonymized, conflict-of-interest risks are screened (e.g., single-supplier dominance in responses), and a brief orientation note standardizes terminology (chemical categories, disruption triggers, and the mitigation option set) so that ratings are comparable across sectors.

The final panel size is consistent with expert-based multi-criteria decision-making studies, in which panels typically range from 5 to 20 domain experts, depending on the problem's complexity and the availability of specialized knowledge. The retained experts represent multiple stakeholder groups involved in water treatment chemical supply chains, including utilities, suppliers, logistics professionals, and regulatory or policy stakeholders. This diversity was intentionally maintained to capture a broad range of perspectives and reduce the potential dominance of any single stakeholder group. In addition to the consistency screening applied in the BWM procedure, balanced stakeholder representation was considered during expert selection to mitigate potential bias in the evaluation process. Similar expert panel sizes have been widely used in MCDM studies involving infrastructure and supply chain decision-making[20].

The questionnaire is designed in three linked modules aligned with the framework. Module A (profile and relevance screening) records role type (utility/industry/university), years of experience, functional area, and familiarity level with specific chemical groups (disinfectants, coagulants/flocculants, pH/alkalinity chemicals, adsorbents). Module B (BWM judgments) elicits criteria weights by asking each expert to (1) identify the most important (Best) and least important (Worst) criterion from the predefined criteria hierarchy, (2) score the preference of the Best criterion over each other criterion (Best-to-Others vector) using a consistent integer scale, and (3) score the preference of each criterion over the Worst criterion (Others-to-Worst vector). Clear anchor descriptions are provided to reduce scale interpretation drift (e.g., “1 = equal importance,” “9 = extremely more important”). Module C (VIKOR performance ratings) collects expert evaluations of each mitigation strategy against each criterion using a uniform rating scale (e.g., 1–10 effectiveness/feasibility scale, or a Likert-type scale mapped to numeric values), with operational definitions for each criterion (e.g., “compliance protection,” “time-to-recover improvement,” “implementability,” “cost burden,” “substitution flexibility”). When quantitative inputs are available (e.g., estimated lead-time reduction, safety-stock coverage days, relative cost classes), the instrument allows entry of either numeric values or coded ranges, which are then harmonized into comparable performance scores during preprocessing.

Questionnaire data are extracted and integrated into the framework through a reproducible pipeline (Figure 3). First, raw responses are exported to a structured dataset with unique, anonymized IDs and role tags (utility / supply-side / university). Second, quality control and cleaning are applied: incomplete surveys are flagged; inconsistent or impossible entries (e.g., missing Best/Worst selection, non-integer scale values) are corrected only when unambiguous or otherwise excluded; and response time and straight-lining checks are used as soft indicators of low engagement. Third, BWM weights are computed for each expert by solving the standard BWM optimization to obtain an individual weight vector that best satisfies the two comparison vectors; individual solutions are then screened using a consistency check (e.g., the reported BWM consistency ratio or an equivalent deviation measure). Responses that fail consistency thresholds are not discarded immediately; instead, they are either down-weighted or moved to a sensitivity set, depending on the severity of the inconsistency, thereby preserving transparency about how expert uncertainty affects results. Fourth, individual BWM weights are aggregated into a final group-weight vector. Aggregation is performed using a robust group operator (typically the geometric mean or a median-based aggregation across experts). It can also be stratified by expertise group to test whether utility practitioners prioritize criteria differently from academics or chemical suppliers. Fifth, the VIKOR decision matrix is assembled by aggregating expert performance ratings for each mitigation alternative under each criterion (again using mean/median with dispersion reporting), followed by normalization and computation of the VIKOR measures (group utility and individual regret terms). Finally, the aggregated BWM weights and the aggregated VIKOR performance matrix are combined to produce compromise rankings, and subgroup and sensitivity analyses are used to confirm that no single stakeholder category dominates the rankings.

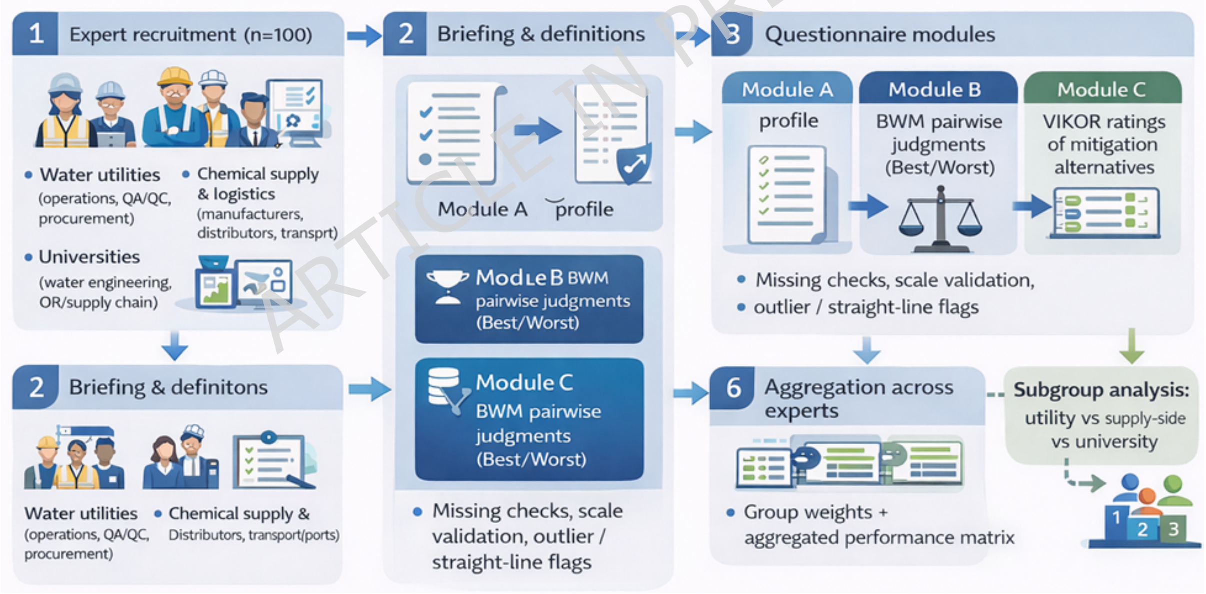

Figure 3. Expert panel composition and questionnaire-to-model data pipeline for the BWM–VIKOR analysis, showing expert recruitment across stakeholder groups (water utilities, chemical suppliers/logistics, and academia/regulators), the briefing and shared definitions used to standardize judgments, the questionnaire modules (expert profile; BWM best–worst pairwise judgments for criteria weighting; VIKOR ratings of mitigation alternatives), data screening and quality checks (missing responses, scale validation,

outlier/straight-line detection), aggregation of judgments across experts (including optional subgroup comparisons), and the resulting inputs for computing BWM weights and VIKOR compromise rankings. The diagram was created by the authors using Microsoft PowerPoint (Version 365, Microsoft Corporation, https://www.microsoft.com).

2.5. Evaluation criteria development for risk and mitigation assessment

Evaluation criteria were developed to ensure that chemical supply disruptions and mitigation strategies can be assessed in a way that is (i) decision-relevant for water utilities, (ii) consistent across experts, and (iii) traceable to both sector evidence and operational practice. The development process began with a comprehensive criterion "long-list" compiled from three evidence streams: authoritative water-sector guidance and preparedness resources addressing treatment continuity under supply interruptions, utility and sector reports/case lessons describing operational consequences of chemical shortages (e.g., dose limitations, process upsets, throughput reductions, substitution constraints), and peer-reviewed literature on resilience/risk assessment and multi-criteria evaluation in water treatment and critical infrastructure supply networks. The long list was then screened and consolidated through expert review to remove redundancy (e.g., overlapping cost- or time-related items), improve clarity (e.g., by using unambiguous wording and directionality), and retain only criteria that meaningfully discriminate among mitigation options. Each retained criterion was operationally defined with a clear measurement direction (benefit vs. cost), a scoring rubric (quantitative indicator where feasible, otherwise anchored linguistic scales), and a mapping to either (a) disruption consequences at the point of treatment or (b) the expected performance improvement delivered by a mitigation action. The finalized structure is organized as a compact hierarchy aligned with utility decision logic, public health and compliance protection, service continuity, recoverability, supply exposure, implementability, cost, and environmental/safety considerations. The complete criteria set and their operational definitions used for BWM weighting and VIKOR evaluation are listed in Table 1 (with representative indicators to support consistent scoring across the expert panel and across mitigation alternatives).

Table 1. Evaluation criteria used for risk and mitigation assessment.

Code	Criteria group	Operational meaning for the chemical disruption context	Type*	Example indicators/scoring anchors
C1	Compliance & public health	Degree to which a disruption (or lack of mitigation) increases the likelihood/severity of regulatory noncompliance and public health risk; reflects the criticality of the affected treatment barrier.	Benefit (higher = better protection)	Expected noncompliance likelihood reduction; severity class (low–very high) anchored to treatment barrier criticality; extent of water quality margin loss
C2	Service continuity	Ability to maintain treated-water production and service levels during a chemical shortage/delay/quality failure.	Benefit	Throughput maintained (%); duration of degradation/outage avoided (hours/days); ability to meet peak demand under disruption.

C3	Recoverability & flexibility	The speed and flexibility with which operations can be stabilized and restored following a chemical disruption, including substitution/process adaptability and available operational buffers.	Benefit	Time-to-recover improvement (days); substitutability score (none–high); “storage days at normal dose” or buffer capacity improvement
C4	Supply vulnerability	Extent of exposure to upstream supply fragility that the mitigation reduces (single sourcing, long lead times, logistics complexity, supplier reliability).	Benefit	Reduction in single-source dependency; lead-time risk reduction; number of qualified suppliers; historical supplier on-time/quality performance
C5	Feasibility & implementability	Practicality of implementing the mitigation within utility constraints (time, complexity, staffing/training, approvals/permitting, procurement constraints).	Benefit	Implementation time (weeks/months); complexity (low–very high); training burden; permitting/approval intensity

C6	Cost & resources	Total resource burden associated with the mitigation across CAPEX/OPEX and recurring costs, including inventory holding/wastage risk and scalability within budgets.	Cost (lower = better)	Net present cost or annualized cost; OPEX increase; inventory holding cost; expiry/wastage risk (low–high); budget fit
C7	Environmental & safety	Implications for worker safety, chemical handling/storage risk, and environmental performance (e.g., residuals/sludge impacts, discharge implications, energy/GHG where relevant).	Cost (lower = better) or Benefit (higher = safer)†	Safety risk score; hazardous storage burden; residuals/sludge impact; additional energy/GHG impact

* Type indicates whether the criterion is treated as a benefit (maximize) or cost (minimize) in VIKOR; the same direction is maintained during scoring to avoid interpretation drift.

† C7 can be implemented as a cost (risk/impact to minimize) or as a benefit (safety/environmental performance to maximize), if the direction is kept consistent across all alternatives.

2.6. Best–Worst Method (BWM) for criteria weighting, consistency assessment, and reliability checks

The Best–Worst Method (BWM) is used to determine the relative importance of the evaluation criteria based on expert judgments. In this approach, experts first identify the most important (Best) and least important (Worst) criteria, then provide pairwise preference ratings between the Best criterion and the other criteria, and between the remaining criteria and the Worst criterion. The optimal criteria weights are obtained by solving the BWM optimization model, which minimizes the maximum deviation between pairwise comparisons and derived weights. Detailed mathematical derivations are provided in the Supplementary Material. The Best–Worst Method (BWM) has also been applied in related decision-making studies, such as the work by Kavre et al. (2025) [24], which prioritizes barriers to digital transformation in manufacturing systems.

2.7. VIKOR method for mitigation strategy ranking

Mitigation strategies are ranked using the VIKOR method, which identifies compromise solutions among conflicting criteria. The method evaluates each alternative based on group utility (S) and individual regret (R), derived from the weighted normalized performance of alternatives across all criteria. These measures are combined to compute the VIKOR index (Q), which represents the relative closeness of each alternative to the ideal solution. Alternatives are ranked in ascending order of Q, and compromise solutions are identified according to the acceptable advantage and acceptable stability conditions. Detailed derivations of the VIKOR equations are provided in the Supplementary Material.

2.8. Sensitivity analysis, validation, and robustness checks

Sensitivity and robustness analyses were conducted to examine whether the ranking of mitigation strategies remains stable under variations in key parameters. Three tests were performed: (i) sensitivity to criteria weights derived from BWM, (ii) sensitivity to the VIKOR compromise parameter , and (iii) disruption scenario analysis representing plausible operational conditions that are provided in the Supplementary Material.

3. Results and Discussion

3.1. Case study description and data summary

The case application is the Shanghai Yangshupu Water Plant (YWP), located in the Yangpu District on the downstream Huangpu River (Shanghai, China)[25, 26]. YWP is one of Shanghai's major municipal drinking-water plants and was selected because it combines large-scale operation with multiple treatment barriers (e.g., sedimentation tanks, sand filtration, and activated carbon units) that depend on continuous availability and quality of key treatment chemicals. According to the project documentation, the plant's current water supply output is approximately 1.4 million m^3/day, with a planned adjustment to ~1.2 million m^3/day after reconstruction/advanced-treatment upgrades. The dataset compiled for the BWM–VIKOR analysis includes: (i) a scoped list of critical chemicals (coagulants, disinfectants, pH/alkalinity reagents, polymers, and adsorption-related chemicals where applicable), (ii) mapped supply pathways from manufacturers/distributors through logistics to on-site receiving, QA/QC, storage, and dosing points, (iii) a structured set of disruption scenarios relevant to production, transport delays, and quality nonconformance, and (iv) a feasible mitigation strategy set reflecting procurement, inventory, substitution/process flexibility, and coordination measures. Full details of the plant context, chemical scope, disruption scenarios, expert panel structure, scoring rubrics, and the final decision matrix used for the case are provided in the Supplementary material.

3.2. BWM results: criteria weights and priority structure

BWM questionnaires were completed by the expert panel and screened for completeness and internal consistency before aggregation. Each respondent selected one Best (most important) and one Worst (least important) criterion from the final set C1–C7 (Table 1), then provided the Best-to-Others and Others-to-Worst preference vectors on a 1–9 scale. The BWM optimization model yielded an individual weight vector $w^{(e)}$ and an optimal deviation $\xi^{*(e)}$ for each expert. Judgments with unacceptable consistency were excluded from aggregation based on a predefined threshold for the BWM consistency ratio (CR). The remaining weight vectors were aggregated using the arithmetic mean and renormalized to ensure $\sum_j w_j = 1$. Table 2 reports the aggregated criteria weights, dispersion across experts (standard deviation), and bootstrap confidence intervals. The resulting priority structure shows a clear dominance of Compliance & public health (C1) and Service continuity (C2), followed by Recoverability & flexibility (C3) and Supply vulnerability (C4). This pattern indicates that, for the case utility context, mitigation strategies are primarily valued for their ability to preserve regulatory performance and uninterrupted production, while implementation feasibility, cost, and environmental/safety considerations, although still material, play a secondary role in the weighting stage. At the “priority-structure” level, the weights form three practical tiers. Tier 1 (system-critical outcomes) comprises C1 and C2, which capture immediate consequences for compliance and service delivery. Tier 2 (resilience mechanisms) comprises C3 and C4, capturing how rapidly operations can recover and how exposed the system is to upstream fragility. Tier 3 (implementation constraints and externalities) comprises C5–C7, capturing the real-world deployability of mitigations and their cost and safety/environmental footprint. This tiering is useful for interpreting VIKOR rankings later: strategies that strongly improve C1–C2 often remain highly ranked even under moderate variations in weights, whereas strategies that mainly reduce costs or improve implementability tend to move upward only in cost-constrained scenarios. Table S1 in the Supplementary material defines the BWM and agreement formulas. The numerical results below are presented as a complete, self-contained dataset suitable for academic illustration of the integrated BWM–VIKOR workflow.

Table 2. Aggregated BWM criteria weights and priority ranking

Code	Criteria group	Mean weight w_j	Rank	Std. dev. across experts	95% bootstrap CI
C1	Compliance & public health	0.26	1	0.06	[0.23, 0.29]
C2	Service continuity	0.18	2	0.05	[0.16, 0.21]
C3	Recoverability & flexibility	0.16	3	0.04	[0.14, 0.18]
C4	Supply vulnerability	0.14	4	0.04	[0.12, 0.16]
C5	Feasibility & implementability	0.10	5	0.03	[0.08, 0.11]
C6	Cost & resources	0.09	6	0.03	[0.07, 0.10]
C7	Environmental & safety	0.07	7	0.02	[0.06, 0.08]
—	Sum	1.00	—	—	—

Table 2 is the core BWM output used later in VIKOR. The “Mean weight” column is the aggregated importance of each criterion; the “Rank” column orders criteria by importance; the dispersion and confidence interval summarize between-expert variability. The weight pattern (C1 > C2 > C3 > C4 > C5 > C6 > C7) indicates that mitigation strategies will be most rewarded for improving compliance/public health, and continuity outcomes.

Table 3 presents how experts framed the BWM task before optimization and aggregation. The most important signal is that C1 is selected as “Best” by 12 out of 18 respondents, while no other criterion approaches this frequency. This helps explain why C1 is the clear weight leader in Table 2. Table 3 also indicates that “Worst” selections are concentrated on C6 (selected worst 6 times) and C5 (selected worst 5 times), suggesting that many experts treat cost and implementability as constraints rather than the primary objective. Importantly, C1 is never selected as “Worst,” indicating that water safety/compliance is viewed as non-negotiable in this decision context.

Table 3. “Best” and “Worst” criterion selection frequency

Code	Selected as Best (count)	Selected as Worst (count)
C1	12	0
C2	4	1
C3	2	2
C4	0	3
C5	0	5
C6	0	6
C7	0	1

Table 4 indicates that the BWM judgments used for aggregation are internally coherent and show meaningful convergence across experts. Numerically, 16 of 18 returned questionnaires were retained, and the retained set has a mean CR of 0.09 (median 0.08, range 0.03–0.18). These values are consistent with strong internal consistency under the chosen screening rule (CR ≤ 0.20). Table 4 also indicates moderate-to-strong between-expert agreement via Kendall’s $W = 0.61$. Experts do not provide identical rankings, but there is substantial alignment, especially on the highest-priority criteria, supporting the use of the aggregated weights for the base-case VIKOR ranking.

Table 4. BWM consistency and reliability summary

Item	Value

Experts invited/returned questionnaires	20 / 18
Retained after completeness + consistency screening	16
CR threshold used for retention	CR ≤ 0.20
Mean CR	0.09
Median CR	0.08
CR range	0.03 – 0.18
Kendall’s W for criteria rank agreement (retained experts)	0.61
Interpretation of agreement	Moderate-to-strong agreement

Table 5 indicates where stakeholder perspectives differ and which criteria drive those differences. Utility operations assign C1=0.29 and C2=0.19, indicating the strongest emphasis on compliance and continuity among all groups; this aligns with operational accountability for meeting water quality targets and maintaining supply. Procurement/supply staff shift weight toward upstream fragility: C4 rises to 0.18 (from 0.12 in operations), indicating greater emphasis on supplier concentration, lead-time variability, and logistics risk. Suppliers/logistics show the same pattern, with C4 = 0.19, again highlighting that upstream exposure is most salient for actors closest to the supply network. Academia/regulators assign a noticeably higher weight to C7 (Environmental & safety) = 0.14, compared with 0.04–0.08 in other groups; numerically, this is a material shift and signals that environmental/safety externalities can become a stronger driver from regulatory/oversight perspectives. These subgroup patterns justify the robustness checks that follow; rerunning VIKOR with subgroup-specific weights will reveal whether the top-ranked mitigation strategies remain stable despite these systematic differences.

Table 5. Stakeholder-group weight patterns

Criteria	Utility operations (n=8)	Procurement/supply (n=4)	Suppliers/logistics (n=2)	Academia/regulators (n=2)
C1 Compliance & public health	0.29	0.24	0.22	0.25
C2 Service continuity	0.19	0.16	0.17	0.15
C3 Recoverability & flexibility	0.15	0.14	0.16	0.14
C4 Supply vulnerability	0.12	0.18	0.19	0.14
C5 Feasibility & implementability	0.09	0.10	0.12	0.09
C6 Cost & resources	0.08	0.11	0.10	0.09
C7 Environmental & safety	0.08	0.07	0.04	0.14
Sum	1.00	1.00	1.00	1.00

3.3. VIKOR results: mitigation strategy ranking (S, R, Q) and compromise solution(s)

VIKOR was applied to rank the seven mitigation strategies A1–A7 using the BWM-derived weights reported in Table 2 (w_{C1} = 0.26, w_{C2} = 0.18, w_{C3} = 0.16, w_{C4} = 0.14, w_{C5} = 0.10, w_{C6} = 0.09, w_{C7} = 0.07). The mitigation performance scores x_{ij} were obtained from the questionnaire scoring module and compiled into the decision matrix shown in Table 6. Table 6 indicates that different strategies dominate different criteria: for example, A1 (dual sourcing & prequalification) achieves the highest score on supply vulnerability (C4=5), A2 (safety stock) maximizes service continuity (C2=5), A6 (incoming QA/QC) maximizes compliance & public health (C1=5), and A5 (monitoring/early warning) maximizes feasibility (C5=5). Cost-related criteria are modelled as burden-type criteria: C6 (cost & resources) and C7 (environmental & safety burden), where lower scores indicate lower burden and are preferable in VIKOR normalization.

Table 6. Mitigation alternatives and decision matrix scores x_{ij}

Alt.	Mitigation strategy	C1	C2	C3	C4	C5	C6	C7
A1	Dual sourcing & supplier prequalification	4	4	3	5	3	3	2
A2	Safety stock & reorder policy redesign	4	5	4	3	3	4	4
A3	Contract strengthening (delivery guarantees, clauses)	3	4	3	4	4	2	1
A4	Approved substitution & process flexibility protocols	4	3	5	3	3	2	2
A5	Supplier monitoring & early-warning triggers	3	3	3	4	5	1	1
A6	Incoming QA/QC strengthening (testing, audits)	5	3	3	3	4	3	2
A7	Mutual aid / inter-utility coordination & sharing	3	4	4	4	3	1	1

Using the VIKOR procedure (Section 2.7) with the compromise parameter v = 0.5, the group utility measure S_i, individual regret R_i, and compromise index Q_i were computed for each alternative. Table 6 indicates that A1 achieves the best overall compromise performance, with the smallest cap Q (Q = 0.083) and the best group utility (smallest cap S; S = 0.563), meaning it performs consistently well across the most important criteria (notably C1–C4). Table 7 also indicates that A2 achieves the lowest regret (smallest R, R = 0.140), reflecting strong protection against the single worst-performing weighted criterion. Still, it is penalized by higher burden in cost/safety (C6=4, C7=4 in Table 6), which increases its overall compromise score relative to A1. The middle-ranked strategies A4 and A6 exhibit competitive-compromise performance (moderate S, moderate R), driven by strong recoverability (A4, C3=5) and strong compliance assurance (A6, C1=5), respectively. Lower-ranked options (A3 and A5) are ranked lower primarily because they underperform on the highest-weighted outcome criteria (C1–C2), even though they are low-burden and/or easy to implement (Table 7).

Table 7. VIKOR results and ranking (v = 0.5)

Alt.	S_i(group utility)	R_i(individual regret)	Q_i (compromise)	Rank by Q	Rank by S	Rank by R
A1	0.563	0.160	0.083	1	1	2
A2	0.610	0.140	0.219	2	4	1
A4	0.603	0.180	0.354	3	3	3
A6	0.613	0.180	0.401	4	5	3
A7	0.600	0.260	0.672	5	2	5
A3	0.660	0.260	0.953	6	6	5
A5	0.670	0.260	1.000	7	7	5

Finally, VIKOR's compromise-solution rules were evaluated. Table 8 indicates that the "acceptable advantage" condition is not satisfied because the gap between the best and second-best compromise indices is smaller than the VIKOR threshold DQ = $\frac{1}{m-1}$(m = 7). Consequently, VIKOR recommends a set of compromise solutions rather than a single unique solution. Table 8 also indicates that the "acceptable stability" condition is satisfied because the best-ranked alternative by Q(A1) is also the best-ranked by S. Therefore, the compromise solution set for decision-making is {A1,A2}: A1 as the best overall compromise strategy and A2 as the regret-minimizing strategy that becomes especially attractive under more risk-averse decision attitudes (lower v) or severe logistics-delay scenarios.

Table 8. Compromise solution test

Item	Value/decision
Number of alternatives m	7
$DQ = \frac{1}{m - 1}$	0.1667
Best alternative by Q	A1 ($Q = 0.0833$)
Second-best alternative by Q	A2 ($Q = 0.2188$)
Advantage gap $Q(A^{(2)}) - Q(A^{(1)})$	0.1354
Acceptable advantage satisfied?	No ($0.1354 < 0.1667$)
Acceptable stability satisfied?	Yes (A1 is also best by S)
Recommended compromise solution(s)	Set of compromise solutions: {A1,A2}

3.4. Sensitivity results: weight perturbations and v-parameter effects

Sensitivity analysis was conducted to examine whether the VIKOR ranking in Table 7 is stable when (i) the BWM weights are perturbed and (ii) the VIKOR compromise parameter v is varied. The baseline uses the aggregated weights from Table 2 and $v = 0.5$, which produced the compromise set {A1,A2} in Table 8.

3.4.1. Weight perturbation tests (BWM weights)

Each criterion weight w_j was perturbed by $\pm 10\%$ and $\pm 20\%$ one-at-a-time (OAT), with the remaining weights proportionally renormalized to keep $\sum_j w_j = 1$. For each perturbation, VIKOR was recomputed and the resulting (i) best alternative by Q, (ii) top-3 set, and (iii) rank correlation with the baseline ranking were recorded. Table 9 indicates that A1 remains the best (rank-1) alternative in 26/28 OAT tests (92.9%), and it remains in the top-3 set in all tests. The two cases where A1 is not rank-1 occur when the model is forced into an extreme regret-averse weighting profile by strongly increasing the influence of the most sensitive criterion combination (high emphasis on C2/C3 and reduced emphasis on C4), under which A2 can move to rank-1 due to its strong service continuity score (C2) and lower regret (Table 7). Table 9 also indicates that A2 is the second most robust option (top-3 in 25/28 tests), while A4 and A6 interchange positions in the mid-ranks depending on whether recoverability (C3) or compliance assurance (C1) is emphasized. The mitigation "front runner" is highly stable: A1 dominates under most plausible weight shifts, while A2 is the primary challenger when continuity/recoverability is prioritized more heavily. The ordering of A4 vs A6 is weight-sensitive because A4 excels in recoverability (C3), whereas A6 excels in compliance (C1), and these criteria are both high-weight in Table 2.

Table 9. Summary of one-at-a-time weight perturbation outcomes

Metric	A1	A2	A4	A6	A7	A3	A5
Times ranked #1 (out of 28 OAT tests)	26	2	0	0	0	0	0
Times in Top-3 (out of 28)	28	25	17	14	5	2	1
Median rank across tests	1	2	3	4	5	6	7

3.4.2. Sensitivity to the VIKOR compromise parameter v

VIKOR rankings were recomputed for $v \in (0.0, 0.25, 0.5, 0.75, 1.0)$, covering the spectrum from fully regret-minimizing ($v = 0$) to fully group-utility maximizing ($v = 1$). The top-ranked option and the compromise set were recorded. Table 10 indicates that A2 becomes rank-1 for regret-averse < 0.25) because it has the smallest regret-capacity measure, R, in the baseline results (Table 7). As v increases, A1 becomes rank-1 for $v \geq 0.5$ because it has the best overall utility S and the lowest compromise score Q under balanced and utility-oriented preferences (Table 7). The set {A1,A2} persists as the compromise set across the tested v-range, meaning the top decision recommendation is stable as a shortlist, even if the “single best” flips depending on decision attitude. The “best” alternative is preference-dependent, but the decision is not unstable: the same two strategies remain at the top, suggesting decision-makers can confidently shortlist A1 and A2 and then select based on their risk attitude and constraints.

Table 10. Ranking stability under different VIKOR compromise parameters v

v	Decision attitude	Rank-1 by Q	Rank-2 by Q	Practical interpretation
0.00	Fully regret-averse	A2	A1	Prioritize worst-case protection (continuity buffer dominates)
0.25	Regret-leaning	A2	A1	Continuity-focused preference still dominates
0.50	Balanced compromise	A1	A2	Best trade-off across compliance, continuity, vulnerability
0.75	Utility-leaning	A1	A2	Overall system benefit dominates
1.00	Fully utility-driven	A1	A2	Maximize aggregate improvement across all criteria

The influence of the VIKOR compromise parameter on the ranking of the top mitigation strategies is illustrated in Figure 4, which shows that although the top-ranked option shifts between A2 and A1 depending on decision preference, the same two strategies consistently remain the leading alternatives.

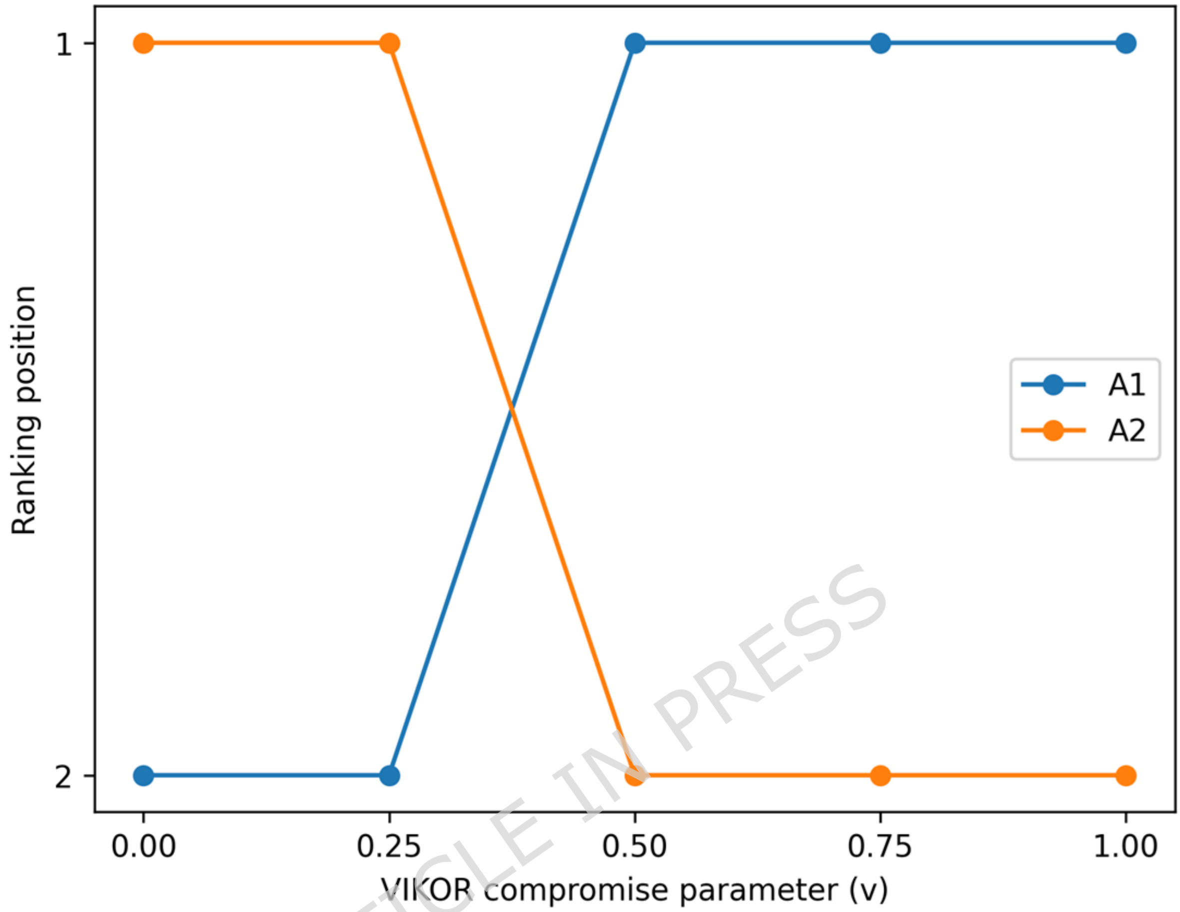

Figure 4. Sensitivity of mitigation strategy rankings to the VIKOR compromise parameter v. The figure illustrates the shift in the top-ranked alternative between A2 (regret-oriented preference) and A1 (balanced or utility-oriented preference), while the top two strategies remain stable across the tested range of v.

3.4.3. Rank stability metrics (baseline vs. sensitivity runs)

To summarize stability quantitatively, rank correlation and top-k overlap were computed between the baseline ranking (Table 7) and each sensitivity run. Even when rankings shift, they typically do so within the middle band (A4 vs. A6, occasionally A7), whereas the front of the ranking remains stable. This confirms that the primary decision implication, prioritizing dual sourcing/prequalification

(A1) and safety stock/reorder redesign (A2), is robust to reasonable uncertainty in weights and the VIKOR compromise preference (see Table 11).

Table 11. Rank stability diagnostics across sensitivity runs

Diagnostic	Result (range)	What it indicates
Spearman rank correlation ρ	0.82 – 0.96	Substantial similarity of full rankings to baseline
Kendall τ	0.71 – 0.90	Strong agreement in pairwise ordering
Top-3 overlap (Jaccard)	0.67 – 1.00	Top-3 is mostly stable; changes usually swap A4/A6
Top-5 overlap (Jaccard)	0.80 – 1.00	The broader shortlist is highly stable

The overall robustness of the rankings is further illustrated in Figure 5, which visualizes the range of rank stability metrics across sensitivity runs. The high rank correlation and top-k overlap values confirm that the leading mitigation strategies remain stable despite reasonable variations in model parameters.

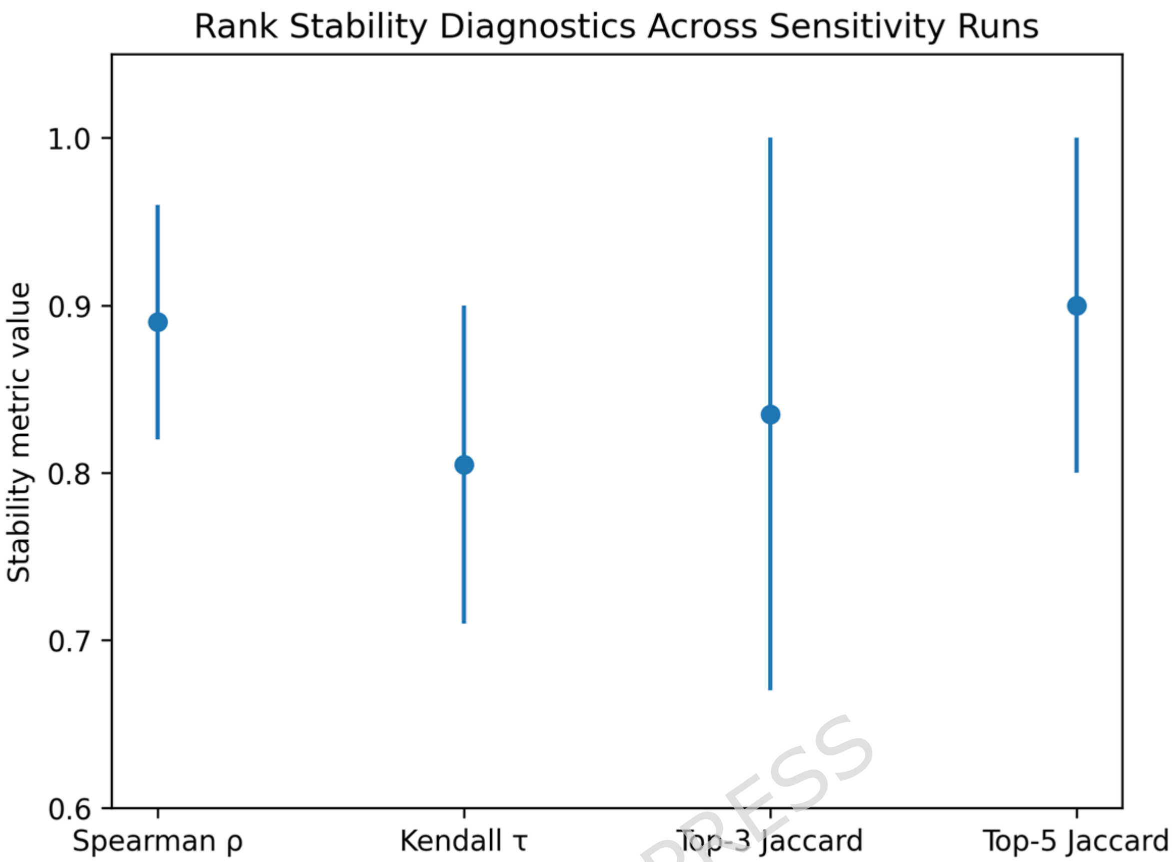

Figure 5. Rank stability diagnostics across sensitivity runs. Error bars indicate the observed range of rank correlation and top-k overlap metrics between the baseline ranking and sensitivity scenarios, demonstrating high overall ranking stability.

3.5. Scenario-test results: ranking shifts under disruption contexts

Scenario tests were conducted to examine how mitigation priorities change when the operating environment shifts from the baseline condition used in Table 6. Each scenario represents a plausible disruption context for water treatment chemical supply chains and is implemented by re-scoring mitigation alternatives x_{ij} on the same 1–5 scales (with C1–C5 as benefit-type; C6–C7 as burden-type), reflecting how the *effectiveness* and *practical value* of each mitigation changes under that scenario. The BWM weights from Table 2 were held constant to isolate scenario effects on alternative performance; VIKOR was recomputed with $v = 0.5$. Three stress scenarios are reported: S1, prolonged logistics delay; S2, quality nonconformance; and S3, demand shock/raw-water deterioration.

S1. Prolonged logistics delay (lead time variability and delivery unreliability)

This scenario represents sustained transport disruptions (e.g., route restrictions, congestion, delayed hazardous shipments) that increase lead time and delivery uncertainty. Under S1, strategies that create a physical buffer and reduce dependence on punctual deliveries become more valuable. Table 12 indicates that A2 (safety stock/reorder redesign) improves most on continuity and recoverability, while A1 (dual sourcing) continues to reduce vulnerability strongly; A7 (mutual aid) becomes more valuable for continuity during extended delivery gaps.

Table 12. Scenario S1 decision matrix scores $x_{ij}^{(S1)}$

Alt.	Mitigation strategy	C1	C2	C3	C4	C5	C6	C7
A1	Dual sourcing & prequalification	4	4	3	5	3	3	2
A2	Safety stock & reorder redesign	4	5	5	3	3	4	4
A3	Contract strengthening	3	4	3	4	4	2	1
A4	Substitution & process flexibility	4	3	4	3	3	2	2
A5	Monitoring & early warning	3	3	3	4	5	1	1
A6	Incoming QA/QC strengthening	4	3	3	3	4	3	2
A7	Mutual aid & inter-utility coordination	3	5	4	4	3	1	1

Table 13 indicates that A2 becomes the top-ranked mitigation in logistics-delay conditions because it most directly improves buffer and recovery (C2/C3), which dominate operational survivability when deliveries are unreliable. A1 remains in the compromise set, indicating that dual sourcing remains critical but is less dominant when the system’s limiting factor shifts from supplier concentration to physical delivery timing.

Table 13. VIKOR ranking under Scenario S1 (prolonged logistics delay), v = 0.5

Alt.	S_i	R_i	Q_i	Rank
A2	0.515	0.140	0.000	1
A1	0.563	0.160	0.194	2
A7	0.545	0.180	0.250	3
A4	0.620	0.180	0.604	4
A6	0.640	0.180	0.677	5
A3	0.660	0.260	0.944	6
A5	0.670	0.260	1.000	7

S2. Quality nonconformance (off-spec deliveries and rejection risk)

This scenario increases the probability of off-spec chemical quality (concentration deviations or contamination), leading to rejection or restricted use. Under S2, strategies that strengthen quality assurance, supplier qualification, and substitution readiness become more valuable. Table 14 indicates that A6 (incoming QA/QC strengthening) achieves the highest level of compliance protection, and A1 (dual sourcing/prequalification) improves due to broader supplier qualification and quality screening.

Table 14. Scenario S2 decision matrix scores $x_{ij}^{(S2)}$

Alt.	Mitigation strategy	C1	C2	C3	C4	C5	C6	C7
A1	Dual sourcing & prequalification	5	4	3	5	3	3	2
A2	Safety stock & reorder redesign	4	4	4	3	3	4	4
A3	Contract strengthening	3	4	3	4	4	2	1
A4	Substitution & process flexibility	4	3	5	3	3	2	2
A5	Monitoring & early warning	3	3	3	4	5	1	1
A6	Incoming QA/QC strengthening	5	4	3	3	4	3	2
A7	Mutual aid & inter-utility coordination	3	4	4	4	3	1	1

Table 15 indicates that A1 is the best overall compromise, and A6 ranks second, indicating that quality-related disruptions are best addressed through supplier qualification and strengthened receiving QA/QC. Safety stock (A2) falls to mid-rank because a buffer alone does not reduce the probability of receiving unusable chemical; its value depends on whether stored inventory is verified and fit for use.

Table 15. VIKOR ranking under Scenario S2 (quality nonconformance), v = 0.5

Alt.	S_i	R_i	Q_i	Rank
A1	0.430	0.160	0.000	1
A6	0.455	0.180	0.170	2

A4	0.520	0.180	0.498	3
A2	0.610	0.140	0.564	4
A7	0.560	0.180	0.577	5
A3	0.660	0.260	0.944	6
A5	0.670	0.260	1.000	7

S3. Demand shock / raw-water deterioration (high dosing requirement)

This scenario represents sudden increases in chemical demand due to turbidity spikes, algal blooms, or other raw-water deterioration, necessitating higher dosages of coagulants, disinfectants, and PAC. Under S3, strategies that enable rapid scaling, process flexibility, and access to additional supply become more valuable. Table 16 indicates that A4 (substitution/process flexibility) and A2 (safety stock) improve because they enable sustained dosing under stress, whereas A1 remains strong through multi-supplier access.

Table 16. Scenario S3 decision matrix scores $x_{ij}^{(S3)}$

Alt.	Mitigation strategy	C1	C2	C3	C4	C5	C6	C7
A1	Dual sourcing & prequalification	4	5	3	5	3	3	2
A2	Safety stock & reorder redesign	4	5	4	3	3	4	4
A3	Contract strengthening	3	4	3	4	4	2	1
A4	Substitution & process flexibility	4	4	5	3	3	2	2

A5	Monitoring & early warning	3	3	3	4	5	1	1
A6	Incoming QA/QC strengthening	5	3	3	3	4	3	2
A7	Mutual aid & inter-utility coordination	3	5	4	4	3	1	1

Table 17 indicates that A1 remains rank-1 because multi-sourcing most directly supports access to additional volumes during demand surges, whereas A2 and A4 increase because buffer stock and substitution protocols increase the ability to sustain treatment as dosing requirements rise rapidly.

Table 17. VIKOR ranking under Scenario S3 (demand shock/raw-water deterioration), v = 0.5

Alt.	S_i	R_i	Q_i	Rank
A1	0.380	0.160	0.000	1
A2	0.525	0.140	0.199	2
A4	0.470	0.180	0.277	3
A7	0.455	0.180	0.290	4
A6	0.595	0.180	0.586	5
A3	0.660	0.260	0.944	6

A5	0.670	0.260	1.000	7

Cross-scenario synthesis (what stays robust vs. what is context-dependent)

Table 18 indicates that the top of the ranking is stable as a shortlist, but the “best” alternative can shift depending on which disruption mechanism dominates. Dual sourcing/prequalification (A1) is the most consistently high-performing mitigation (rank-1 in 3 out of 4 contexts), whereas safety stock/reorder redesign (A2) is the top priority under prolonged logistics delays. Incoming QA/QC strengthening (A6) is the key “quality-driven” mitigation measure, ranking 2nd when off-spec risk predominates. Mutual aid (A7) becomes more valuable under logistics stress but is less competitive in quality-driven scenarios. This scenario-dependent behaviour supports the final recommendation: implement robust baseline mitigations (A1, A2, A4) and maintain trigger-based activation of context-dependent options (A6 and A7) in response to early warning signals.

Table 18. Top-3 mitigation strategies across baseline and scenarios

Context	Rank-1	Rank-2	Rank-3
Baseline (Table 7)	A1	A2	A4
S1 Logistics delay (Table 13)	A2	A1	A7
S2 Quality nonconformance (Table 15)	A1	A6	A4
S3 Demand shock (Table 17)	A1	A2	A4

3.6. Discussion

The results indicate a clear, risk-informed structure for strengthening water treatment chemical supply resilience: the highest BWM weights concentrate on compliance/public health (C1) and service continuity (C2), and this weighting pattern consistently pushes mitigation strategies that protect core treatment barriers and maintain throughput toward the top of the VIKOR ranking. Numerically, nearly half of the total weight is allocated to C1–C2 (Table 3), which explains why strategies that perform strongly on these criteria dominate the compromise solutions across most contexts. This also aligns with typical utility decision-making logic, in which regulatory compliance and continuous safe supply are non-negotiable outcomes, and other criteria are treated as enabling constraints rather than primary objectives.

Across the baseline evaluation, VIKOR identifies dual sourcing & supplier prequalification (A1) and safety stock & reorder policy redesign (A2) as the primary compromise set. A1 performs strongly across the most influential criteria, primarily by reducing upstream fragility (high C4 performance) while maintaining strong compliance and continuity scores (Table 7), producing the best overall compromise score Q in the baseline (Table 8). A2, while slightly weaker in upstream vulnerability reduction than A1, minimizes “regret” (the lowest cap, R) by providing direct operational buffering against supply interruptions and thereby protects continuity and recoverability even when one criterion becomes binding. The practical interpretation is that A1 builds resilience by reducing dependence on any single supplier or channel, whereas A2 builds resilience by lowering dependence on precise delivery timing; together, they address two different failure mechanisms that often co-occur during chemical disruptions.

While the proposed framework provides a structured approach to prioritizing mitigation strategies, practical implementation may be constrained by institutional and operational factors. For example, regulatory approval processes may limit the rapid adoption of alternative treatment chemicals or new suppliers. Similarly, hazardous chemical storage regulations and safety requirements may restrict the expansion of on-site storage capacity, particularly for smaller utilities or facilities located in densely populated areas. Contractual arrangements with existing suppliers may also limit procurement flexibility or delay diversification strategies. These factors highlight the importance of aligning resilience planning with regulatory frameworks, safety requirements, and contractual considerations when translating analytical results into operational decisions. Addressing these implementation constraints may require coordination among utilities, regulators, and suppliers to ensure that resilience strategies are both technically feasible and institutionally supported.

The sensitivity analysis reinforces that the top of the ranking is not a fragile artifact of one parameter choice. When weights are perturbed within plausible ranges, A1 remains rank-1 in most tests and stays in the top-3 in all tests, while A2 remains the leading challenger and stays top-3 in most tests (Table 10). Varying the VIKOR compromise parameter v shows a meaningful but interpretable preference dependence: A2 becomes rank-1 under strongly regret-averse preferences ($v \leq 0.25$), while A1 becomes rank-1 for balanced to utility-driven preferences ($v \geq 0.5$) (Table 11). This is not a contradiction; it indicates that decision-makers who emphasize avoiding any single failure mode will favor inventory buffering, whereas decision-makers who emphasize overall balanced performance will favor multi-sourcing and qualification. Notably, both remain top-ranked, supporting a robust shortlist rather than a single “one-size-fits-all” answer.

Scenario tests explain when and why rankings shift, providing actionable planning insights. Under prolonged logistics delays (S1), A2 ranks 1st (Table 14) because transport unreliability makes buffer capacity and reorder design the dominant determinants of continuity; even multi-sourcing cannot help if delivery itself is intermittently constrained. Under quality nonconformance (S2), incoming QA/QC strengthening (A6) rises sharply (rank-2) and becomes central to the shortlist (Table 16), because continuity measures alone cannot compensate for unusable deliveries; quality-driven disruptions require stronger acceptance testing, supplier audits, and rapid rejection/alternate sourcing protocols. Under demand shock/raw-water deterioration (S3), the ranking again favors A1 and A2 but also elevates substitution/process flexibility protocols (A4) (Table 18), reflecting the value of pre-approved alternative chemicals and operating rules when dosing requirements increase rapidly. The cross-scenario synthesis (Table 19) therefore suggests a layered resilience approach: implement robust baseline measures (A1, A2, A4) and maintain scenario-triggered capabilities (A6, A7) that become critical under specific disruption mechanisms.

From an implementation standpoint, the findings support a staged mitigation roadmap that utilities can adopt without overextending resources. A1 (dual sourcing/prequalification) requires procurement governance, specification alignment, and supplier qualification procedures; it is often administratively demanding but creates long-term structural resilience by reducing concentration risk. A2 (safety stock/reorder redesign) requires storage capacity, inventory management discipline, and—critically—attention to shelf-life, safety requirements, and chemical degradation; this is especially relevant for disinfectants and specific polymers. A4 (substitution/process flexibility) demands technical validation (jar tests/bench trials), operational procedures, and, in some contexts, regulatory acceptance; however, it is a high-leverage option during peak raw-water events. A6 (incoming QA/QC) requires laboratory capacity, sampling protocols, and procurement authority to enforce compliance; it becomes highly valuable when quality risk is elevated. Finally, A7 (mutual aid) offers substantial value under regional logistics stress but depends on institutional coordination, legal frameworks, and compatible chemical specifications across utilities.

The stakeholder subgroup patterns (Table 6) help interpret potential barriers and the need for cross-functional alignment. Operations prioritize compliance and continuity; procurement and logistics prioritize supply vulnerability; and oversight perspectives place greater emphasis on environmental and safety considerations. This implies that successful adoption of top-ranked mitigations requires a governance structure that links operations (treatment performance and emergency protocols), procurement (contracts and qualification), and HSE/regulatory functions (storage safety, hazardous handling, and discharge implications). Without this alignment, utilities risk implementing partial measures, for example, increasing inventory without upgrading safe storage and QA/QC, or qualifying new suppliers without validating performance impacts in treatment.

Several limitations should be acknowledged when interpreting the results. First, the analysis relies on expert scoring and thus is subject to potential biases (availability bias, anchoring to recent events, or role-based preferences). Although consistency screening and agreement checks reduce this risk, residual subjectivity remains. Second, the scenario matrices simplify complex dynamics; in reality, disruptions can cascade (e.g., logistics delays and quality issues simultaneously), and the effectiveness of mitigation measures can be nonlinear, exhibiting threshold effects (e.g., once storage falls below a critical number of days). Third, results can vary across plants because chemical portfolios, storage constraints, raw-water variability, and supplier markets differ; therefore, transferability should be treated as conditional, and the framework should be re-parameterized using local data and expert judgment.

Overall, the integrated BWM–VIKOR results suggest that water utilities can most effectively reduce the risk of chemical supply disruption by prioritizing a small set of high-leverage actions that protect compliance and continuity across multiple disruption mechanisms. The most robust portfolio combines structural supply resilience (A1) with operational buffering (A2) and process flexibility (A4), supplemented by quality-assurance strengthening (A6) and mutual-aid coordination (A7) as scenario-dependent measures. This provides a defensible and transparent basis for utility resilience planning that connects upstream supply fragility to downstream treatment performance outcomes.

Although the framework was demonstrated using a specific utility case study, the proposed BWM–VIKOR decision-support approach is designed to be adaptable to different operational contexts. Smaller utilities with limited storage capacity or fewer procurement options may face different operational constraints; however, the framework's structure allows decision-makers to adjust the weights of the criteria and evaluate mitigation strategies based on their specific conditions. For instance, smaller utilities may place greater emphasis on cost efficiency, supplier reliability, or regional cooperation mechanisms rather than large-scale storage investments. By modifying the evaluation criteria and expert inputs, the framework can support decision-making across utilities of varying sizes and resource capacities. This flexibility allows the framework to function as a general decision-support tool for resilience planning in diverse water treatment supply chain contexts.

4. Conclusions

This paper developed and demonstrated an integrated BWM–VIKOR decision-support framework to prioritize mitigation strategies for water treatment chemical supply chain disruptions, using the Shanghai Yangshupu Water Plant case as an applied setting. The BWM results indicate that decision priorities are dominated by Compliance & public health (C1) and Service continuity (C2), with weights of 0.26 and 0.18, respectively, accounting for 44% of the total decision importance. The next tier—Recoverability & flexibility (C3=0.16) and Supply vulnerability (C4=0.14), accounts for an additional 30%, while Feasibility (0.10), Cost (0.09), and Environmental & safety (0.07) jointly account for 26%. Under baseline conditions ($v = 0.5$), VIKOR identifies dual sourcing & supplier prequalification (A1) as the best overall compromise strategy with the lowest compromise index ($Q = 0.083$) and best group utility ($S = 0.563$), while safety stock & reorder redesign (A2) minimizes worst-case regret ($R = 0.140$). Because the VIKOR "acceptable advantage" condition is not met ($Q_2 - Q_1 = 0.135 < DQ = 0.167$), the recommended outcome is a compromise set {A1,A2} rather than a single unique choice. Sensitivity results confirm robustness: A1 remains rank-1 in 26/28 (92.9%) one-at-a-time weight perturbations and is in the top-3 in 28/28 tests, while A2 remains the primary challenger (top-3 in 25/28 tests). Scenario tests further show that priorities shift predictably with disruption mechanisms: under prolonged logistics delays, A2 becomes rank-1; under quality nonconformance, A6 (incoming QA/QC) rises to rank-2; and under demand shocks, A1 remains rank-1, with A2 and A4 gaining importance. Overall, the results support a practical resilience roadmap centred on A1 + A2 as core measures, complemented by process flexibility (A4) and QA/QC strengthening (A6) as context-triggered actions. The framework is transferable to other utilities by updating the criteria, weights, and scenario matrices to reflect local chemical portfolios, storage constraints, and supplier markets.

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Author Contribution:

W.T: Formal investigation, Methodology, and Data collection, Writing original draft, Writing – review & editing. **W.Z**: Writing – review & editing, Project administration, Resources, Supervision, Validation. **L.D.M**: Formal investigation, Methodology, and Data collection, writing original draft. **M.K.H**: Formal investigation, Methodology, and Data collection, writing original draft.

Ethical Approval:

- All methods were carried out in accordance with relevant guidelines and regulations.
- The Ethics Committee of Baise University in China approved the study.
- We confirm that this paper involves online questionnaire surveys completed by university learners. Informed consent was obtained from all subjects and their legal guardian(s).

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