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Research paper

Prospective strategic appraisal of water supply resources for the oil refinery based on a quantitative decision matrix

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ABSTRACT

This study proposes an integrated, multi-criteria framework for the strategic assessment of water supply resources in water-intensive industrial systems. The approach's novelty lies in the structured integration of SWOT, AHP, ELECTRE TRI, and QSPM to reduce subjective bias and enable reproducible strategy prioritization, while incorporating scenario based quantitative indicators to evaluate resilience. The framework was applied to a refinery water supply system under hydrological and operational constraints. The internal and external evaluation matrices yielded weighted scores of 2.641 and 3.322, respectively, indicating a dominant external influence. The QSPM results identified strategy WO2 as the preferred option (TAS = 13.174), outperforming ST1 (TAS = 12.290). To assess robustness under future conditions, three scenario-based indicators were introduced: Environmental Stress Coefficient (ESC), Opportunity Leverage Index (OLI), and System Performance Gap (SPG). These indicators were conceptually derived and adapted to provide a simplified quantitative representation of system behavior. The results show increasing environmental stress (ESC: 0.20–0.43), declining opportunity utilization (OLI: 0.43–0.94), and a widening performance gap (SPG: 0.26–0.57), indicating growing system vulnerability. The proposed framework offers a practical decision-support tool to enhance water resource resilience and support long-term planning in industrial systems under uncertainty.

1. Introduction

Increasing water scarcity, driven by climate variability and growing industrial demand, has become a critical challenge for water-intensive industries such as oil refineries. In such environments, ensuring a reliable and sustainable water supply is not only an operational requirement but also a strategic necessity. Traditional decision-making approaches often fail to adequately address the combined effects of environmental uncertainty, infrastructure constraints, and regulatory pressures. This study makes several contributions to the field. First, it proposes an integrated multi-criteria framework that combines strategic analysis with quantitative prioritization. Second, it introduces a set of novel scenario-based indicators (ESC, OLI, and SPG) to assess system performance under future uncertainty. Third, it provides a case-specific application in a refinery context, demonstrating the practical applicability of the proposed approach in real-world industrial systems.

Over the past two decades, numerous assessments have shown that pressures on freshwater resources are intensifying due to declining surface-water reliability, aquifer depletion, and increased interannual hydrological variability [1,2]. In water-stressed regions of the Middle East, these pressures are even more pronounced, where rapid population growth, energy-intensive economies, and protracted drought cycles converge to undermine long-term water security [3,4].

Industrial facilities—particularly oil refineries—are among the most water-dependent infrastructures in the energy sector. They require substantial volumes of freshwater for steam generation, cooling, desalting, and various process and utility services, making their operational continuity closely tied to the stability of local water supply systems [5,6]. Consequently, environmental regulations, higher abstraction costs, and the degradation of conventional water sources have pushed the refining industry toward more integrated and forward-looking water management strategies. In recent years, multiple studies have highlighted the need for holistic frameworks that incorporate technological, environmental, economic, and regulatory dimensions rather than relying solely on process-level optimization [7,8]. Parallel to these developments, circular and resource-efficient approaches—such as industrial water reuse, advanced treatment technologies, and hybrid water

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Nomenclature

AHP	Analytic Hierarchy Process
AS	Attractiveness Score
CI	Consistency Index
CR	Consistency Ratio
EFEM	External Factor Evaluation Matrix
ESC	Environmental Stress Coefficient
IFEM	Internal Factor Evaluation Matrix
KOR	Kermanshah Oil Refinery
MCDM	Multi-Criteria Decision Making
O	Opportunity
OLI	Opportunity Leverage Index
QSPM	Quantitative Strategic Planning Matrix
RI	Random Index
S	Strength
SPG	Strategic Performance Gap
SWOT	Strength-Weakness-Opportunity-Threats
T	Threats
TAS	Total Attractiveness Score
W	Weakness
WDN	Water Distribution Network

networks—have increasingly been recognized as essential components of sustainable refinery operations [9,10].

At the strategic level, industrial water planning has gradually shifted toward decision-support frameworks that can integrate heterogeneous sources of information, account for uncertainty, and evaluate multiple conflicting criteria. MCDM methods have therefore emerged as valuable tools for guiding industrial water management, as they enable the synthesis of expert judgments, quantitative indicators, environmental constraints, and long-term strategic considerations [11,12]. The application of hybrid MCDM approaches—such as combining SWOT for situational diagnosis, AHP for criteria weighting, ELECTRE TRI for option sorting, and QSPM for selecting strategic priorities—has gained momentum in recent years because of its ability to handle complexity while preserving transparency and rationality in decision processes [13–15]. Such hybrid models also align with international trends that emphasize anticipatory planning and resilience-building in industrial water systems, especially amid climate-related risks and regulatory uncertainty [16,17].

In Iran, the combination of prolonged droughts, falling groundwater levels, and growing municipal and agricultural competition has placed additional stress on industrial water users. Western regions of the country have experienced substantial reductions in surface-water flows and aquifer reliability, elevating the vulnerability of water-intensive industries and underscoring the need for robust and adaptive water-supply strategies [18,19].

Growing pressures on global freshwater systems have reshaped industrial water management, particularly in regions where climate variability, groundwater depletion, and competing demands undermine supply reliability [1,3]. These constraints are intensified in semi-arid regions, where hydrological instability and demographic growth exacerbate long-term water stress [4]. Oil refineries are especially vulnerable because of their dependence on high-quality water for energy-intensive operations and their production of wastewater streams that require advanced treatment before reuse or discharge [5,6]. Complementary research on industrial circular-water practices emphasizes integrating internal recycling, cascading, and source diversification to strengthen resilience, particularly in water-intensive sectors [9,20].

Within this evolving context, MCDM has become central to supporting balanced decision processes. AHP continues to be widely applied for criterion-weight estimation derived from expert judgment [21,11], while outranking methods such as ELECTRE TRI provide robustness when alternatives differ in uncertainty, scale, or data completeness [22,14]. Empirical applications in water-intensive industries further demonstrate the usefulness of combining unit-level analysis with system-level integration. Studies implementing IFEM/EFEM analyses reveal that evaluating internal and external factors at the unit scale—followed by weighted aggregation—can highlight how diverse sources contribute to overall system resilience [23,8]. Parallel evaluations of treatment and supply alternatives emphasize that decision criteria must reflect not only technological performance but also life-cycle impacts, cost variability, and hydrological reliability [24,25].

The most recent literature reinforces two major trends: (i) the adoption of more sophisticated hybrid MCDM frameworks with improved sensitivity and consistency analysis [20,26], and (ii) the maturation of regulatory expectations and circular-water practices, which together increase the strategic importance of long-term planning for refinery water systems [27,28].

Recent advancements in multi-criteria decision-making (MCDM) for water and industrial systems have increasingly emphasized the integration of uncertainty modeling, scenario-based evaluation, and hybrid decision frameworks. For instance, Najafi et al. [29] proposed a Z-number-based group decision-making framework that explicitly incorporates both uncertainty and reliability of expert judgments, significantly improving decision robustness in wastewater reuse systems. Similarly, Yang et al. [30] introduced a fuzzy ensemble MCDM approach integrating multiple intuitionistic fuzzy methods, demonstrating enhanced stability and consistency in water resource decision-making under uncertainty. Yan and Wang [31] applied TOPSIS to rank water scarcity management strategies under uncertainty.

In parallel, recent studies have focused on expanding the scope of decision-support systems toward integrated and cross-sectoral applications. Davis et al. [32] developed a hybrid MCDM framework for water–energy nexus optimization, highlighting the importance of multi-dimensional criteria and validation across multiple decision logics. Likewise, Chen et al. [33] presented a decision-support framework for industrial water cycle valorization, emphasizing stakeholder interactions and system-level optimization.

From an industrial perspective, Vatikiotis et al. [34] proposed a decision-support system based on mixed-integer optimization for industrial water management, achieving significant reductions in freshwater consumption and improved reuse efficiency. In the refinery context, Mianzan et al. [35] evaluated sustainability aspects of oily sludge treatment technologies, demonstrating the importance of multi-criteria assessment in selecting environmentally and economically viable options. Additionally, recent work by Li et al. [36] on desalination systems highlights the growing role of MCDM techniques in complex water infrastructure decision-making.

Despite the extensive application of multi-criteria decision-making and strategic management tools such as SWOT, AHP, ELECTRE, and QSPM in water resource planning and industrial systems, several limitations remain evident in the existing body of research. First, these approaches are often applied either independently or through loosely coupled integrations, which may lead to inconsistencies in decision logic and an increased reliance on subjective expert judgment. Second, most studies adopt a static perspective, focusing on current system conditions without adequately accounting for future uncertainties associated with hydrological variability, regulatory constraints, and operational risks. More importantly, there is a lack of comprehensive frameworks that incorporate forward-looking scenario analysis supported by quantitative indicators capable of capturing system resilience, opportunity utilization, and performance gaps under evolving conditions.

To address these shortcomings, this study develops a structured and integrated decision-making framework that combines SWOT, AHP, ELECTRE TRI, and QSPM within a coherent workflow. The present study also develops a comprehensive hybrid strategic appraisal framework that integrates AHP, SWOT analysis, ELECTRE TRI, and the QSPM to evaluate water supply resources and identify priority strategies for future KOR water management (Fig. 1). The proposed approach reduces subjectivity through multi-stage quantitative evaluation and introduces a set of new scenario-based indicators, including the Environmental Stress Coefficient (ESC), Opportunity Leverage Index (OLI), and System Performance Gap (SPG), to enable dynamic assessment of system behavior under future scenarios. This integration provides a more robust and forward-looking basis for strategic planning compared to conventional methods, particularly in water-stressed industrial environments.

While previous studies have combined SWOT, AHP, and QSPM for strategic decision-making, these approaches often remain limited by compensatory aggregation, reliance on subjective judgments, and the absence of scenario-based evaluation. The present study addresses these limitations by introducing a structured and forward-looking decision framework. The integration of ELECTRE TRI enables non-compensatory classification under uncertainty, while the proposed new scenario-based indicators (ESC, OLI, SPG) provide a quantitative basis for evaluating system behavior under future conditions.

This combination enables the framework to move beyond static, purely judgment-based decision models toward a more robust, data-driven, and scenario-informed approach to strategic water resource management. The added value of the proposed framework lies not in merely combining established methods but in introducing a structured, scenario-based, and quantitatively robust decision-making process. By incorporating non-compensatory classification and forward-looking indicators, the framework addresses key limitations of existing hybrid approaches and provides a more reliable basis for strategic decision-making under uncertainty.

2. Methods and materials

Unlike conventional studies that apply decision-making methods in isolation or through simple aggregation, the present study introduces a structured multi-layer decision framework in which each method performs a distinct and complementary role within a unified analytical architecture. The integration is not merely sequential, but functionally interdependent, ensuring consistency between qualitative strategic assessment and quantitative prioritization. In addition, the proposed framework incorporates scenario-based quantitative indicators (ESC, OLI, and SPG), enabling evaluation of system performance under varying future conditions. This represents a significant extension beyond traditional static MCDM approaches, which typically lack mechanisms for capturing dynamic environmental uncertainty. Therefore, the methodological contribution of this study lies in transforming conventional decision-making into a forward-looking, scenario-responsive process, supported by a coherent integration of strategic analysis, multi-criteria evaluation, and quantitative performance assessment.

Each method within the proposed framework is designed to address a specific layer of the decision process: SWOT identifies strategic factors, AHP quantifies their relative importance, ELECTRE TRI performs structured classification under uncertainty, and QSPM enables quantitative prioritization of strategic alternatives. This layered integration ensures methodological consistency and reduces subjectivity across the decision process. Existing approaches often suffer from fragmentation, where strategic analysis, weighting, and prioritization are performed independently, leading to inconsistencies and reduced reliability of results. The proposed framework addresses this issue by providing a coherent and interconnected structure that aligns all stages of the decision-making process.

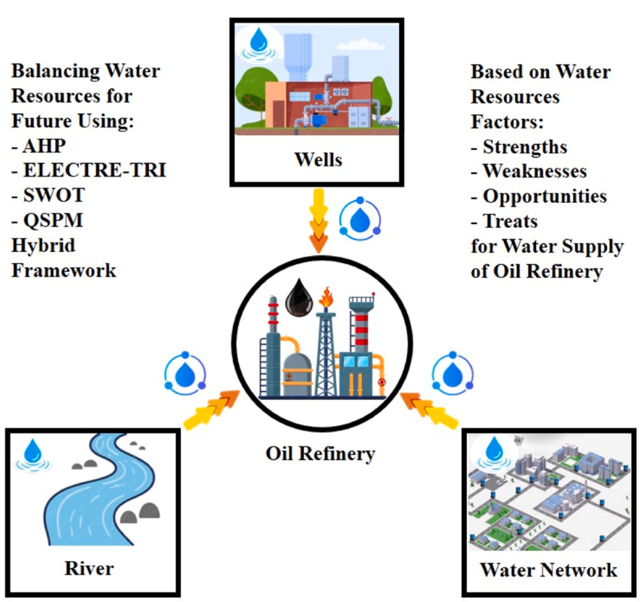

Fig. 1. Conceptual scheme of study description.

2.1. ELECTRE TRI sorting and prioritization model

The ELECTRE TRI model is a prominent method within the ELECTRE family of non-compensatory MCDM approaches, used for assigning alternatives into predefined categories. This model is particularly suitable when dealing with a set of quantitative and qualitative criteria that are heterogeneous and potentially conflicting in nature. Based on the theoretical foundation established by Roy [37] and subsequent developments by Yu [38], the ELECTRE TRI model utilizes outranking relations rather than linear ranking. It establishes a comparative process between alternatives and boundary profiles (b_h), thereby enabling a structured and precise classification of alternatives (Fig. 2). Due to its non-compensatory nature, this approach prevents misleading compensation among criteria, making it an effective tool for environmental and infrastructure assessments—including performance analysis of refinery wastewater treatment systems.

In ELECTRE TRI, each alternative (a) is evaluated against boundary profiles (b_h) to determine its assigned category (C_h). The model's decision-making mechanism is based on three key components: the Concordance Index, the Discordance Index, and the Credibility Index.

a) Concordance Index: The Concordance Index indicates the proportion of criteria for which the performance of alternative "a" is better than or at least equal to the boundary profile b_h. For each criterion, a partial concordance value $c_j(a, b_h)$ is calculated, and the overall concordance is derived from the weighted combination of all criteria. This index serves as the first necessary condition for establishing an outranking relationship [37].
b) Discordance Index: The Discordance Index becomes active when the performance difference between the alternative and the boundary profile in a specific criterion exceeds acceptable limits. To define these differences, three thresholds of Indifference (q), Preference (p), and Veto (v) are considered. As outlined in the report, these

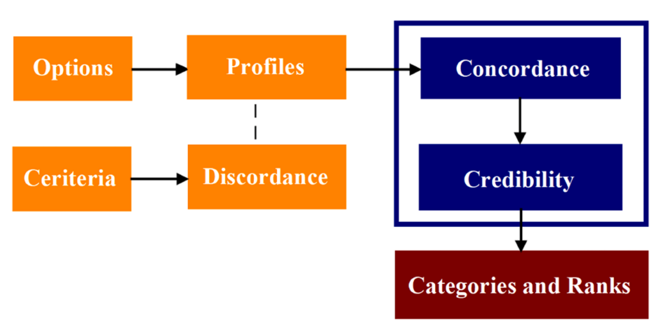

Fig. 2. The operational mechanism of the ELECTRE TRI model for categorizing alternatives.

thresholds play a fundamental role in constructing pseudo-criteria and conducting a detailed analysis of the differences $g_j(a) - g_j(b_h)$. If the veto threshold is triggered, it can single-handedly invalidate the outranking relationship—even if the Concordance Index is high.

c) Credibility Index: After integrating the Concordance and Discordance Indices, the Credibility Index $\sigma(a, b_h)$ is computed, reflecting the strength of the alternative's outranking over the boundary profile. According to established methodology, an outranking relationship is confirmed only if the credibility value meets or exceeds the discrimination threshold λ—that is, $\sigma(a, b_h) \geq \lambda$ [22]. The value of λ is typically chosen within the range of 0.5 to 0.9 and determines the strictness of the classification process.

The defined criteria (g1–g5) serve as the evaluation dimensions in the ELECTRE TRI model, where each strategy is assessed against predefined profiles to determine its classification under uncertainty (Table 1). Together, these criteria provide a comprehensive basis for evaluating strategic alternatives within the ELECTRE TRI framework.

The application of ELECTRE TRI requires the specification of the indifference threshold (q), preference threshold (p), veto threshold (v), and cutting level (λ). To ensure comparability across the performance matrices, all criterion performances were expressed on a harmonized 0 – 100 desirability scale before the outranking calculations. Higher values consistently represented more favorable performance. For criteria originally associated with cost, implementation burden, or operational difficulty, the direction of the scale was transformed so that higher scores indicated greater desirability. Consequently, q, p and v are expressed as score points on the same 0 – 100 scale, whereas λ is a dimensionless credibility threshold. The parameter values were determined through a structured iterative calibration procedure rather than being adopted as arbitrary constants. Preliminary values were first specified according to the operational interpretation of each parameter and the logical consistency condition ($0 \leq q < p < v$).

The indifference threshold represented the maximum performance difference that could reasonably be regarded as negligible, the preference threshold represented the minimum difference required to establish a clear preference, and the veto threshold represented a critical disadvantage that could not be fully compensated by favorable performance on the remaining criteria. The cutting level represented the minimum credibility required to validate an outranking relation.

A systematic parameter search was subsequently performed over predefined plausible intervals. The values of q, p, v and λ were varied around their preliminary settings, while maintaining the consistency condition $q < p < v$. Each admissible parameter configuration was applied to the complete set of performance matrices. The final values of $q = 5$, $p = 10$, $v = 30$ and $\lambda=0.70$ were selected from within the identified stability region rather than from an isolated boundary configuration (Table 2). On the harmonized scale, these values respectively represent a five-point negligible difference, a ten-point clear-preference difference, and a thirty-point critical disadvantage. A credibility index of at least 0.70 was required to validate an outranking relation. A common parameter set was applied to all five criteria and all performance matrices because the criterion values had been transformed to the same direction and measurement scale. This uniform specification avoids differences in threshold interpretation among the matrices and allows the classification results to be reproduced using a single parameter structure.

A separate one-at-a-time sensitivity analysis was conducted by varying each parameter within its plausible interval while holding the remaining parameters at their final values. The relatively low sensitivity associated with q, p, v and λ indicates that the classification pattern was not dependent on a narrowly specified threshold combination.

Table 1
Definition of evaluation criteria.

Criterion	Description	Evaluation Basis	Unit	Role in MCDM
g_1 (a)	Ease of implementation	Expert opinion / Likert scale	Qualitative/ Score	Positive (higher is better)
g_2 (b)	Ease of operation	Expert opinion / Likert scale	Qualitative/ Score	Positive (higher is better)
g_3 (c)	Implementation cost	Financial data / Cost estimate	Index / Score	Negative (lower is better)
g_4 (d)	Operational cost	Financial data / Cost estimate	Qualitative/ Score	Negative (lower is better)
g_5 (e)	Effectiveness	Expert opinion / Likert scale	Index / Score	Positive (higher is better)

2.2. AHP weighting model

The AHP is widely recognized as a robust methodology for determining the relative weights of criteria in MCDM processes. By systematically employing pairwise comparisons and structured mathematical computations, AHP facilitates the derivation of criterion weights that reflect decision-makers' preferences and judgments. In this approach, criteria are compared in pairs to determine their relative importance, leading to the construction of a pairwise comparison matrix. The principal eigenvector of this matrix is then computed to establish the final weights for each criterion. These weights, which indicate the relative significance of the criteria in the final decision, are validated using a consistency index to ensure the reliability and coherence of the judgments made [21].

AHP is particularly valuable in situations involving both qualitative and quantitative criteria, as it effectively transforms qualitative judgments into quantifiable values, enabling the integration of heterogeneous criteria within a structured evaluation framework [39]. Key advantages of AHP in weighting include its capacity to assess the logical consistency of judgments, flexibility in aggregating inputs from multiple experts, and the ability to produce transparent and justifiable results. These characteristics have established AHP as a reputable and widely applied method for criterion weighting across various fields, including management, environmental planning, and project evaluation [40].

In this method, matrix A is formed as follows, where a_{ij} represents the preference of criterion i over criterion j:

$$A = \begin{vmatrix} 1 & a_{12} & a_{1n} \\ a_{21} & 1 & a_{2n} \\ a_{n1} & a_{n2} & \ddots 1 \end{vmatrix} \tag{1}$$

For each row i of the matrix, the geometric mean is calculated as follows:

$$GM_i = \left(\prod_{j=1}^{n} a_{ij} \right)^{1/n} \tag{2}$$

The normalized weight of each criterion is obtained from the following equation:

$$w_i = \frac{GM_i}{\sum_{k=1}^{n} GM_k} \tag{3}$$

The vector of normalized weights is considered as the principal eigenvector:

$$W = [w_1, w_2, \ldots, w_n]^T \tag{4}$$

To ensure the consistency of judgments, the following indices are calculated:

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(AW)_i}{w_i} \tag{5}$$

Table 2
ELECTRE TRI parameter settings.

Parameter	Operational interpretation	Range	Assigned value	Unit or scale basis
q (indifference)	Maximum performance disadvantage regarded as negligible	3–7	5	Score points on the harmonized 0–100 desirability scale
p (preference)	Minimum performance disadvantage required to establish a clear preference	8–15	10	
v (veto)	Critical disadvantage that cannot be fully compensated by favorable performance on other criteria	20–45	30	
λ (cutting level)	Minimum credibility required to validate an outranking relation	0.60–0.75	0.70	Dimensionless credibility level

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n - 1} \tag{6}$$

$$CR = \frac{CI}{RI} \tag{7}$$

where RI is extracted from a table of random indices. The acceptability condition for consistency is CR $<$ 0.1. The obtained weights (w_i) represent the relative importance of each criterion in the decision-making process and are used in subsequent stages for evaluating alternatives.

The AHP weighting process in this study is based on structured expert judgments collected through questionnaires distributed among domain specialists and refinery managers. The respondents evaluated the relative importance of criteria using pairwise comparisons, following the standard Saaty scale. The individual pairwise comparison matrices obtained from the experts were aggregated using the geometric mean method to derive a collective judgment matrix. This approach ensures that the final weights reflect a consistent group perspective rather than individual bias. To ensure the reliability of the AHP results, the consistency of the pairwise comparison matrices was evaluated using the CR. The CR is calculated based on the CI and the RI, following standard AHP procedures. All calculated CR values were found to be below the acceptable threshold of 0.10, indicating that the expert judgments are logically consistent. Specifically, the CR values ranged between 0.04 and 0.09 across different comparison matrices, confirming the robustness of the weighting process (Table 3).

2.3. SWOT strategic model

The SWOT model is a structured framework for strategic analysis, utilized to identify and organize factors influencing a system, project, or process [41]. This method is built upon four core dimensions: Strengths, Weaknesses, Opportunities, and Threats. Its primary objective is to construct a comprehensive overview of the internal and external conditions of the decision-making system. In the context of water resource management and the optimization of industrial treatment systems, SWOT analysis serves as a suitable tool for systematically categorizing key factors and providing reliable input for MCDM models [42].

In this model, factors are organized into two distinct levels:

1. Internal Factors: These encompass Strengths and Weaknesses, relating to intra-organizational, operational, and technical characteristics.
2. External Factors: These include Opportunities and Threats, arising from environmental, economic, institutional, and regulatory conditions.

Table 3
Consistency ratios of AHP pairwise comparison matrices.

Description	CR Value	Acceptable Threshold	Status
Internal factors (SW)	0.06	$<$ 0.10	Acceptable
External factors (OT)	0.08	$<$ 0.10	Acceptable
Criteria weighting	0.05	$<$ 0.10	Acceptable
Sub-criteria comparisons	0.04–0.09	$<$ 0.10	Acceptable

The model's output is a four-quadrant matrix that facilitates the combination of these factors to analyze potential strategies. These combinations are typically analyzed within the following four overarching strategic paradigms:

- SO Strategies (Offensive): Leveraging strengths to capitalize on opportunities.
- WO Strategies (Conservative): Utilizing opportunities to mitigate weaknesses.
- ST Strategies (Competitive): Employing strengths to counteract threats.
- WT Strategies (Defensive): Minimizing weaknesses and avoiding threats.

2.4. QSPM quantitative model

The QSPM is used as a comprehensive analytical tool in the strategic planning process. This matrix, by systematically combining internal and external factors, enables the evaluation and prioritization of different strategies based on the relative attractiveness of each. Relying on the outputs of previous analytical matrices such as the IFEM and the EFEM, QSPM provides a structured framework for selecting optimal strategies.

The QSPM implementation process begins with determining the weight of each internal and external factor:

$$w_i = \frac{R_i}{\sum_{i=1}^{n} R_i} \tag{8}$$

Where Ri represents the importance rating of each factor and Wi is its normalized weight.

In the next step, potential strategies—mainly extracted from the SWOT matrix—are identified, and for each of these strategies in relation to each factor, an AS on a scale of 1 to 4 is assigned. This qualitative scale includes different levels of attractiveness, where a score of 4, 3, 2, and 1 indicates very high, high, moderate, and low attractiveness, respectively.

After assigning the attractiveness scores, the Weighted Attractiveness Score for each strategy is calculated through the following relation:

$$WAS_j = \sum_{i=1}^{n} \left(W_i \times AS_{ij} \right) \tag{9}$$

where W_i is the weight of the i th factor, and AS_{ij} is the attractiveness score of the j-th strategy relative to the i th factor. The TAS for each strategy is obtained by summing the weighted scores in both internal and external factors. Strategies are ranked based on the final TAS score, and those achieving the highest TAS are selected as the top strategies.

The assignment of attractiveness scores in the QSPM matrix was conducted through a structured expert evaluation process to ensure consistency, transparency, and reproducibility. Experts were asked to assess each strategic alternative with respect to each identified factor using a standardized scoring scale ranging from 1 to 4, where 1 indicates low attractiveness and 4 indicates high attractiveness. This scale is consistent with established QSPM applications and ensures comparability across evaluations (Table 4). The scoring process was guided by clearly defined criteria to minimize subjective interpretation. Experts were instructed to consider the relative ability of each strategy to address specific strengths, weaknesses, opportunities, and threats.

To aggregate individual judgments, the arithmetic mean method was applied to the collected scores, producing a representative group evaluation. Before aggregation, responses were reviewed to identify potential outliers or inconsistencies. Where necessary, iterative consultation with the expert panel was conducted to refine the evaluations and ensure convergence toward a stable consensus. The resulting aggregated scores were then combined with the AHP-derived weights to compute the TAS for each strategy. This integration ensures that the final prioritization reflects both the relative importance of factors and the effectiveness of strategies in addressing them. This structured scoring and aggregation procedure reduces subjectivity, enhances transparency, and improves the robustness of the QSPM-based decision-making process. The structured aggregation of expert judgments ensures that the QSPM results are not driven by individual opinions but represent a consistent and collective evaluation.

2.5. *Studied area*

The KOR, located in Kermanshah City in western Iran, is one of the region's principal industrial complexes, supplying refined petroleum products to both local and national markets (Fig. 3). The refinery relies on three primary water supply sources to support its operational units, including steam generation, cooling systems, desalting units, and wastewater treatment facilities. These sources comprise (i) groundwater wells, which historically formed the backbone of the refinery's supply system; (ii) the Qarasoo River, a significant regional surface water source subject to seasonal flow variability and water quality fluctuations; and (iii) the municipal drinking-water distribution network, used as a complementary source. Each water source exhibits distinct strengths, limitations, and environmental vulnerabilities, making the refinery's water supply portfolio inherently complex. Variability in hydrological conditions, operational risks, and regulatory constraints necessitates a structured, multi-method decision-making framework capable of evaluating water supply performance from strategic, operational, and environmental perspectives. To achieve this, the present study integrates AHP, SWOT, ELECTRE TRI, and QSPM within a unified analytical workflow.

2.6. *Study framework*

To conduct the present research and determine the selected strategy for enhancing the performance of the KOR's water supply resources, a novel hybrid framework integrating MCDM systems and strategic management tools was developed (Fig. 4). Within this framework, data concerning the strengths, weaknesses, opportunities, and threats (SWOT) of each unit (wells, Qarasoo River, and the city's WDN), along with the necessary information for determining the weights of the indices in the ELECTRE TRI model using the AHP, were first collected from the organization's managers and experts.

Table 4
QSPM scoring and aggregation procedure.

Step	Description	Method	Purpose
1	Individual scoring	Expert judgment (scale 1–4)	Evaluate strategy effectiveness
2	Score validation	Iterative review	Reduce inconsistency
3	Aggregation	Arithmetic mean	Obtain group consensus
4	Integration	Weighted by AHP	Compute TAS values

The expert panel involved in this study consisted of 15 professionals with direct experience in refinery water resource management and related operational domains. Specifically, the panel included research managers, operations managers, engineering managers, utility managers, energy managers, and technical experts from the corresponding departments. These experts were selected using a purposive sampling approach, which is commonly applied in multi-criteria decision-making studies. The selection criteria included (i) professional experience in refinery operations, (ii) involvement in water and utility management, and (iii) familiarity with strategic planning and operational constraints of the system. This approach ensures that the collected judgments reflect both practical knowledge and strategic insight relevant to the decision problem.

To aggregate expert judgments, individual pairwise comparison matrices were collected from each expert. The consistency ratio was evaluated for each matrix to ensure logical consistency of judgments. The final aggregated comparison matrix was obtained using the geometric mean method, which is widely recognized as a robust aggregation technique in group decision-making and AHP applications. This method preserves the reciprocal property of pairwise comparisons and reduces the influence of extreme judgments. The resulting aggregated weights were then used as input for subsequent stages of the decision-making framework.

To ensure the robustness and credibility of the input data, the reliability and validity of the expert-based questionnaire were systematically evaluated (Table 5). First, the internal consistency of the collected responses was assessed using Cronbach's alpha coefficient. The analysis was performed across the identified SWOT factors, considering the set of expert evaluations. The results yielded a Cronbach's alpha value exceeding 0.80, indicating a high level of internal consistency and reliability among the responses.

Second, the consistency of pairwise comparisons in the AHP stage was examined using the CR. All calculated CR values were below the acceptable threshold of 0.1, confirming that the expert judgments were logically consistent and suitable for deriving reliable weights. Third, content validity was ensured through a structured expert validation process. The initial list of SWOT factors was developed based on a literature review and refined through multiple rounds of expert consultation. This iterative process ensured that the selected factors were relevant, comprehensive, and representative of the refinery's operational and environmental context.

The questionnaire consisted of multiple grouped items associated with SWOT-factor evaluation, pairwise comparisons, scenario assessment variables, and strategic prioritization criteria. Cronbach's alpha coefficients were calculated separately for each questionnaire category to assess internal consistency reliability. The obtained alpha values exceeded the commonly accepted threshold, indicating satisfactory reliability of the collected expert judgments. Additionally, the consistency of the AHP pairwise comparison matrices was evaluated using the Consistency Ratio (CR) proposed by Saaty (1980). All recalculated CR values remained below the acceptable threshold of 0.10, confirming the logical consistency of the expert comparisons.

The questionnaire items were designed based on the identified SWOT factors, scenario evaluation variables, and strategic decision criteria derived from literature review and expert consultation. The final questionnaire structure was reviewed by domain specialists prior to distribution to ensure content validity and conceptual clarity. All pairwise comparison matrices satisfied the Saaty consistency requirement ($CR < 0.10$), indicating acceptable consistency of expert judgments.

Subsequently, the SWOT options were reviewed, the final options were selected, and submitted to the ELECTRE TRI model to determine their class and weight. On the other hand, the AHP method was used to determine the weight of each classification criterion for the ELECTRE TRI model. The ELECTRE TRI model then utilized this information to determine the category, rank, and consequently the weight of each option for forming the IFEM and EFEM.

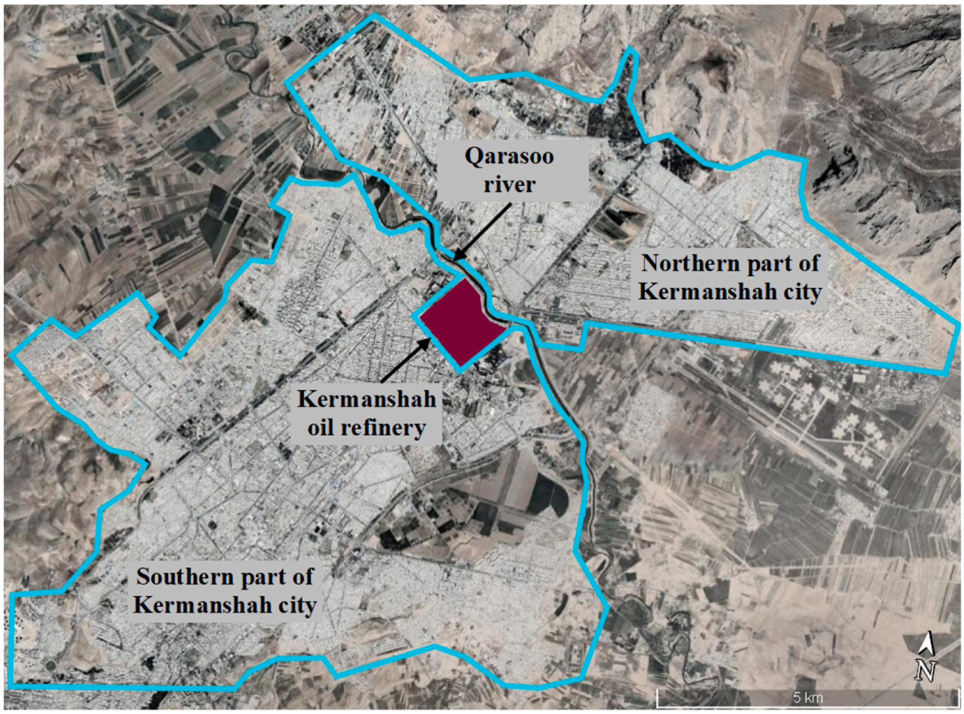

Fig. 3. Location of the study area in Kermanshah city.

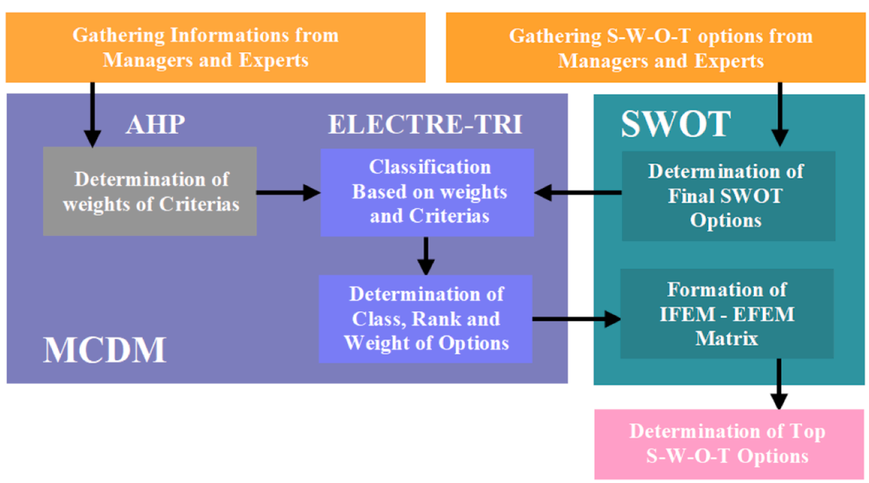

Fig. 4. Proposed framework for determining the top SWOT options for each water supply unit (Wells, WDN and River).

Table 5
Reliability and consistency assessment results of questionnaires.

Test	Method	Acceptable Threshold	Result	Interpretation
Internal consistency	Cronbach's alpha	> 0.70	0.82–0.88	High reliability
Internal consistency	CR	< 0.10	0.04–0.09	Acceptable
Content validity	Expert validation	Qualitative	Confirmed	Valid structure
Sensitivity check	Scenario variation	Stability required	Stable	Robust results

Determining the weights and ranks using the multivariate decision-making models ELECTRE TRI and AHP, based on specific indices, eliminates the influence of the researcher's or user's personal opinions from the analyses. This ensures that only the inputs from the organization's managers and expert specialists influence the strategic decisions through a purely scientific process.

Following the formation of the IFEM and EFEM, from among the S, W, O, and T options, those with the highest weighted scores are selected for each unit. Now that the S, W, O, and T options for each unit are specified, the selected options for each unit are multiplied by a Global Weight which shows the weight of that unit (determined by the AHP method) and entered into the overall IFEM and EFEM (Fig. 5). After determining the final IFEM and EFEM, the total overall Global Score is calculated, and based on this, the type of superior strategy is determined. Subsequently, the top strategies are analyzed, reviewed, and compared quantitatively using the QSPM model, ultimately leading to the identification of the optimal strategy.

The detailed decision-making framework is illustrated in Fig. 6. The process begins with data collection and identification of internal and external factors through expert surveys. These factors are structured into

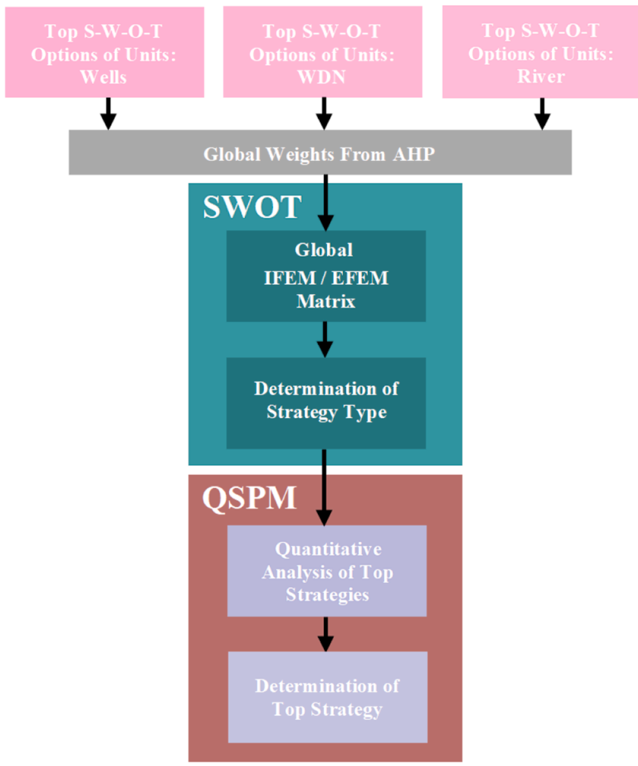

Fig. 5. Final framework for formation of global IFEM / EFEM and top strategy selection.

IFEM and EFEM matrices and subsequently evaluated using AHP and ELECTRE TRI to assign weights and classify their relative importance. Based on these results, strategic alternatives are formulated within the SWOT framework and quantitatively assessed using the QSPM model to identify the preferred strategy.

To further enhance the robustness of the decision-making process, a scenario-based evaluation layer is incorporated following the strategy selection stage. In this phase, the selected strategy is assessed under different future conditions using three quantitative indicators: ESC, OLI, and SPG. These indicators provide additional insight into system behavior under uncertainty and enable evaluation of the resilience and adaptability of the selected strategy without altering the initial ranking results.

The selection of SWOT, AHP, ELECTRE TRI, and QSPM in this study is based on their complementary capabilities in addressing different dimensions of complex decision-making problems. SWOT analysis was employed as an initial step to systematically identify internal and external factors affecting the refinery's water resource system. Despite its effectiveness in structuring strategic factors, SWOT remains inherently qualitative and does not provide a mechanism for prioritization. To address this limitation, the AHP was used to assign quantitative weights to the identified factors. AHP enables pairwise comparison and consistency checking, thereby reducing subjectivity and improving the reliability of the weighting process. ELECTRE TRI was selected due to its non-compensatory nature and its ability to perform classification under uncertainty. Unlike compensatory methods such as TOPSIS, ELECTRE TRI does not assume full trade-offs among criteria, making it particularly suitable for decision environments where certain criteria cannot be offset by others. This characteristic is critical in water resource management, where environmental risks and operational constraints must be treated with caution.

Finally, the QSPM was applied to prioritize the strategic alternatives. QSPM provides a structured and transparent mechanism for evaluating the relative attractiveness of strategies based on weighted factors, directly linking analytical results to actionable decisions. Alternative multi-criteria decision-making methods, including TOPSIS and PROMETHEE, were considered; however, these methods are primarily ranking-oriented and rely on compensatory assumptions, which may not adequately capture the hierarchical and uncertainty-sensitive nature of the problem addressed in this study. Therefore, the selected combination of methods enables a comprehensive, robust, and consistent decision-making process by integrating qualitative strategic analysis, quantitative weighting, non-compensatory classification, and final prioritization within a unified framework. The proposed methodological structure ensures that strategic decisions are not only analytically sound but also practically actionable, bridging the gap between theoretical decision models and real-world implementation.

The strength of the proposed framework lies in its ability to integrate complementary decision logics within a unified structure. By combining compensatory and non-compensatory methods, the framework reduces the risk of biased or unrealistic trade-offs and enhances the robustness of strategic decisions in complex environments.

2.7. *Comparison with state-of-the-art studies*

The comparison presented in Table 6 highlights several important distinctions between the proposed framework and existing approaches. Previous studies have widely demonstrated the effectiveness of MCDM methods in addressing complex water management problems; however, they predominantly focus on static decision environments and lack integration of future uncertainty. For instance, comprehensive reviews by Cinelli et al. [11] and Mardani et al. [12] emphasize the applicability of MCDM techniques across various domains, but also reveal that most implementations do not incorporate dynamic scenario analysis. Similarly, studies such as Liu et al. [23] provide integrated assessments of industrial water systems but offer limited capability for evaluating long-term resilience under uncertain future conditions.

To systematically evaluate the methodological contribution of the proposed framework, a comparative benchmarking analysis was conducted against recent hybrid MCDM and industrial water-management studies. The comparison criteria were selected based on the primary methodological gaps identified in the literature, including scenario integration, resilience-oriented assessment, uncertainty handling, strategic prioritization capability, and robustness analysis. The comparison demonstrates that most existing studies focus either on static multi-criteria ranking or isolated sustainability assessment. In contrast, the proposed framework integrates scenario-sensitive indicators, strategic prioritization, resilience-oriented evaluation, and sensitivity analysis within a unified decision-support structure specifically developed for refinery water-resource systems.

A key limitation identified in the literature is the absence of explicit quantitative indicators to capture system behavior under stress. Many studies rely on qualitative interpretation or ranking outputs without translating results into interpretable resilience metrics. This gap has also been noted in recent reviews of MCDM applications in water allocation, where uncertainty and future variability are often insufficiently addressed. In contrast, the proposed framework extends beyond conventional approaches by explicitly linking strategic decision-making with scenario-based evaluation. The introduction of ESC, OLI, and SPG provides a quantitative mechanism to assess environmental pressure, opportunity utilization, and system performance gaps under different future conditions.

Furthermore, the integration of multiple decision-making methods (SWOT, AHP, ELECTRE TRI, and QSPM) reduces methodological bias and enhances the robustness of the results. Unlike single-method approaches, this hybrid structure allows for cross-validation of decisions and improves the reliability of strategic prioritization. Overall, the proposed framework advances the state-of-the-art by transforming static MCDM analysis into a dynamic, scenario-informed, and quantitatively interpretable decision-support system for industrial water resource

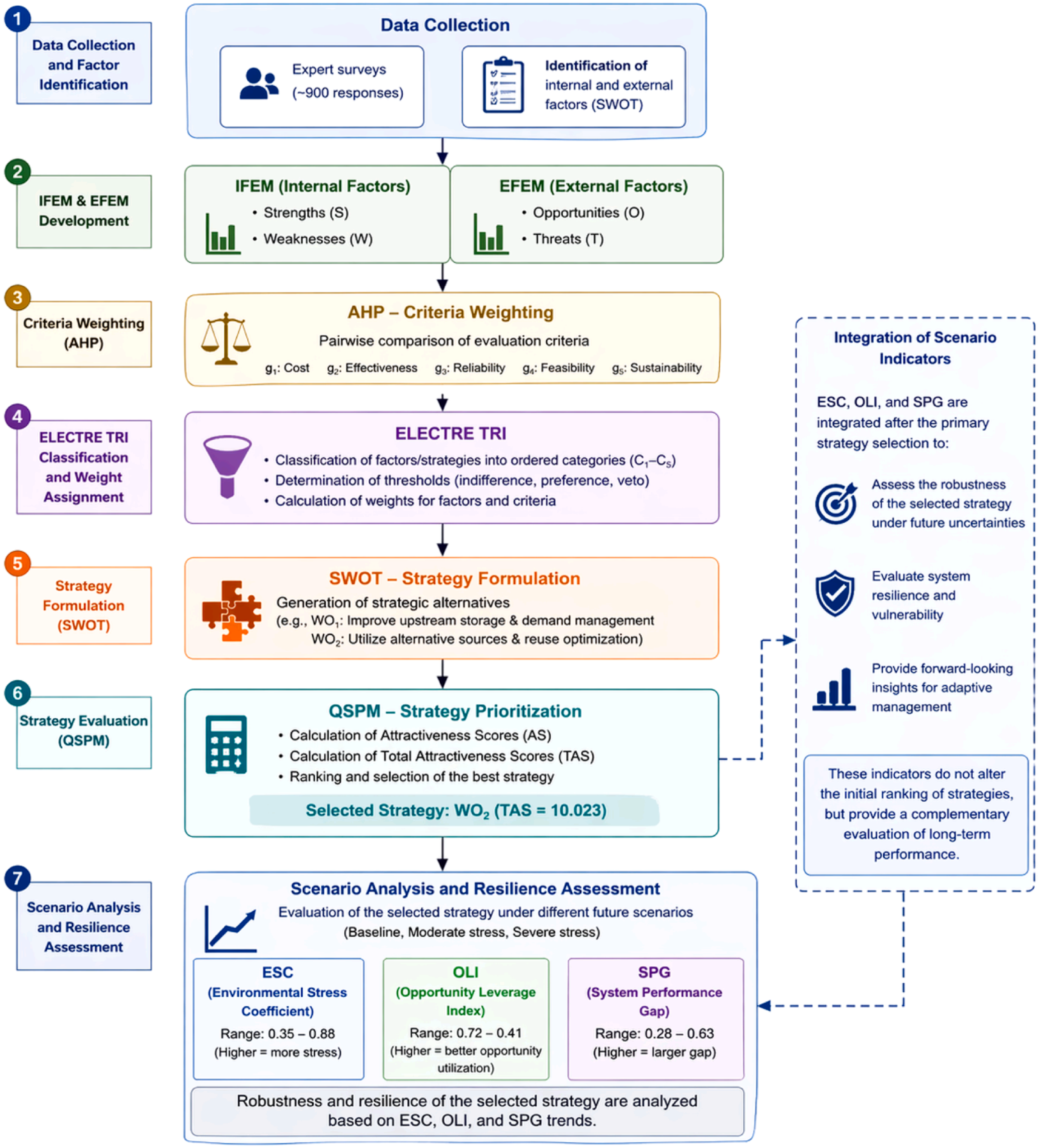

Fig. 6. Integrated decision-making framework combining SWOT, AHP, ELECTRE TRI, and QSPM, enhanced with scenario-based indicators (ESC, OLI, and SPG) for evaluating refinery water resource strategies under uncertainty.

management.

As shown in Table 6, recent studies have significantly advanced the understanding of water resource management, particularly in terms of treatment technologies, reuse strategies, and system-level optimization. However, most existing works remain limited in three key aspects: (i) lack of explicit scenario-based analysis, (ii) absence of comprehensive quantitative indicators for system performance and resilience, and (iii) insufficient integration of strategic analysis with multi-criteria decision-making frameworks.

In contrast, the proposed framework in this study addresses all three limitations simultaneously. It not only incorporates explicit future scenarios but also introduces quantitative indicators (ESC, OLI, and SPG) to evaluate system behavior under varying conditions. Moreover, it integrates strategic analysis tools (SWOT) with advanced decision-making techniques (AHP, ELECTRE TRI, and QSPM), resulting in a high level of decision integration. This comparison clearly demonstrates that the proposed approach advances the state-of-the-art by bridging the gap between qualitative strategic planning and quantitative, scenario-based decision support in industrial water resource management.

Table 6
State-of-the-art comparison of recent hybrid framework and scenario-based MCDM frameworks in water-resource management.

Study	Methodology	Scenario Analysis	Quantitative Indicators	Bias Control	Application Scope
Cinelli et al. [11]	General MCDA review	No	No	Limited	Sustainability assessment
Mardani et al. [12]	MCDM review	No	No	Limited	General decision-making
Govindan et al. [14]	ELECTRE-based approaches	No	No	Moderate	Operational research
Liu et al. [23]	Integrated assessment	Partial	No	Moderate	Industrial water systems
Guo et al. [25]	Review	No	No	Low	Refinery wastewater
Karkou et al. [20]	System analysis	Limited	No	Moderate	Industrial water systems
Florides et al. [27]	Review	No	No	Low	Water reuse
Kato and Kansha [28]	Review	No	No	Low	Wastewater treatment
Wang et al. [26]	System modeling	Yes	Partial	Moderate	Water stress mitigation
Yan and Wang [31]	TOPSIS	Yes	No	Moderate	water-scarcity management
This study	SWOT–AHP–ELECTRE TRI–QSPM	Yes	ESC, OLI, SPG	High	Strategic water planning

3. Results

The extensive data presented in the tables reflects the multi-layered nature of the proposed decision framework, where multiple criteria, expert judgments, and analytical steps are integrated to derive final results. To enhance transparency, the derivation of tabulated values is explicitly described as follows:

First, the SWOT factors are identified and structured into internal (strengths and weaknesses) and external (opportunities and threats) categories. These factors form the basis for subsequent quantitative analysis. Second, the relative importance of each factor is determined using the AHP method. Expert judgments collected through pairwise comparisons are aggregated using the geometric mean, and the resulting matrices are used to compute normalized weights. These weights are presented in the corresponding columns of the IFEM and EFEM tables. Third, in the ELECTRE TRI stage, each factor or alternative is evaluated against predefined profiles using the weighted criteria. The resulting outranking relations lead to the classification of factors into prioritized categories, which are reflected in the classification columns of the respective tables. Fourth, in the QSPM matrix, each strategic alternative is evaluated against the identified factors using attractiveness scores (AS), assigned by experts on a standardized scale. These scores are aggregated and multiplied by the corresponding AHP-derived weights to compute the Total Attractiveness Score (TAS) for each strategy. Finally, the scenario-based indicators (ESC, OLI, SPG) are computed using normalized formulations based on aggregated factor contributions under each scenario. These values represent system performance under different future conditions and are presented in the scenario analysis tables.

This stepwise computational structure ensures that all tabulated values can be traced back to their original inputs, enhancing the transparency, reproducibility, and interpretability of the results. Note that in tables, weights are derived from AHP pairwise comparisons; AS values represent aggregated expert scores; TAS values are computed as the weighted sum of AS values. The volume of tabulated data is an inherent feature of comprehensive multi-criteria analyses, where detailed representation is necessary to ensure analytical rigor and decision transparency.

3.1. Formulation of SWOT and AHP model options

The research process began with the development of a structured questionnaire and the collection of approximately 900 technical responses from managers and experts of the KOR regarding the internal (strengths and weaknesses) and external (opportunities and threats) factors associated with water resources management.

The decision-making process in this study is based on structured expert elicitation involving a panel of domain specialists from the refinery. The expert group included senior and mid-level professionals from research management, operations, engineering, utilities, and energy departments, all of whom are directly involved in water resource planning and management. Experts were selected using a purposive sampling approach, ensuring that participants possessed relevant expertise, practical experience, and decision-making responsibilities. This approach is consistent with established practices in multi-criteria decision-making studies, where the quality of expertise is prioritized over sample size. The reported dataset of approximately 900 responses represents the total number of individual judgments collected across different stages of the framework, rather than the number of experts. These responses include pairwise comparisons for AHP weighting, category assignments in ELECTRE TRI, and attractiveness scores in the QSPM matrix.

To ensure consistency and reliability, expert judgments were aggregated using established methods. For AHP pairwise comparisons, the geometric mean method was applied to combine individual matrices into a collective judgment matrix. For ELECTRE TRI and QSPM stages, a consensus-based aggregation approach was employed, supported by iterative review and validation among the expert panel. This structured elicitation and aggregation process enhances the robustness, transparency, and reproducibility of the proposed decision framework. The use of structured aggregation techniques ensures that the results are not driven by individual opinions but reflect a collective and consistent expert perspective.

Subsequently, these inputs—representing the collective technical insight of the refinery's professional staff—underwent a comprehensive evaluation and screening procedure. The refined and validated factors were then extracted as the final outputs and presented in Tables 7, 8, 9 for three water resources units: Wells, Qarasoo River, and WDN. In this stage, additional questionnaire-based data were also gathered to support the implementation of the AHP model, particularly for determining the criterion weights required for the ELECTRE-TRI analysis and global weights of each unit.

3.2. Determining the weights and rankings of factors in IFEMs and EFEMs

The clustering options within the ELECTRE TRI system correspond directly to the factors listed in the IFEM and EFEM matrices. Therefore, it is essential to determine which criteria are used to classify these factors and how their weights are assigned within these matrices. To this end, five criteria (g_1, g_2, …, g_5)—including ease of implementation, ease

Table 7
Selected internal and external factors for wells.

External		Internal	
Key Factor	Strength	Key Factor	Opportunity
$S_{we}1$	Supply of water in quantities exceeding the refinery's operational demand	$O_{we}1$	Potential for producing industrial and potable water as a new product
$S_{we}2$	Ease of operation and on-site installation within the refinery	$O_{we}2$	Possibility of use in other refinery units, including fire suppression and related applications
$S_{we}3$	Low operational cost	$O_{we}3$	Potential for integrated operation with other water sources
$S_{we}4$	Low SiO_2 concentration	$O_{we}4$	Access to new technologies for optimizing chlorination
$S_{we}5$	Relative reliability of water supply	—	—
$S_{we}6$	Relatively stable water quality	—	—
$S_{we}7$	Relatively low well-water temperature	—	—
$S_{we}8$	Absence of biological contamination	—	—
External		Internal	
Key Factor	Weakness	Key Factor	Threat
$W_{we}1$	Decline in discharge rate, drop in groundwater level, and potential well depletion.	$T_{we}1$	Risk of contamination due to leakage from storage tanks, pipeline failures, or refinery units
$W_{we}2$	Reduced water quality due to high hardness and its increase in recent years	$T_{we}2$	Land subsidence and deterioration of the well casing
$W_{we}3$	High costs associated with hardness reduction	$T_{we}3$	Decline in groundwater table in the well field and surrounding areas
$W_{we}4$	Energy and chemical consumption required for pumping and chlorination	$T_{we}4$	Potential drilling of additional wells in the surrounding areas and their negative impacts
$W_{we}5$	Imposition of maintenance and repair costs	$T_{we}5$	Occurrence of consecutive droughts
$W_{we}6$	Requirement for treatment processes	$T_{we}6$	The possibility of restrictions imposed by regulatory or environmental authorities
$W_{we}7$	Dependence on electrical power amid recent supply challenges	$T_{we}7$	Risk of accidents in the chlorination unit
—	—	$T_{we}8$	Aging of pipelines and equipment
—	—	$T_{we}9$	Over-extraction of groundwater

Table 8
Selected internal and external factors for the Qarasoo River.

External		Internal	
Key Factor	Strength	Key Factor	Opportunity
$S_{ri}1$	Possibility of direct use without treatment for fire suppression and landscaping	$O_{ri}1$	Availability of trained and knowledgeable personnel for operating the river intake and its treatment system
$S_{ri}2$	Easy accessibility due to the proximity of the river to the refinery	$O_{ri}2$	Potential for constructing a conventional filtration treatment system
$S_{ri}3$	Low pumping cost	$O_{ri}3$	Potential for obtaining environmental compliance credits for the refinery
$S_{ri}4$	Potential for storing water during high-flow seasons and using it in emergencies	$O_{ri}4$	Opportunity for cooperation, shared use, or water sales to other institutions.
$S_{ri}5$	Low water hardness	$O_{ri}5$	Reduced dependence on groundwater wells and improved passive defense and operational resilience
External		Internal	
Key Factor	Weakness	Key Factor	Threat
$W_{ri}1$	Need for treatment and lack of a suitable treatment system	$T_{ri}1$	Insufficient financial resources for constructing an appropriate treatment facility
$W_{ri}2$	Lack of monitoring and control to prevent conventional and industrial pollutants from entering the river	$T_{ri}2$	Occurrence of persistent drought periods
$W_{ri}3$	Variability in river water quality	$T_{ri}3$	Sediment inflow and the need for dredging the intake area
$W_{ri}4$	Fluctuations in river discharge	$T_{ri}4$	Regulatory and environmental restrictions
$W_{ri}5$	Financial burden associated with permitting procedures	$T_{ri}5$	High cost and challenges associated with obtaining withdrawal permits at the refinery's required demand
$W_{ri}6$	Formation of scale and corrosion in pipelines and pumps	$T_{ri}6$	Dependence on electricity and frequent power outages in recent years

of operation, implementation cost, operational cost, and effectiveness—were selected for clustering the factors and assigning their associated weights.

The next step in the ELECTRE TRI procedure involves determining the weight of each criterion and defining the boundaries of the classification categories. These parameters are subsequently applied to prioritize and weight the internal and external factors within the IFEM and EFEM structures. While the weight ranges assigned to strengths, weaknesses, opportunities, and threats may vary, each must comply with the predefined rules presented in Table 10.

As noted earlier, the weights of the ELECTRE TRI criteria for performance matrix in this study were derived using the AHP method. Accordingly, the aggregated pairwise comparison matrix—constructed based on expert judgments—is presented in Table 11. Table 12 further summarizes the decision criteria along with their respective weights used in the ELECTRE TRI model.

At this stage of the analysis, the internal and external factors incorporated into the IFE and EFE matrices are evaluated, weighted, and categorized through the ELECTRE TRI multi-criteria decision-making approach. The procedure begins with the development of a performance matrix, which serves as the main input structure of the ELECTRE TRI model. In this research, the evaluated factors are classified into five distinct categories. After defining the classification structure, the corresponding alternatives are introduced into the model for assessment. The results make the classification of items and the range of weights assigned to each class. As a representative example, Tables 13–24 presents total of 12 performance matrices were developed in this study for the Strengths, Weaknesses, Opportunities, and Threats associated with wells, the Qarasoo River, and the WDN.

After developing the IFEMs and EFEMs for each individual water supply unit, a consolidated set of matrices must be constructed to represent the overall strategic assessment of the refinery's water system. This integration requires selecting the highest-scoring internal and external factors from each unit and adjusting their global weights based on the relative importance of that unit within the refinery's operational context. Accordingly, the normalized score of each selected factor is multiplied by the global weight assigned to its corresponding unit, and the resulting weighted factors are transferred to the final consolidated global IFEMs and EFEMs.

This procedure ensures that the contributions of the three primary water supply sources—groundwater wells, the Qarasoo River, and the WDN—are reflected proportionally and in accordance with their

Table 9
Selected internal and external factors for WDN.

External		Internal	
Key Factor	Strength	Key Factor	Opportunity
$S_{dn}1$	Excellent water quality with very low hardness	$O_{dn}1$	Possibility of establishing a long-term agreement with the Regional Water Authority and the municipal water utility
$S_{dn}2$	Very easy accessibility	$O_{dn}2$	Potential for direct use in the DM (demineralization) unit
$S_{dn}3$	Significant reduction in groundwater well extraction	$O_{dn}3$	Feasibility of extending pipelines from the municipal network to all refinery units
$S_{dn}4$	No need for treatment or construction of a treatment facility	—	—
$S_{dn}5$	Reduced labor and equipment costs	—	—
$S_{dn}6$	No need for electrical energy for pressurization, considering frequent power outages and shortages	—	—
External		**Internal**	
Key Factor	Weakness	Key Factor	Threat
$W_{dn}1$	Very high cost of potable water for industrial applications	$T_{dn}1$	Risk of water supply interruption due to the prioritization of drinking-water provision
$W_{dn}2$	Limitations in supply volume from the municipal drinking-water network	$T_{dn}2$	Restrictive policies on industrial withdrawals from the municipal system during crisis periods
		$T_{dn}3$	Dependence on decisions made by external governmental agencies

Table 10
Scores assigned to boundary parameters between categories and the corresponding weight ranges.

Category	Score	Boundary	Criteria					Range of assigned weights of internal and external factors
			g_1	g_2	g_3	g_4	g_5	
C1	5	b4	90	80	90	90	70	≥ 0.200
C2	4	b3	65	55	65	60	55	0.080 – 0.200
C3	3	b2	45	40	40	40	30	0.040 – 0.080
C4	2	b1	20	20	20	10	10	0.020 – 0.040
C5	1	—	—	—	—	—	—	0.010 – 0.020

strategic significance. The global weights of these units were derived from expert and managerial judgments using the AHP. Tables 25 and 26 present the final AHP-based weights assigned to each water supply unit, which serve as the foundation for synthesizing the unit-level matrices into the final comprehensive internal and external factor matrices.

3.3. Formation of IFEMs and EFEMs in the SWOT model

Based on the decision criteria and their corresponding weights presented in Table 12, along with the predefined boundaries and category thresholds in Table 10, the ELECTRE TRI model is applied to determine the admissible weight ranges for all internal and external factors. Once these ranges are identified, the final weight assigned to each factor is selected according to the category to which it has been classified. These weighted values are then used to complete the IFEM and EFEM matrices. The outcomes of this step are summarized in Tables 27–29.

Following the determination of the weight attributed to each internal and external factor, the IFEM and EFEM matrices are constructed for each water supply unit. These matrices provide a structured representation of the internal conditions—strengths and weaknesses—and the external environment—opportunities and threats—associated with each source. Tables 30–32 present the resulting IFEM and EFEM matrices for the refinery's three principal water supply units: groundwater wells, the Qarasoo River, and the WDN.

This stage plays a critical role in the analytical framework, as the assigned weights reflect the relative importance and categorical classification of each factor. These matrices subsequently serve as the foundation for developing the aggregated internal and external matrices and for conducting the final QSPM-based strategic evaluation.

Fig. 7 illustrates the sensitivity of the ELECTRE TRI classification outcomes to variations in the λ (cutting level) parameter for the IFEM and EFEM matrices associated with the three investigated water-supply resources, including wells, the Qarasoo River, and the WDN. The heat map presents the magnitude of changes in the obtained classification outputs and assigned weights under different λ values ranging from 0.65 to 0.75. The graphical representation indicates that the observed variations remain relatively limited across all investigated alternatives, with most sensitivity values remaining close to zero. This behavior demonstrates that moderate modifications in the λ parameter do not substantially alter the final classification structure of the ELECTRE TRI model.

A more detailed examination of the results shows that the highest observed variation corresponds to the Qarasoo River alternative at $\lambda = 0.75$, where the sensitivity value reaches 0.091. Nevertheless, even this maximum deviation remains comparatively small relative to the overall scale of the classification framework. Similarly, the Wells and WDN alternatives exhibit only minor fluctuations in the assigned category outputs across the investigated λ range. The obtained results therefore confirm that the ELECTRE TRI classification process maintains a high degree of stability against reasonable changes in the cutting-level parameter. From a methodological perspective, this finding is

Table 12
Decision criteria and their AHP-derived weights for ELECTRE TRI.

No.	Criterion name	Criterion description	Weight
1	g_1 (a)	Ease of implementation	0.13
2	g_2 (b)	Ease of operation	0.20
3	g_3 (c)	Implementation cost	0.23
4	g_4 (d)	Operational cost	0.16
5	g_5 (e)	Effectiveness	0.28
Total	—	—	1.00

Table 11
Aggregate matrix of pairwise comparisons for the main criteria for ELECTRE TRI.

Main criteria	a	b	c	d	e
a	1.000	0.650	0.565	0.813	0.464
b	1.539	1.000	0.870	1.250	0.714
c	1.769	1.150	1.000	1.438	0.821
d	1.231	0.800	0.696	1.000	0.571
e	2.154	1.400	1.217	1.750	1.000

Table 13
Performance matrix of Strength items in ELECTRE TRI model for wells.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$S_{we}1$	91	82	95	93	79	C1	≥ 0.200	0.200
$S_{we}2$	77	73	69	81	59	C2	0.080 – 0.200	0.100
$S_{we}3$	56	48	61	51	33	C3	0.040 – 0.080	0.070
$S_{we}4$	34	38	34	16	27	C4	0.020 – 0.040	0.035
$S_{we}5$	60	44	58	54	42	C3	0.040 – 0.080	0.060
$S_{we}6$	48	50	57	55	38	C3	0.040 – 0.080	0.050
$S_{we}7$	12	18	17	7	8	C5	0.010 – 0.020	0.010
$S_{we}8$	40	35	29	22	19	C4	0.020 – 0.040	0.030

Table 14
Performance matrix of Weakness items in ELECTRE TRI model for wells.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$W_{we}1$	96	84	94	97	73	C1	≥ 0.200	0.220
$W_{we}2$	69	56	70	63	59	C2	0.080 – 0.200	0.090
$W_{we}3$	48	39	50	49	38	C3	0.040 – 0.080	0.050
$W_{we}4$	27	28	25	10	16	C4	0.020 – 0.040	0.025
$W_{we}5$	2	10	2	13	1	C5	0.010 – 0.020	0.010
$W_{we}6$	17	30	20	33	10	C4	0.020 – 0.040	0.025
$W_{we}7$	21	24	20	21	17	C4	0.020 – 0.040	0.025

Table 15
Performance matrix of Opportunity items in ELECTRE TRI model for wells.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$O_{we}1$	37	19	33	29	11	C4	0.020 – 0.040	0.025
$O_{we}2$	66	69	63	63	55	C2	0.080 – 0.200	0.085
$O_{we}3$	89	79	99	95	71	C1	≥ 0.200	0.210
$O_{we}4$	47	46	45	50	28	C3	0.040 – 0.080	0.045

Table 16
Performance matrix of Threat items in ELECTRE TRI model for wells.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$T_{we}1$	63	72	80	62	59	C2	0.080 – 0.200	0.090
$T_{we}2$	2	5	9	1	1	C5	0.010 – 0.020	0.010
$T_{we}3$	89	90	88	99	76	C1	≥ 0.200	0.200
$T_{we}4$	57	39	47	37	37	C3	0.040 – 0.080	0.045
$T_{we}5$	69	65	78	58	54	C2	0.080 – 0.200	0.125
$T_{we}6$	25	18	28	10	23	C4	0.020 – 0.040	0.025
$T_{we}7$	77	54	82	76	55	C2	0.080 – 0.200	0.085
$T_{we}8$	57	48	49	37	40	C3	0.040 – 0.080	0.045
$T_{we}9$	5	8	6	1	1	C5	0.010 – 0.020	0.010

important because λ is one of the most influential parameters within outranking-based decision models, and excessive sensitivity to λ variations could reduce the robustness and reliability of the final prioritization process.

Overall, the sensitivity analysis confirms that the proposed integrated decision-making framework is sufficiently robust with respect to λ parameter uncertainty. The limited variation observed in the classification outputs indicates that the resulting IFEM and EFEM weights, and consequently the strategic prioritization outcomes, are not significantly dependent on small changes in λ values. Therefore, the final rankings and strategic evaluations obtained in this study can be considered stable and reliable under different plausible ELECTRE TRI parameter settings. This stability further supports the applicability of the proposed framework for strategic water-resource planning and decision-making in refinery and industrial water-management systems.

Following the development of the IFEM and EFEM for each of the water supply units, the next step involves synthesizing these results into an integrated set of matrices to provide a comprehensive strategic assessment of the refinery's overall water supply system. This integration requires selecting the highest-scoring internal and external factors

Table 17
Performance matrix of Strength items in ELECTRE TRI model for the Qarasoo River.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$S_{ri}1$	47	39	38	46	33	C3	0.040 – 0.080	0.065
$S_{ri}2$	65	58	75	64	54	C2	0.080 – 0.200	0.180
$S_{ri}3$	14	1	4	2	11	C5	0.010 – 0.020	0.015
$S_{ri}4$	24	22	25	10	13	C4	0.020 – 0.040	0.031
$S_{ri}5$	92	88	99	90	69	C1	≥ 0.200	0.220

Table 18
Performance matrix of Weakness items in ELECTRE TRI model for the Qarasoo River.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$W_{ri}1$	90	85	100	91	69	C1	≥ 0.200	0.200
$W_{ri}2$	29	21	33	24	7	C4	0.020 – 0.040	0.025
$W_{ri}3$	42	47	39	50	34	C3	0.040 – 0.080	0.051
$W_{ri}4$	75	53	66	74	53	C2	0.080 – 0.200	0.190
$W_{ri}5$	2	2	12	2	3	C5	0.010 – 0.020	0.014
$W_{ri}6$	8	9	4	11	2	C5	0.010 – 0.020	0.019

Table 19
Performance matrix of Opportunity items in ELECTRE TRI model for the Qarasoo River.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$O_{ri}1$	52	39	57	44	29	C3	0.040 – 0.080	0.041
$O_{ri}2$	89	84	95	93	69	C1	≥ 0.200	0.220
$O_{ri}3$	4	11	2	9	2	C5	0.010 – 0.020	0.015
$O_{ri}4$	8	6	4	2	7	C5	0.010 – 0.020	0.011
$O_{ri}5$	76	70	65	64	56	C2	0.080 – 0.200	0.190

Table 20
Performance matrix of Threat items in ELECTRE TRI model for the Qarasoo River.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$T_{ri}1$	3	4	3	8	2	C5	0.010 – 0.020	0.015
$T_{ri}2$	89	86	89	91	71	C1	≥ 0.200	0.200
$T_{ri}3$	42	38	55	45	30	C3	0.040 – 0.080	0.072
$T_{ri}4$	73	66	70	80	55	C2	0.080 – 0.200	0.130
$T_{ri}5$	33	17	17	10	18	C4	0.020 – 0.040	0.035
$T_{ri}6$	54	47	41	53	37	C3	0.040 – 0.080	0.071

Table 21
Performance matrix of Strength items in ELECTRE TRI model for WDN.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$S_{dn}1$	94	90	92	93	73	C1	≥ 0.200	0.230
$S_{dn}2$	57	46	43	43	41	C3	0.040 – 0.080	0.075
$S_{dn}3$	42	44	42	51	31	C3	0.040 – 0.080	0.055
$S_{dn}4$	33	19	33	11	18	C4	0.020 – 0.040	0.038
$S_{dn}5$	3	5	2	13	3	C5	0.010 – 0.020	0.019
$S_{dn}6$	21	32	27	16	13	C4	0.020 – 0.040	0.038

from each unit and adjusting their weighted importance based on the relative significance of that unit within the refinery's operational framework.

Accordingly, the normalized score of each selected factor is

Table 22
Performance matrix of Weakness items in ELECTRE TRI model for WDN.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$W_{dn}1$	75	68	66	58	53	C2	0.080 – 0.200	0.110
$W_{dn}2$	42	43	57	39	34	C3	0.040 – 0.080	0.045

Table 23
Performance matrix of Opportunity items in ELECTRE TRI model for WDN.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$O_{dn}1$	96	84	99	94	79	C1	≥ 0.200	0.200
$O_{dn}2$	42	37	46	53	34	C3	0.040 – 0.080	0.060
$O_{dn}3$	79	61	80	58	58	C2	0.080 – 0.200	0.110

Table 24
Performance matrix of Threat items in ELECTRE TRI model for WDN.

Performance matrix						Weight determination process		
Alternatives	g_1	g_2	g_3	g_4	g_5	class	Range of weights	Proposed weight
$T_{dn}1$	91	86	97	90	70	C1	≥ 0.200	0.210
$T_{dn}2$	77	58	69	77	62	C2	0.080 – 0.200	0.120
$T_{dn}3$	46	48	41	50	38	C3	0.040 – 0.080	0.065

Table 25
Aggregate matrix of pairwise comparisons for the main criteria for the determination of global weight.

Main criteria	f	g	h
f	1.000	1.313	1.615
g	0.762	1.000	1.231
h	0.619	0.813	1.000

Table 26
Decision criteria and their AHP-derived weights for the determination of global weight.

No.	Criterion code	Weight
1	f	0.42
2	g	0.32
3	h	0.26
Total	—	1.00

multiplied by the global weight assigned to the corresponding unit—weights that were previously derived through the AHP method. This procedure ensures that the influence of each factor is proportionally scaled to reflect the operational importance of its source. The resulting weighted factors are then transferred to the final consolidated IFEM and EFEM matrices. Table 26 presents the global AHP-derived weights of the three main water supply units. Based on these weights, the integrated internal and external factor matrices were constructed. Table 33 summarizes these final global IFEM and EFEM matrices, which collectively represent the comprehensive strategic evaluation of the refinery's water supply system.

The strategic position of the refinery water supply system was

Table 27
Weights of IFEM and EFEM matrix options from the ELECTRE TRI model for wells.

Strength	Weights	Weakness	Weights	Opportunity	Weights	Threat	Weights
$S_{we}1$	0.200	$W_{we}1$	0.220	$O_{we}1$	0.025	$T_{we}1$	0.090
$S_{we}2$	0.100	$W_{we}2$	0.090	$O_{we}2$	0.085	$T_{we}2$	0.010
$S_{we}3$	0.070	$W_{we}3$	0.050	$O_{we}3$	0.210	$T_{we}3$	0.200
$S_{we}4$	0.035	$W_{we}4$	0.025	$O_{we}4$	0.045	$T_{we}4$	0.045
$S_{we}5$	0.060	$W_{we}5$	0.010	---	---	$T_{we}5$	0.125
$S_{we}6$	0.050	$W_{we}6$	0.025	---	---	$T_{we}6$	0.025
$S_{we}7$	0.010	$W_{we}7$	0.025	---	---	$T_{we}7$	0.085
$S_{we}8$	0.030	---	---	---	---	$T_{we}8$	0.045
---	---	---	---	---	---	$T_{we}9$	0.010

Table 28
Weights of IFEM and EFEM matrix options from the ELECTRE TRI model for the Qarasoo River.

Strength	Weights	Weakness	Weights	Opportunity	Weights	Threat	Weights
$S_{ri}1$	0.065	$W_{ri}1$	0.200	$O_{ri}1$	0.041	$T_{ri}1$	0.015
$S_{ri}2$	0.180	$W_{ri}2$	0.025	$O_{ri}2$	0.220	$T_{ri}2$	0.200
$S_{ri}3$	0.015	$W_{ri}3$	0.051	$O_{ri}3$	0.015	$T_{ri}3$	0.072
$S_{ri}4$	0.031	$W_{ri}4$	0.190	$O_{ri}4$	0.011	$T_{ri}4$	0.130
$S_{ri}5$	0.220	$W_{ri}5$	0.014	$O_{ri}5$	0.190	$T_{ri}5$	0.035
---	---	$W_{ri}6$	0.019	---	---	$T_{ri}6$	0.071

Table 29
Weights of IFEM and EFEM matrix options from the ELECTRE TRI model for WDN.

Strength	Weights	Weakness	Weights	Opportunity	Weights	Threat	Weights
$S_{dn}1$	0.230	$W_{dn}1$	0.110	$O_{dn}1$	0.200	$T_{dn}1$	0.210
$S_{dn}2$	0.075	$W_{dn}2$	0.045	$O_{dn}2$	0.060	$T_{dn}2$	0.120
$S_{dn}3$	0.055	---	---	$O_{dn}3$	0.110	$T_{dn}3$	0.065
$S_{dn}4$	0.038	---	---	---	---	---	---
$S_{dn}5$	0.019	---	---	---	---	---	---
$S_{dn}6$	0.038	---	---	---	---	---	---

Table 30
IFEM and EFEM matrices for Wells.

IFEM analysis					EFEM analysis				
Key factor	MCDM Class	Weight	Score	Weighted score	Key factor	MCDM Class	Weight	Score	Weighted score
Strength					Opportunity				
$S_{we}1$	C1	0.200	5	1.000	$O_{we}1$	C4	0.025	2	0.050
$S_{we}2$	C2	0.100	4	0.400	$O_{we}2$	C2	0.085	4	0.340
$S_{we}3$	C3	0.070	3	0.210	$O_{we}3$	C1	0.210	5	1.050
$S_{we}4$	C4	0.035	2	0.070	$O_{we}4$	C3	0.045	3	0.135
$S_{we}5$	C3	0.060	4	0.240	---	---	---	---	---
$S_{we}6$	C3	0.050	4	0.200	---	---	---	---	---
$S_{we}7$	C5	0.010	1	0.010	---	---	---	---	---
$S_{we}8$	C4	0.030	2	0.060	---	---	---	---	---
Total				2.190	Total				1.575
Weakness					Threat				
$W_{we}1$	C1	0.220	5	1.100	$T_{we}1$	C2	0.090	4	0.360
$W_{we}2$	C2	0.090	4	0.360	$T_{we}2$	C5	0.010	1	0.010
$W_{we}3$	C3	0.050	3	0.150	$T_{we}3$	C1	0.200	5	1.000
$W_{we}4$	C4	0.025	2	0.050	$T_{we}4$	C3	0.045	3	0.135
$W_{we}5$	C5	0.010	1	0.010	$T_{we}5$	C2	0.125	5	0.625
$W_{we}6$	C4	0.025	2	0.050	$T_{we}6$	C4	0.025	2	0.050
$W_{we}7$	C4	0.025	2	0.050	$T_{we}7$	C2	0.085	4	0.340
---	---	---	---	---	$T_{we}8$	C3	0.045	3	0.135
---	---	---	---	---	$T_{we}9$	C5	0.010	1	0.010
Total				1.770	Total				2.665

determined using separate normalized internal and external coordinates derived from the global SWOT factor totals. In this approach, the internal coordinate ($X = (S - W) / (S + W)$) expresses the balance between Strengths and Weaknesses, whereas the external coordinate ($Y = (O - T) / (O + T)$) expresses the balance between Opportunities and Threats [43, 44]. Based on the revised global strategic-factor matrix, the total scores were $S = 1.429$, $W = 1.212$, $O = 1.528$, and $T = 1.794$. Therefore, the normalized coordinates were obtained as $X = 0.082$ and $Y = -0.080$. The positive value of X indicates that the aggregate Strength score is moderately higher than the aggregate Weakness score, whereas the negative value of Y indicates that Threats outweigh Opportunities. Accordingly, the strategic position of the refinery water supply system lies in the ST quadrant, representing a relatively stronger internal condition within a threat dominated external environment (Fig. 8).

The SWOT quadrant was used as a diagnostic characterization of the overall strategic environment. The quadrant analysis identifies the aggregate internal–external posture of the system, whereas the QSPM evaluates the relative attractiveness of individual implementable strategies against the complete set of identified Strengths, Weaknesses, Opportunities, and Threats [44,45]. Therefore, after reconstructing the complete SWOT matrix, candidate strategies were generated from all four combinations, including Strength–Opportunity, Strength–Threat, Weakness–Opportunity, and Weakness–Threat strategies.

Feasible strategies originating from different SWOT combinations

Table 31
IFEM and EFEM matrices for Qarasoo River.

IFEM analysis					EFEM analysis				
Key factor	MCDM Class	Weight	Score	Weighted score	Key factor	MCDM Class	Weight	Score	Weighted score
Strength					Opportunity				
$S_{ri}1$	C3	0.065	3	0.195	$O_{ri}1$	C3	0.041	3	0.123
$S_{ri}2$	C2	0.180	4	0.720	$O_{ri}2$	C1	0.220	5	1.100
$S_{ri}3$	C5	0.015	1	0.015	$O_{ri}3$	C5	0.015	1	0.015
$S_{ri}4$	C4	0.031	2	0.062	$O_{ri}4$	C5	0.011	1	0.011
$S_{ri}5$	C1	0.220	5	1.100	$O_{ri}5$	C2	0.190	4	0.760
Total				2.092	Total				2.009
Weakness					Threat				
$W_{ri}1$	C1	0.200	5	1.000	$T_{ri}1$	C5	0.015	1	0.015
$W_{ri}2$	C4	0.025	2	0.050	$T_{ri}2$	C1	0.200	5	1.000
$W_{ri}3$	C3	0.051	3	0.153	$T_{ri}3$	C3	0.072	3	0.216
$W_{ri}4$	C2	0.190	4	0.760	$T_{ri}4$	C2	0.130	2	0.260
$W_{ri}5$	C5	0.014	1	0.014	$T_{ri}5$	C4	0.035	2	0.070
$W_{ri}6$	C5	0.019	1	0.019	$T_{ri}6$	C3	0.071	3	0.213
Total				1.996	Total				1.774

Table 32
IFEM and EFEM matrices for WDN.

IFEM analysis					EFEM analysis				
Key factor	MCDM Class	Weight	Score	Weighted score	Key factor	MCDM Class	Weight	Score	Weighted score
Strength					Opportunity				
$S_{dn}1$	C1	0.230	5	1.150	$O_{dn}1$	C1	0.200	5	1.000
$S_{dn}2$	C3	0.075	3	0.225	$O_{dn}2$	C3	0.060	3	0.180
$S_{dn}3$	C3	0.055	3	0.165	$O_{dn}3$	C2	0.110	4	0.440
$S_{dn}4$	C4	0.038	2	0.076	---	---	---	---	---
$S_{dn}5$	C5	0.019	1	0.019	---	---	---	---	---
$S_{dn}6$	C4	0.038	2	0.076	---	---	---	---	---
Total				1.711	Total				1.620
Weakness					Threat				
$W_{dn}1$	C2	0.110	4	0.440	$T_{dn}1$	C1	0.210	5	1.050
$W_{dn}2$	C3	0.045	3	0.135	$T_{dn}2$	C2	0.120	4	0.480
---	---	---	---	---	$T_{dn}3$	C3	0.065	3	0.195
Total				0.575	Total				1.725

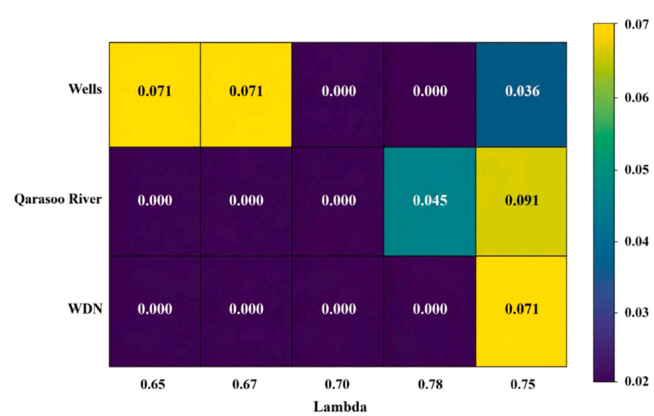

Fig. 7. Sensitivity analysis of ELECTRE TRI classification results under different λ (lambda) values for IFEM and EFEM matrices of wells, Qarasoo River, and WDN.

were retained for quantitative comparison. These retained strategies included ST1, ST2, WO1, WO2 and WT1 (Table 34). The WO1 strategy consists of constructing a conventional filtration system on the Qarasoo River to compensate for the decrease in flow rate and the drop in the well water level. The WO2 strategy was reformulated as a risk-adjusted long-term water-supply agreement with the regional water authority, incorporating a guaranteed minimum allocation, emergency-supply provisions, strategic storage, and backup-source integration to compensate for declining well discharge and groundwater levels. This revised formulation explicitly incorporates the risks associated with possible municipal-supply interruption and restrictive industrial-water policies.

Following reconstruction of the complete SWOT matrix, five feasible candidate strategies originating from the ST, WO, and WT combinations were retained for quantitative evaluation. Each strategy was formulated through the direct matching of one internal factor with one external factor, consistent with the conventional SWOT strategy-generation structure. The retained alternatives are presented in Table 23 and were subsequently evaluated using the newly administered QSPM.

In the final stage, the retained strategies were evaluated using a newly administered QSPM. Each expert independently assessed the relative attractiveness of every retained strategy against all internal and

Table 33
The global IFEM and EFEM for the water supply system of KOR.

IFEM analysis				EFEM analysis			
Key factor	Weighted score	Global Weight	Global score	Key factor	Weighted score	Global Weight	Global score
Strength				Opportunity			
$S_{we}1$	1.000	0.420	0.420	$O_{we}2$	0.340	0.420	0.143
$S_{we}2$	0.400	0.420	0.168	$O_{we}3$	1.050	0.420	0.441
$S_{ri}5$	1.100	0.260	0.286	$O_{ri}2$	1.100	0.260	0.286
$S_{ri}2$	0.720	0.260	0.187	$O_{ri}5$	0.760	0.260	0.198
$S_{dn}1$	1.150	0.320	0.368	$O_{dn}1$	1.000	0.320	0.320
---	---	---	---	$O_{dn}3$	0.440	0.320	0.141
Total			1.429	Total			1.528
Weakness				Threat			
$W_{we}1$	1.100	0.420	0.462	$T_{we}1$	0.360	0.420	0.151
$W_{we}2$	0.360	0.420	0.151	$T_{we}3$	1.000	0.420	0.420
$W_{ri}1$	1.000	0.260	0.260	$T_{we}5$	0.625	0.420	0.263
$W_{ri}4$	0.760	0.260	0.198	$T_{we}7$	0.340	0.420	0.143
$W_{dn}1$	0.440	0.320	0.141	$T_{ri}2$	1.000	0.260	0.260
---	---	---	---	$T_{ri}4$	0.260	0.260	0.068
---	---	---	---	$T_{dn}1$	1.050	0.320	0.336
---	---	---	---	$T_{dn}2$	0.480	0.320	0.154
Total			1.212	Total			1.794
	Total global score		2.641		Total global score		3.322

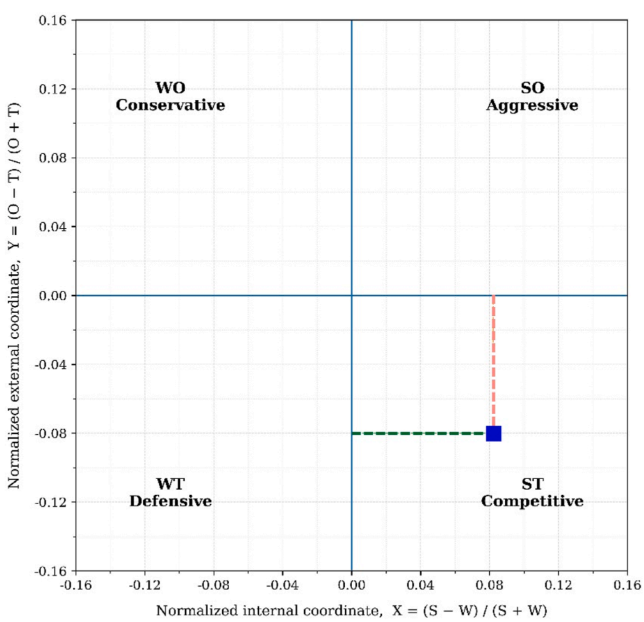

Fig. 8. Strategic position of the refinery water supply system based on normalized internal and external SWOT coordinates.

external strategic factors using the standard four-point attractiveness scale [4]. The individual evaluations were aggregated using the arithmetic mean, and the TAS and STAS values were recalculated from the beginning. The final preferred strategy was therefore determined through alternative-specific quantitative evaluation rather than solely from the aggregate quadrant label.

3.4. Determination of top strategy using the QSPM

Table 35 presents the QSPM used to evaluate the key internal and external factors influencing the water supply resources of the KOR. In this matrix, the weight of each key factor—previously determined through the SWOT, AHP, IFEM, and EFEM analyses—is first incorporated into the corresponding column. Subsequently, the AS for each factor under each strategic alternative is assigned independently based on the collective judgment of experts and specialists. The AS value reflects the degree to which a given strategy is capable of addressing, mitigating, or leveraging a specific factor. Next, the AS is multiplied by the weight assigned to the same factor, generating a quantitative indicator known as the TAS. This value illustrates the relative influence of each factor on the selection of a particular strategic alternative and provides a basis for meaningful comparison across strategies.

Finally, by summing the TAS values of all internal and external factors for each strategy, an overall score is produced. This cumulative value—referred to as the strategic priority or attractiveness index—serves as the principal criterion for ranking the strategic alternatives. Strategies that achieve the highest TAS are considered the most favorable options for implementation and resource allocation.

Through this structured process, the QSPM transforms the selection of strategic alternatives from a subjective and judgment-based activity into a transparent, data-driven, and quantitatively grounded MCDM procedure, thereby offering a scientifically defensible foundation for sustainable water resource management at the refinery.

The results of the revised QSPM analysis show that WO2 is the highest-ranked strategy, with a Sum Total Attractiveness Score (STAS) of 13.174. It is followed by ST1 with 12.290, WO1 with 10.738, WT1 with 10.085, and ST2 with 9.245. The difference of 0.884 between WO2 and ST1 indicates a clear, although not excessive, preference for WO2. This ranking is methodologically important because ST1, which directly reflects the ST-dominant strategic posture identified through the normalized SWOT coordinates, achieved the second-highest score. Therefore, the QSPM results remain consistent with the aggregate ST position while showing that WO2 provides the most attractive strategy at the individual alternative level. The superiority of WO2 is consequently not based on the quadrant label alone, but on its more balanced response to the complete set of internal and external strategic factors.

The distribution of the QSPM contributions across the four SWOT dimensions further clarifies the basis of this result. For WO2, the strength, weakness, opportunity, and threat components contributed 3.933, 3.029, 3.787, and 2.425, respectively, producing the final STAS of 13.174. In contrast, ST1 obtained its strongest contribution from the threat dimension, with a subtotal of 5.224, which explains its close alignment with the ST-dominant strategic position and its second-place

Table 34
Retained SWOT candidate strategies for QSPM evaluation.

Strategy		Description
ST1	$S_{we}1–T_{we}5$	Preserving part of the current excess well supply capacity as a controlled emergency reserve to maintain refinery water supply during consecutive drought periods.
ST2	$S_{dn}1–T_{dn}2$	Implementing a quality based allocation protocol that reserves high quality municipal water for essential refinery units during crisis-related restrictions on industrial withdrawals from the municipal network.
WO1	$W_{we}1$- $O_{ri}2$	Construction of a conventional filtration system on the Qarasoo River to compensate for the decrease in flow rate and the drop in the well water level.
WO2	$W_{we}1$- $O_{dn}1$	Establishing a risk-adjusted long-term water-supply agreement with the Regional Water Authority and the municipal water utility, incorporating a guaranteed minimum allocation, emergency-supply provisions, strategic storage, and backup-source integration to compensate for declining well discharge and groundwater levels.
WT1	$W_{dn}2–T_{dn}1$	Implementing an emergency demand-management and critical use prioritization program to reduce the operational consequences of limited municipal supply volume and the risk of water supply interruption.

Table 35
QSPM matrix for quantitative comparison of strategies.

Key Factor Description	Key factor	Global Score	ST1		ST2		WO1		WO2		WT1	
			AS	TAS	AS	TAS	AS	TAS	AS	TAS	AS	TAS
Water Supply Exceeding the Refinery's Water Demand	$S_{we}1$	0.420	4	1.680	1	0.420	1	0.420	1	0.420	1	0.420
Ease of Operation and On-site Implementation at the Refinery	$S_{we}2$	0.168	3	0.504	2	0.336	3	0.504	2	0.336	3	0.504
Low Water Hardness	$S_{ri}5$	0.286	1	0.286	0	0.000	2	0.572	4	1.144	0	0.000
Easy Accessibility Given the Proximity of the River and the Refinery	$S_{ri}2$	0.187	0	0.000	0	0.000	4	0.748	3	0.561	0	0.000
High Quality	$S_{dn}1$	0.368	0	0.000	4	1.472	2	0.736	4	1.472	2	0.736
Reduced Discharge, Declining Water Levels, and Risk of Well Depletion	$W_{we}1$	0.462	3	1.386	1	0.462	3	1.386	4	1.848	2	0.924
Quality Deterioration Due to High Well Water Hardness in Recent Years	$W_{we}2$	0.151	0	0.000	2	0.302	0	0.000	0	0.000	0	0.000
Need for Treatment and Lack of Adequate Treatment Facilities	$W_{ri}1$	0.260	0	0.000	0	0.000	1	0.260	4	1.040	0	0.000
Fluctuations in River Water Discharge	$W_{ri}4$	0.198	2	0.396	0	0.000	1	0.198	0	0.000	1	0.198
Extremely High Cost of Potable Water for Industrial Use	$W_{dn}1$	0.141	3	0.423	3	0.423	4	0.564	1	0.141	4	0.564
Potential for Use in Other Refinery Units, Including Firefighting, etc.	$O_{we}2$	0.143	3	0.429	3	0.429	1	0.143	1	0.143	2	0.286
Potential for Combined Utilization with Other Sources	$O_{we}3$	0.441	4	1.764	2	0.882	3	1.323	3	1.323	2	0.882
Feasibility of Constructing Conventional Filtration Treatment Systems	$O_{ri}2$	0.286	0	0.000	0	0.000	1	0.286	4	1.144	0	0.000
Reduced Dependency on Wells and Enhanced Passive Defense Capability	$O_{ri}5$	0.198	1	0.198	1	0.198	2	0.396	2	0.396	2	0.396
Possibility of Long-Term Contracts with Regional Water Company	$O_{dn}1$	0.320	0	0.000	2	0.640	1	0.320	2	0.640	1	0.320
Feasibility of Piping from the Municipal Network to All Refinery Units	$O_{dn}3$	0.141	0	0.000	4	0.564	0	0.000	1	0.141	2	0.282
Risk of Contamination Due to Tank Leakage and Pipeline Ruptures	$T_{we}1$	0.151	0	0.000	1	0.151	0	0.000	0	0.000	0	0.000
Declining Groundwater Levels in Wells and Surrounding Aquifers	$T_{we}3$	0.420	4	1.680	1	0.420	0	0.000	0	0.000	2	0.840
Occurrence of Repeated Droughts	$T_{we}5$	0.263	4	1.052	2	0.526	2	0.526	3	0.789	3	0.789
Risk of Accidents in the Chlorination Unit	$T_{we}7$	0.143	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
Incidence of Prolonged Droughts	$T_{ri}2$	0.260	4	1.040	1	0.260	1	0.260	2	0.520	3	0.780
Existence of Legal and Environmental Restrictions	$T_{ri}4$	0.068	2	0.136	2	0.136	2	0.136	2	0.136	3	0.204
Risk of Water Cutoff Due to Prioritization of Potable Water	$T_{dn}1$	0.336	3	1.008	3	1.008	4	1.344	2	0.672	4	1.344
Restrictive Policies on Industrial Use of WDN Water During Crises	$T_{dn}2$	0.154	2	0.308	4	0.616	4	0.616	2	0.308	4	0.616
STAS				12.290		9.245		10.738		13.174		10.085
Strategic Priority				2		5		3		1		4

ranking. WO2 did not receive the highest threat-related score; instead, its final superiority resulted from relatively strong and balanced performance across strengths, weaknesses, and opportunities, together with a moderate ability to manage the principal threats. This pattern supports the distinction between the overall strategic posture and the alternative-specific prioritization performed through the QSPM.

Regarding strengths, the effectiveness of WO2 is primarily reinforced by Sdn1, Sri5, and Sri2. Sdn1, representing the high quality of municipal-network water, received an attractiveness score of 4 and contributed 1.472 to the WO2 total. This factor directly supports the operational reliability of a long-term supply agreement because it reduces the need for extensive pretreatment before the supplied water is used in refinery units. Sri5, referring to the low hardness of river water, also received an attractiveness score of 4 and contributed 1.144. Its importance is related to the backup-source integration incorporated into the revised WO2 package, because lower-hardness supplementary water can improve source substitution and operational flexibility. Sri2, representing the easy accessibility of the Qarasoo River because of its proximity to the refinery, received an attractiveness score of 3 and contributed 0.561. Swe2 made a moderate contribution of 0.336, whereas Swe1 received a lower attractiveness score because the existing excess well capacity is not the principal basis of WO2. Accordingly, WO2 benefits mainly from the quality, accessibility, and substitutability of available water sources rather than from continued reliance on groundwater capacity.

Among the weaknesses, Wwe1 and Wri1 are the principal factors supporting WO2. Wwe1, describing reduced well discharge, declining groundwater levels, and the risk of well depletion, received the maximum attractiveness score of 4 and contributed 1.848, which is the largest individual contribution to WO2. This result is consistent with the main purpose of the strategy, namely, reducing the operational vulnerability created by the long-term deterioration of groundwater availability. Wri1, representing the need for treatment and the lack of adequate treatment facilities, also received an attractiveness score of 4 and contributed 1.040. The revised WO2 strategy addresses this limitation through its combination of guaranteed external supply, emergency provisions, strategic storage, and backup-source integration. By contrast, Wdn1 received a score of 1, indicating that the extremely high cost of potable water for industrial use remains a limitation of the strategy rather than a factor fully resolved by it. Wwe2 and Wri4 were not assigned attractiveness scores because deterioration in well-water hardness and fluctuations in river discharge are not directly corrected by the contractual component of WO2. This differentiated scoring demonstrates that the strategy was not uniformly assigned high values and that its limitations were explicitly retained in the analysis.

Regarding opportunities, WO2 achieved a subtotal of 3.787. The largest opportunity-related contributions were associated with Owe3 and Ori2. Owe3, representing the potential for combined utilization of multiple water sources, received an attractiveness score of 3 and contributed 1.323. This factor is highly relevant because the revised WO2 is not defined as unconditional dependence on municipal water; instead, it incorporates the municipal network within a broader risk-adjusted supply arrangement that includes strategic storage and backup-source integration. Ori2, referring to the feasibility of constructing a conventional filtration-treatment system, received an attractiveness score of 4 and contributed 1.144. This opportunity strengthens the backup component of WO2 by making treated river water a technically feasible substitute when the contracted municipal allocation is insufficient or temporarily restricted. Odn1, the possibility of entering into a long-term agreement with the Regional Water Authority, contributed 0.640 with an attractiveness score of 2. Although this opportunity constitutes the contractual basis of WO2, its score was kept moderate because the effectiveness of such an agreement depends on enforceable allocation conditions, emergency provisions, and institutional acceptance. Ori5 contributed 0.396, while Owe2 and Odn3 made smaller contributions, indicating that these opportunities support the strategy but are not its primary determinants.

In relation to threats, WO2 obtained a subtotal of 2.425, lower than the corresponding threat subtotal of ST1. This finding is consistent with the ST-dominant strategic posture, because ST1 was specifically designed to use existing strengths to confront the principal external threats and therefore received high attractiveness scores for declining groundwater levels, repeated droughts, prolonged dry periods, and supply interruptions. Nevertheless, WO2 still demonstrates a meaningful capacity to manage the most relevant threats. Twe5, representing repeated droughts, received an attractiveness score of 3 and contributed 0.789, while Tri2, representing prolonged dry periods, received a score of 2 and contributed 0.520. Most importantly, Tdn1 and Tdn2 were directly incorporated into the revised evaluation and were no longer assigned zero attractiveness scores. Both received an attractiveness score of 2, contributing 0.672 and 0.308, respectively. These moderate scores indicate that the guaranteed minimum allocation, emergency-supply provisions, strategic storage, and backup-source integration can partially mitigate the risks of municipal-water cutoff and restrictive industrial-water policies, but cannot eliminate them completely. This treatment explicitly reflects the institutional vulnerability of WO2 rather than excluding adverse factors from the QSPM.

Taken together, the revised results show that WO2 provides the most balanced strategic response across the complete SWOT structure. Its first-place ranking is primarily driven by its strong capacity to address declining well performance, utilize high-quality and technically accessible alternative sources, and exploit opportunities for combined and contract-based supply arrangements. At the same time, the second-place ranking of ST1 confirms that threat-oriented strategies remain highly relevant under the identified ST-dominant strategic posture. WO2 therefore does not replace or invalidate the ST diagnosis; instead, it emerges as the most attractive implementable alternative because it combines contractual security, source diversification, emergency provisions, strategic storage, and backup-source integration within a single risk adjusted framework. Consequently, WO2 is identified as the preferred strategy for long-term refinery water supply planning, while ST1 represents the most important complementary strategy for strengthening resilience against drought, groundwater decline, and supply interruption.

3.5. Discussion on strategic prospective scenarios

3.5.1. Definition of future scenarios

Drawing on the observed hydrological conditions of the Kermanshah region, trends in climate variability, operational patterns of the refinery, and the threats and opportunities identified through the SWOT and ELECTRE–TRI analyses, three forward-looking scenarios can be developed to characterize the potential futures of the refinery's water supply system. These scenarios integrate key factors such as recurring droughts, river flow instability, groundwater depletion risks, rising municipal water costs, regulatory pressures, and positive developments such as opportunities for long-term contracts, hybrid sourcing, or conventional filtration upgrades.

1) Stable Conditions with Moderate Improvement (Optimistic/Low-Risk): In this scenario, climatic stressors remain moderate, and no severe decline occurs in groundwater tables or river flow. The Qarasoo River continues to provide a reliable, though seasonal, supply; the groundwater wells remain functional; and opportunities for institutional cooperation—such as long-term water agreements—gradually improve.
2) Moderate Stress and Manageable Instability (Middle/Realistic Scenario): Here, recurring droughts become more frequent, groundwater levels show a gradual decline, and river discharge becomes highly variable. The WDN faces rising tariffs and increasing regulatory constraints. Despite these pressures, the system remains manageable through adaptive multi-source planning. Advantages

such as high-quality municipal water (Sdn1) remain valuable complements, while collaborative opportunities (Owe2, Odn3) may expand as water authorities seek joint solutions.

3) Severe Stress and Structural Constraints (Pessimistic/Crisis Scenario): Under this scenario, intense and recurrent droughts, sharp groundwater drawdown, and periodic exhaustion of well capacity (Wwe1) pose critical risks. River flow becomes unreliable, with episodes of sedimentation and pollution (Wri2, Tri3), while municipal water withdrawals face strict regulatory restrictions (Tdn1, Tdn2) and unaffordable costs (Wdn1). Simultaneously, operational threats-such as contamination from pipeline failures (Twe1) and risks in chlorination operations (Twe7)-intensify. This scenario reflects a high-uncertainty, high-cost environment that demands strategic redesign of the refinery's water sourcing structure, reducing dependence on single sources and reinforcing hybrid and contingency schemes.

3.5.2. Performance assessment of the selected strategy

Following the development of the three prospective scenarios, the performance of the highest ranked WO2 strategy was assessed under different levels of future water stress. This assessment does not represent a separate QSPM ranking for each scenario, rather, it examines how the feasibility and implementation requirements of WO2 may change under increasingly restrictive conditions. The complementary roles of ST1 and WO1 were also considered. Under the relative resource stability scenario, WO2 remains strategically useful, although its immediate urgency is limited. The refinery can focus on preliminary contractual arrangements, identification of minimum guaranteed allocations, planning of strategic storage, and preparation for backup source integration. At the same time, ST1 can be initiated by preserving part of the well capacity as an emergency reserve, while the technical feasibility of WO1 can be evaluated.

Under moderate water stress, WO2 becomes more advantageous because it supports structured use of contracted supplies, strategic storage, and alternative sources. Opportunities such as combined use of multiple sources, reduced dependence on wells, and long-term supply agreements strengthen its applicability. Its performance can be further improved through ST1 and, where river flow and treatment feasibility are adequate, through gradual implementation of WO1. Under a severe water crisis, WO2 remains the most comprehensive strategic framework, but its effectiveness is conditional. The nonzero but moderate attractiveness scores assigned to Tdn1 and Tdn2 indicate that emergency provisions, guaranteed minimum allocation, storage, and backup integration can reduce the effects of municipal supply restrictions but cannot eliminate them completely. In this condition, ST1 becomes particularly important by preserving limited emergency groundwater capacity, while WT1 can support continuity through critical use prioritization and demand management. Therefore, WO2 provides the most robust long-term pathway, provided that it is implemented within a coordinated multi-source and contingency management system.

3.5.3. Potential impacts on refinery performance

The impacts of the three prospective scenarios on refinery performance can be evaluated through their operational, economic, and strategic consequences. The revised QSPM results identify WO2 as the preferred long-term strategy, ST1 as the principal complementary resilience strategy, and WO1 as a conditional infrastructure option.

Under relative resource stability, refinery operations are expected to continue with limited disruption. The main benefits of WO2 are improved preparedness, contractual security, storage planning, and backup source readiness. Preserving part of the well capacity through ST1 can also reduce excessive pressure on groundwater resources. Under moderate water stress, WO2 can improve operational flexibility by enabling water allocation among contracted supplies, stored water, wells, and potentially treated river water. This reduces dependence on any single source and lowers the risk of unplanned interruptions. However, implementation may involve additional costs for storage, monitoring, treatment, and source integration.

Under a severe crisis, simultaneous pressure on groundwater, river flow, and municipal supply may increase treatment costs and the risk of production curtailment. WO2 can mitigate these effects through emergency allocation, strategic storage, and backup integration, but residual risks associated with Tdn1 and Tdn2 remain. In this condition, ST1, WT1, and selected elements of ST2 become more important for emergency supply, demand prioritization, and protection of critical refinery units. Overall, the revised strategic package improves refinery resilience by reducing single source dependency and strengthening emergency preparedness. WO2 remains the preferred strategy, while the importance of complementary strategies increases as environmental and institutional constraints become more severe.

3.5.4. Operational roadmap for the various term horizons

Drawing upon the results of the QSPM, the ST-dominant strategic posture identified through the normalized SWOT coordinates, and the relative performance of the evaluated alternatives, an integrated operational roadmap can be formulated for short-, medium-, and long-term planning horizons. The roadmap is centered on WO2 as the highest-ranked strategy (STAS = 13.174), while ST1, with the second-highest score (STAS = 12.290), represents the principal complementary resilience strategy. WO1, ranked third (STAS = 10.738), is considered a supporting infrastructure option whose implementation depends on the technical and hydrological feasibility of treating and using Qarasoo River water. WT1 and ST2 provide additional contingency and demand-management measures but are not treated as the primary implementation pathways. Accordingly, the roadmap does not assign a different preferred strategy to each future scenario; rather, it adjusts the intensity, sequencing, and combination of actions according to the severity of water stress.

In the short term, the primary objective should be to establish immediate operational readiness and improve the refinery's capacity to detect and respond to abrupt changes in water availability and quality. Priority actions should include the installation or upgrading of real-time monitoring systems for well discharge, groundwater levels, river flow, source water quality, and municipal network reliability. These actions should be accompanied by integrated data management across wells, the Qarasoo River intake, and the municipal water network, as well as clearly defined emergency response protocols for water supply interruptions. At this stage, institutional preparations for WO2 should also begin through preliminary negotiations with the Regional Water Authority and the municipal water utility, identification of minimum critical water requirements, and assessment of feasible emergency allocation mechanisms. Simultaneously, a portion of the existing well supply capacity should be operationally designated as a controlled emergency reserve in accordance with ST1, rather than being continuously exploited at maximum capacity. These short term measures constitute low regret actions because they improve preparedness under both stable and stressed conditions without requiring immediate large scale infrastructure investment.

In the medium term, the strategic emphasis should shift from monitoring and preparedness toward risk adjusted source management and implementation of the main contractual and operational components of WO2. The refinery should seek to establish a long term water supply agreement incorporating a guaranteed minimum allocation, emergency supply provisions, clear allocation priorities, and operational arrangements for periods of regional water shortage. However, because the QSPM results show only moderate attractiveness of WO2 in relation to Tdn1 and Tdn2, the agreement should not be treated as an unconditional guarantee against municipal water interruption or restrictive industrial water policies. It should instead be supported by strategic storage, predefined demand reduction procedures, and backup source integration. During this horizon, ST1 should be implemented more systematically by maintaining selected well capacity for emergency use, optimizing groundwater abstraction patterns, and preventing excessive dependence on declining groundwater reserves. Technical and economic feasibility studies for WO1 should also be completed, including evaluation of river flow reliability, treatment requirements, treatment-plant capacity, seasonal water-quality variability, and the costs of integrating treated river water into the refinery's internal network.

In the long term, the objective should be to establish a diversified and structurally resilient water supply system capable of remaining operational under prolonged drought, declining groundwater availability, river flow variability, and institutional restrictions on municipal supply. Full implementation of the risk adjusted WO2 package should therefore include enforceable contractual arrangements, strategic water-storage capacity, emergency allocation procedures, and physical integration of backup sources. ST1 should remain an essential complementary component by preserving controlled groundwater reserves for periods in which contracted or surface water supplies are temporarily insufficient. Where river discharge and treatment feasibility are adequate, phased implementation of WO1 can further strengthen source diversification by providing treated river water as an additional supply option. The long term configuration should consequently be based on a hybrid architecture rather than dependence on a single source. Such an arrangement would reduce reliance on declining groundwater resources, limit vulnerability to municipal supply restrictions, and allow substitution among wells, treated river water, stored water, and contracted regional supplies according to operational conditions.

The practical emphasis of this roadmap should vary across the prospective scenarios without changing the overall QSPM ranking. Under relative resource stability, implementation should concentrate on monitoring, institutional preparation, controlled groundwater use, contract development, and technical planning for future treatment and storage infrastructure. Under moderate water stress, active implementation of WO2 and ST1 becomes more important, including use of contractual allocations, strategic storage, optimized well operation, and accelerated preparation of the WO1 treatment option. Under a severe water crisis, emergency provisions within WO2, stored water reserves, critical-use prioritization, and the controlled emergency capacity retained through ST1 should be activated simultaneously. Nevertheless, the risks represented by Tdn1 and Tdn2 cannot be considered fully eliminated, because municipal-water prioritization and restrictive industrial-use policies may still limit contracted supply. Similarly, the contribution of WO1 under severe crisis conditions would depend on the continued availability of sufficient river flow and operable treatment facilities.

Collectively, this three-tiered roadmap is consistent with both the revised QSPM ranking and the ST-dominant strategic posture of the refinery's water-supply system. WO2 provides the principal long-term implementation framework because it combines contractual security, strategic storage, emergency provisions, and backup source integration. ST1 strengthens this framework by directly addressing drought, groundwater decline, and supply disruption through controlled preservation of well capacity, while WO1 offers a technically valuable supporting option where river water availability and treatment feasibility are confirmed. The resulting roadmap therefore provides a phased and adaptable pathway for improving water security at KOR while avoiding excessive reliance on any single water source and maintaining operational continuity under increasing environmental and institutional uncertainty.

3.6. Quantitative analysis of prospective strategies

For the refinery's water supply system, it is essential to develop a set of quantitative indicators capable of capturing the underlying dynamics of environmental pressure, opportunity reconfiguration, and operational performance shifts across different future conditions. These indicators serve as analytical tools that translate qualitative trends—such as hydrological stress, regulatory tightening, or technological potential—into measurable values that can be systematically compared across scenarios.

Within this framework, three new key indices are introduced. The ESC reflects the relative intensity of external stressors acting on the water supply system and indicates how vulnerable or exposed the refinery may become under each scenario. The OLI quantifies the degree to which emergent opportunities—technological, institutional, or infrastructural—remain available or can be leveraged as system conditions evolve. Finally, the SPG provides a numerical representation of the widening or narrowing gap between the system's current performance and the performance level required for long-term resilience.

Together, these indicators form the analytical backbone for comparing future scenarios and evaluating the strategic adaptability of preferred options such as WO2. By translating complex environmental and operational uncertainties into comparable numerical scales, they enhance the rigor, interpretability, and policy relevance of the scenario-based strategic analysis.

Let i index the SWOT factors with AHP-derived weights w_i ($\Sigma\, w_i = 1$). For each scenario, let x_i(s) $\in [0,1]$ denote the normalized performance of factor i under scenario s. Let S, W, O, T be the sets of strengths, weaknesses, opportunities, and threats, respectively.

1. Environmental Stress Coefficient (ESC): This coefficient represents the intensity of external environmental stresses affecting the refinery's water supply system. It incorporates factors such as drought frequency, groundwater decline, legal constraints, inter-sectoral competition for water, and river flow fluctuations. Higher values indicate stronger external stress and reduced reliability of the water sources.

$$ESC = \frac{\sum_{i=1}^{n}\left[\left(W_{T,\ i} \times N_i\right)\ \times\ AS_i\right]}{\sum_{i=1}^{n} W_{\ i}} \tag{10}$$

where $W_{T,i}$ is the weight assigned to the threat in the EFEM matrix, Ni is the normalized environmental stress variable under the corresponding scenario, AS_i is the threat attractiveness score in QSPM for strategies, and W_i is the weight assigned to the EFEM matrix. This index can be either relative or standardized. When a "relative coefficient" is used, its value may be greater than 1, meaning that the pressure has increased relative to the baseline value. However, in the standardized version, for quantitative comparisons between scenarios, all values are normalized to a range of 0 to 1 to allow for direct comparison. The higher values indicate greater hydro-environmental stress.

2. Opportunity Leverage Index (OLI): This index measures the potential of each scenario to support opportunity driven strategies — particularly WO-type strategies aimed at leveraging external opportunities to compensate for internal weaknesses. Higher values indicate that the scenario provides more strategic flexibility, greater potential for synergy between sources, and better conditions for implementing opportunity based management.

$$OLI = \frac{\sum_{i=1}^{n}\left[\left(W_{O,\ i}/N_i\right)\ \times TAS_O\right]}{\sum_{i=1}^{n} W_{\ i}} \tag{11}$$

where $W_{O,i}$ is the weight assigned to the opportunities in the EFEM matrix, Ni is the normalized opportunities variable under the corresponding scenario and TAS_O is the total attractiveness score for opportunities in QSPM for strategies. Scenarios that, due to environmental or infrastructure conditions, enable better utilization of complementary resources or the development of sustainable solutions receive a higher score. This index is defined for comparison of scenarios in the standard range of 0 to 1. The higher values must be normalized indicate a stronger ability to exploit external opportunities.

3. Strategic Performance Gap (SPG): The performance gap expresses the distance between the refinery's existing water-supply performance level and the desired optimal condition for sustainable, resilient operations. Higher values signal larger deficits in reliability, cost efficiency, operational resilience, and risk exposure. These values are derived from a normalized comparison of weighted QSPM outputs, IFEM–EFEM matrices, and expert scoring.

$$SPG = \frac{\sum_{i=1}^{n}[(W_i \times N_i) \times (4 - AS_i)]}{\sum_{i=1}^{n} W_i} \quad (12)$$

where W_i is the weight assigned to all factors in the IFEM and EFEM, Ni is the normalized strategic performance variable under the corresponding scenario and AS_i is the attractiveness score in QSPM for all factors. This index shows how much of a gap each scenario creates between the current situation and the desired situation. The higher this value, the more challenging the scenario is for water resources management and requires stronger interventions. This index is also normalized to a range of 0 to 1 for proper comparison between scenarios. The larger values indicate a wider gap between current and desired performance.

To further clarify the computational procedure associated with the investigated indicators, Table 36 provides the normalized scenario inputs together with the corresponding scenario weighting coefficients (Ni). As shown in the table, the obtained Ni coefficients for the high-risk, moderate-risk, and stable condition scenarios are equal to 0.96, 0.77, and 0.44, respectively.

The proposed scenario indicators were calculated using weighted normalized variables representing environmental, operational, and strategic conditions under different future scenarios. Three scenario states, including Stability Scenario, Moderate Stress Scenario, and High Stress Scenario, were considered to simulate varying levels of water-resource pressure and operational uncertainty. For each scenario, the corresponding input variables were first normalized to ensure comparability among heterogeneous criteria. The normalized variables were then aggregated using weighted composite relationships derived from expert based AHP weighting and scenario evaluation procedures.

3.6.1. Theoretical basis

The proposed scenario-based indicators, including the ESC, OLI, and SPG, are grounded in well-established theoretical concepts in water resource management and decision analysis. The ESC is conceptually linked to environmental stress and water scarcity indices, representing the relative intensity of external pressures on the system. It reflects the combined effects of hydrological variability, resource depletion, and external constraints. The OLI is derived from the concept of opportunity utilization efficiency, capturing the system's ability to leverage available external opportunities under varying conditions. The SPG is based on performance gap analysis frameworks, representing the deviation between the current system states and desired operational targets.

These indicators are adapted and reformulated to provide a simplified, interpretable, and scenario-sensitive representation of system behavior within the context of strategic decision-making for industrial water systems.

Internal consistency is ensured since all indicators are linear (or convex) aggregations of the same weight vector w_i derived from AHP (CR < 0.1). This guarantees coherence between factor importance and indicator outcomes. Considering convergence validation, scenarios with higher ESC and SPG and lower OLI correspond to higher TAS sensitivity and reinforce the selection of WO2 as the dominant strategy (Table 37). This alignment confirms that indicator trends are consistent with QSPM-based prioritization. Robustness was evaluated by perturbing x_i(s) within ±10% and λ (ELECTRE TRI) within [0.65, 0.75]. The resulting changes in ESC, OLI, and SPG remained monotonic and within narrow bounds, and did not alter the strategic ranking, confirming stability. The proposed indicators provide a theoretically grounded and quantitatively validated bridge between multi-criteria evaluation and scenario-based resilience assessment.

The conceptual formulation of ESC was informed by environmental stress assessment frameworks and global water-stress studies [16,17,1]. Similarly, OLI was developed based on operational resilience and industrial water-management concepts reported in recent decision-support studies [23,34,32]. The SPG indicator was theoretically associated with adaptive strategic management and resilience-oriented decision-analysis frameworks [37,33,40].

3.6.2. Outcome of analysis

Table 38 and Fig. 9 show the comparison between three distinct trajectories for the refinery's future water security. The proposed scenario indicators were calculated using weighted normalized variables representing environmental, operational, and strategic conditions under different future scenarios. Three scenario states, including Stability Scenario, Moderate Stress Scenario, and High Stress Scenario, were considered to simulate varying levels of water-resource pressure and operational uncertainty. For each scenario, the corresponding input variables were first normalized to ensure comparability among heterogeneous criteria. The normalized variables were then aggregated using weighted composite relationships derived from expert based AHP

Table 37
Validation of scenario-based indicators.

Test	Method	Result/Observation
Internal consistency	AHP weights (CR < 0.1)	Coherent aggregation
Convergence with QSPM	TAS vs. (ESC, OLI, SPG) trends	Consistent ranking
Sensitivity (±10% inputs)	Perturbation of x_i(s), λ	Stable, monotonic
Scenario coherence	Stability → High-stress progression	ESC↑, OLI↓, SPG↑

Table 36
Normalized scenario inputs and weighted calculation process.

Indicator Component	Weight Coefficient	High-Risk Scenario	Moderate Scenario	Stability Scenario	Weighted Scenario Coefficient		
					High-Risk Scenario	Moderate Scenario	Stability Scenario
	I	II	III	IV	I*II	I*III	I*IV
Water Supply Reliability	0.25	0.98	0.76	0.44	0.245	0.19	0.11
Operational Flexibility	0.2	0.96	0.68	0.39	0.192	0.136	0.078
Infrastructure Resilience	0.2	0.94	0.84	0.47	0.188	0.168	0.094
Policy Adaptability	0.15	0.93	0.76	0.38	0.139	0.114	0.057
Resource Diversification	0.2	0.97	0.8	0.49	0.194	0.16	0.098
			Total (=Ni)		0.958	0.768	0.437

Table 38
Comparison between three distinct trajectories for the refinery's future water security.

Scenario	ESC	SPG	OLI
Relative Resource Stability	0.20	0.26	0.94
Moderate Water Stress	0.35	0.46	0.54
Severe Water Crisis	0.43	0.57	0.43

weighting and scenario evaluation procedures.

The relative resource stability scenario exhibits the lowest environmental stress coefficient (ESC = 0.20), the lowest strategic performance gap (SPG = 0.26), and the highest opportunity leverage index (OLI = 0.94). These results indicate a comparatively favorable operating environment in which external pressures on the refinery's water supply system are limited, the gap between current and desired performance is relatively small, and the potential to exploit available opportunities is substantial. Such conditions are particularly supportive of opportunity oriented strategies, especially WO2, because they provide greater institutional and operational flexibility for establishing long-term supply agreements, integrating multiple water sources, developing strategic storage, and improving coordination among wells, the river intake, and the municipal network. Therefore, this scenario represents the most suitable condition for proactive and phased implementation of the preferred strategy before more severe water-stress conditions emerge.

3.6.3. Providing a reproducible calculations of scenario-based indices

To provide a reproducible quantitative assessment of the refinery's future water supply conditions, three complementary indicators were calculated for the relative resource stability, moderate water stress, and severe water crisis scenarios. The weighted scenario coefficients obtained in Table 36 were applied consistently in all three calculations. The corresponding normalized coefficients were 0.958 for the severe water crisis scenario, 0.768 for the moderate water stress scenario, and 0.437 for the relative resource stability scenario.

Table 39 presents the complete calculation pathway for the ESC. The threat weights $W_{T,i}$ were extracted from the global EFEM matrix, whereas the attractiveness scores were obtained from the final QSPM evaluation of WO2. For each threat, the intermediate contribution was calculated by multiplying the threat weight, the corresponding scenario coefficient, and the QSPM attractiveness score. The sum of these contributions was divided by the total threat weight of 1.795. As you will see below, given that the highest calculated value of the indices is 2.824 and belongs to the OLI, the resulting relative coefficient was subsequently divided by 3 to obtain a standardized value between 0 and 1 for scenario comparison. Tdn1 and Tdn2 factors represent, respectively, the risk of municipal water cutoff due to prioritization of potable demand and restrictive policies governing industrial use of municipal network water during crisis conditions. Their inclusion ensures that the ESC calculation reflects the residual institutional and supply risks associated with reliance on contracted regional or municipal water.

The ESC increases progressively from 0.20 under relative resource stability to 0.35 under moderate water stress and 0.43 under a severe water crisis. The comparatively low ESC in the stability scenario indicates limited external pressure and relatively reliable access to the

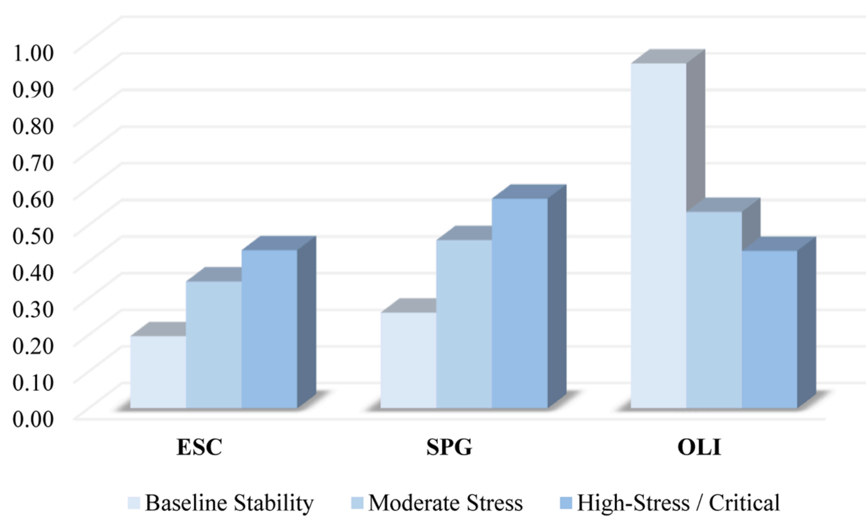

Fig. 9. Comparative visualization of ESC, OLI, and SPG across scenarios.

Table 39
Calculation of the ESC under the three prospective scenarios.

Ni						Σ [(Wti*Ni)*AS]/ Wi			Normalized ESC coefficients		
	$W_{t,i}$	High-Risk Scenario Coefficient	Moderate Scenario Coefficient	Stability Scenario Coefficient	AS	High-Risk Scenario	Moderate Scenario	Stability Scenario	High-Risk Scenario	Moderate Scenario	Stability Scenario
	I	II	III	IV	V	I*II*V	I*III*V	I*IV*V			
$T_{we}1$	0.151	0.96	0.77	0.44	0.00	0.000	0.000	0.000			
$T_{we}3$	0.420	0.96	0.77	0.44	0.00	0.000	0.000	0.000			
$T_{we}5$	0.263	0.96	0.77	0.44	3.00	0.756	0.606	0.345			
$T_{we}7$	0.143	0.96	0.77	0.44	0.00	0.000	0.000	0.000			
$T_{ri}2$	0.260	0.96	0.77	0.44	2.00	0.498	0.399	0.227	0.43	0.35	0.20
$T_{ri}4$	0.068	0.96	0.77	0.44	2.00	0.130	0.104	0.059			
$T_{dn}1$	0.336	0.96	0.77	0.44	2.00	0.644	0.516	0.294			
$T_{dn}2$	0.154	0.96	0.77	0.44	2.00	0.295	0.237	0.135			
Wi	1.795					1.294	1.038	0.590			

existing water sources. Under moderate stress, increasing drought exposure, declining source reliability, and institutional restrictions begin to exert a more noticeable influence on the system. In the severe scenario, repeated droughts, prolonged dry periods, regulatory constraints, and the risk of municipal-water interruption produce the highest level of environmental pressure.

The largest contributions to the ESC are associated with repeated droughts, prolonged dry periods, and municipal supply restrictions. The selected WO2 strategy remains exposed to institutional constraints even when long-term contractual arrangements are established. Therefore, the strategy can reduce the consequences of these threats through guaranteed minimum allocation, emergency provisions, strategic storage, and backup source integration, but it cannot completely eliminate them.

The SPG calculation is presented in Table 40. Unlike the ESC, which is limited to external threats, the SPG incorporates all selected strengths, weaknesses, opportunities, and threats from the global IFEM and EFEM matrices. For each factor, the difference between the maximum attractiveness score and the actual WO2 attractiveness score was calculated as $4-AS_i$. This gap was then multiplied by the factor weight and the corresponding scenario coefficient. A factor receiving an attractiveness score of 4 therefore creates no performance gap, whereas factors with low or zero attractiveness scores produce larger contributions. The total weight of the factors included in the SPG calculation was 5.965. After aggregation, the weighted sums were divided by this total weight and subsequently standardized by division by 3.

The SPG follows the same general direction as the ESC, increasing from 0.26 in the stability scenario to 0.46 under moderate stress and 0.57 under severe crisis conditions. The relatively small gap in the stability scenario indicates that existing and proposed strategic capacities are more closely aligned with the level of performance required under comparatively favorable conditions. This does not mean that no intervention is required, rather, it indicates that the necessary improvements can be implemented gradually and with lower operational pressure. Under moderate water stress, the performance gap becomes more substantial. Increasing groundwater decline, river flow variability, treatment limitations, and municipal supply uncertainty require stronger institutional and infrastructural responses. In the severe scenario, the SPG reaches its highest value, demonstrating that the distance between existing system capabilities and the performance required for reliable refinery operation becomes considerably larger.

The most important SPG contributions are associated with declining groundwater levels, river discharge fluctuations, well water quality deterioration, municipal supply interruption, and factors that received limited attractiveness under WO2. Conversely, factors such as Sdn1, Sri5, Wwe1, Wri1, and Ori2 produce no residual gap because WO2 received the maximum attractiveness score for these factors. The results therefore show that WO2 addresses several major weaknesses and opportunities effectively, but additional measures remain necessary for risks that are only partially covered by the selected strategy.

Table 41 provides the complete calculation of the OLI. The opportunity weights were extracted from the global EFEM matrix, while the corresponding TAS values were obtained from the opportunity component of the final QSPM for WO2. Because favorable scenario conditions improve the practical accessibility of external opportunities, the weighted opportunity contribution was calculated by dividing each opportunity weight by the scenario coefficient and multiplying the result by its TAS value. The six opportunity contributions were then aggregated and divided by the total opportunity weight of 1.529. The resulting relative OLI was standardized by division by 3.

The OLI shows the opposite trend to the ESC and SPG. It decreases from 0.94 under relative resource stability to 0.54 under moderate water stress and 0.43 under a severe water crisis. The high OLI in the stability scenario indicates that favorable hydrological and institutional conditions provide substantial scope for exploiting external opportunities. These conditions are particularly suitable for establishing long-term supply agreements, integrating multiple water sources, developing treatment and storage infrastructure, and implementing WO2 in a phased and proactive manner. The largest contributions to the OLI arise from Owe3, Ori2, and Odn1. These factors represent the potential for combined use of multiple sources, the feasibility of constructing a conventional filtration treatment system, and the possibility of establishing

Table 40
Calculation of the SPG under the three prospective scenarios.

Ni							Σ [(Wi*Ni)*(4-AS)]/ Wi			Normalized SPG coefficients		
	Wi	High-Risk Scenario Coefficient	Moderate Scenario Coefficient	Stability Scenario Coefficient	AS	Gap (4-AS)	High-Risk Scenario	Moderate Scenario	Stability Scenario	High-Risk Scenario	Moderate Scenario	Stability Scenario
	I	II	III	IV	V	VI	I*II*VI	I*III*VI	I*IV*VI			
$S_{we}1$	0.420	0.96	0.77	0.44	1.00	3.00	1.207	0.968	0.551			
$S_{we}2$	0.168	0.96	0.77	0.44	2.00	2.00	0.322	0.258	0.147			
$S_{ri}5$	0.286	0.96	0.77	0.44	4.00	0.00	0.000	0.000	0.000			
$S_{ri}2$	0.187	0.96	0.77	0.44	3.00	1.00	0.179	0.144	0.082			
$S_{dn}1$	0.368	0.96	0.77	0.44	4.00	0.00	0.000	0.000	0.000			
$W_{we}1$	0.462	0.96	0.77	0.44	4.00	0.00	0.000	0.000	0.000			
$W_{we}2$	0.151	0.96	0.77	0.44	0.00	4.00	0.579	0.464	0.264			
$W_{ri}1$	0.260	0.96	0.77	0.44	4.00	0.00	0.000	0.000	0.000			
$W_{ri}4$	0.198	0.96	0.77	0.44	0.00	4.00	0.759	0.608	0.346			
$W_{dn}1$	0.141	0.96	0.77	0.44	1.00	3.00	0.405	0.325	0.185			
$O_{we}2$	0.143	0.96	0.77	0.44	1.00	3.00	0.411	0.329	0.187			
$O_{we}3$	0.441	0.96	0.77	0.44	3.00	1.00	0.422	0.339	0.193			
$O_{ri}2$	0.286	0.96	0.77	0.44	4.00	0.00	0.000	0.000	0.000	0.57	0.46	0.26
$O_{ri}5$	0.198	0.96	0.77	0.44	2.00	2.00	0.379	0.304	0.173			
$O_{dn}1$	0.320	0.96	0.77	0.44	2.00	2.00	0.613	0.492	0.280			
$O_{dn}3$	0.141	0.96	0.77	0.44	1.00	3.00	0.405	0.325	0.185			
$T_{we}1$	0.151	0.96	0.77	0.44	0.00	4.00	0.579	0.464	0.264			
$T_{we}3$	0.420	0.96	0.77	0.44	0.00	4.00	1.609	1.290	0.734			
$T_{we}5$	0.263	0.96	0.77	0.44	3.00	1.00	0.252	0.202	0.115			
$T_{we}7$	0.143	0.96	0.77	0.44	0.00	4.00	0.548	0.439	0.250			
$T_{ri}2$	0.260	0.96	0.77	0.44	2.00	2.00	0.498	0.399	0.227			
$T_{ri}4$	0.068	0.96	0.77	0.44	2.00	2.00	0.130	0.104	0.059			
$T_{dn}1$	0.336	0.96	0.77	0.44	2.00	2.00	0.644	0.516	0.294			
$T_{dn}2$	0.154	0.96	0.77	0.44	2.00	2.00	0.295	0.237	0.135			
Wi	5.965						1.716	1.376	0.783			

Table 41
Calculation of the OLI under the three prospective scenarios.

Ni						Σ [(Wo,i / Ni)*TAS]/ Wi			Normalized OLI coefficients		
	$W_{O,i}$	High-Risk Scenario Coefficient	Moderate Scenario Coefficient	Stability Scenario Coefficient	TAS	High-Risk Scenario	Moderate Scenario	Stability Scenario	High-Risk Scenario	Moderate Scenario	Stability Scenario
	I	II	III	IV	V	(I/II)*V	(I/III)*V	(I/IV)*V			
$O_{we}2$	0.143	0.96	0.77	0.44	0.143	0.021	0.027	0.047			
$O_{we}3$	0.441	0.96	0.77	0.44	1.323	0.609	0.760	1.335			
$O_{ri}2$	0.286	0.96	0.77	0.44	1.144	0.342	0.426	0.749			
$O_{ri}5$	0.198	0.96	0.77	0.44	0.396	0.082	0.102	0.179	0.43	0.54	0.94
$O_{dn}1$	0.320	0.96	0.77	0.44	0.640	0.214	0.267	0.469			
$O_{dn}3$	0.141	0.96	0.77	0.44	0.141	0.021	0.026	0.045			
Wi	1.529					1.288	1.607	2.824			

long-term agreements with the Regional Water Authority. Their importance confirms that the strategic value of WO2 is derived not from exclusive dependence on municipal water, but from combining contractual security with treatment capacity, source diversification, and backup integration.

Under moderate stress, opportunities remain available, but their practical use becomes more difficult because of declining source reliability and increasing institutional constraints. Under severe crisis conditions, the OLI falls to 0.43, showing that environmental and regulatory pressures restrict the refinery's ability to convert technically feasible opportunities into reliable operational solutions. Long-term contracts, river-water treatment, and source integration may still contribute to resilience, but their effectiveness increasingly depends on emergency provisions, available storage, enforceable allocations, and the physical availability of backup water.

The combined behavior of the three indicators reveals a clear transition from favorable conditions toward increasing strategic vulnerability. Under relative resource stability, the refinery experiences the lowest environmental pressure (ESC = 0.20) and performance gap (SPG = 0.26), together with the highest opportunity leverage (OLI = 0.94). This scenario therefore provides the most suitable setting for proactive implementation of WO2. Under moderate water stress, ESC and SPG rise to 0.35 and 0.46, respectively, while OLI declines to 0.54, indicating that strategic opportunities remain available but become more difficult and costly to exploit. At this stage, implementation of WO2 should be accelerated and supported by ST1, improved monitoring, controlled groundwater use, and progressive development of treatment and storage infrastructure.

The severe water crisis scenario presents the most challenging condition, with the highest ESC=0.43 and SPG=0.57 and the lowest OLI=0.43. This pattern shows that the refinery's capacity to exploit external opportunities decreases precisely when the need for strategic intervention becomes greatest. Although WO2 remains the preferred long-term strategy because of its balanced response across the QSPM factors, its effectiveness under severe conditions depends on enforceable contractual safeguards, strategic storage, backup source integration, emergency groundwater reserves, and demand prioritization measures. Overall, the simultaneous increase in environmental stress and performance gap, together with the decline in opportunity leverage, confirms the importance of implementing WO2 before severe stress emerges and combining it with complementary ST and contingency measures to maintain refinery water security.

3.6.4. *Sensitivity analysis*

A two-stage sensitivity analysis was conducted to examine the stability of the scenario indicators and the robustness of the integrated decision-support framework. In the first stage, the normalized ESC, OLI, and SPG values were recalculated under −20%, −10%, +10%, and +20% variations relative to their base values. In the second stage, the effects of variations in AHP weights, ELECTRE TRI thresholds, the cutting level, and expert scores on the three indicators were evaluated. This structure allows the sensitivity of the scenario results to be distinguished from the sensitivity associated with the internal parameters of the decision model.

As shown in Fig. 10, ESC preserves a consistent increasing pattern from the relative resource stability scenario to the severe water crisis scenario. Under relative stability, ESC varies from 0.16 to 0.24 around its base value of 0.20. The corresponding ranges are 0.28 – 0.42 for moderate water stress and around base values of 0.35. Although the absolute values change proportionally with the imposed perturbations, the relative ordering of the three scenarios remains unchanged. This result indicates that the increase in environmental pressure from stability to severe crisis is not dependent on a narrow set of input assumptions.

The OLI exhibits the opposite scenario pattern. Its base value decreases from 0.94 under relative resource stability to 0.54 under moderate water stress and 0.43 under severe crisis conditions. Across the ±20% variation range, the corresponding values remain within 0.752 – 1.128, 0.432 – 0.648, and 0.344 – 0.516, respectively. The stable ordering confirms that the potential to exploit external opportunities is greatest under relatively favorable hydrological and institutional conditions and becomes progressively constrained as water stress increases. The value above 1 obtained for the +20% perturbation of the stability scenario represents a proportional sensitivity output relative to the base case and is not interpreted as a final standardized scenario score.

SPG also maintains a stable and monotonic pattern across the tested conditions. Its base values increase from 0.26 under relative resource stability to 0.46 under moderate stress and 0.57 under severe crisis conditions. Under the imposed perturbations, SPG varies within 0.208 – 0.312, 0.368 – 0.552, and 0.456 – 0.684, respectively. This result indicates that the distance between the existing water-supply performance and the desired resilient condition widens systematically as environmental and institutional pressures intensify. The unchanged ordering of the SPG values further confirms that the identified performance deficits are structurally associated with scenario severity rather than with minor variations in model inputs.

Taken together, the sensitivity patterns of ESC, OLI, and SPG provide a coherent representation of the refinery's future water supply conditions. Increasing scenario severity is accompanied by higher environmental stress and a wider performance gap, while the ability to exploit external opportunities declines. The preservation of these relationships under all tested perturbations supports the stability of the scenario interpretation and indicates that the resulting conclusions are not driven by small changes in the input parameters.

The comparative assessment in Table 42 further clarifies the contribution of the integrated framework relative to the individual decision methods. SWOT provides a structured identification of internal and external factors but does not quantify uncertainty or future variation. AHP strengthens the weighting and prioritization process, although it has limited ability to represent non-compensatory relationships.

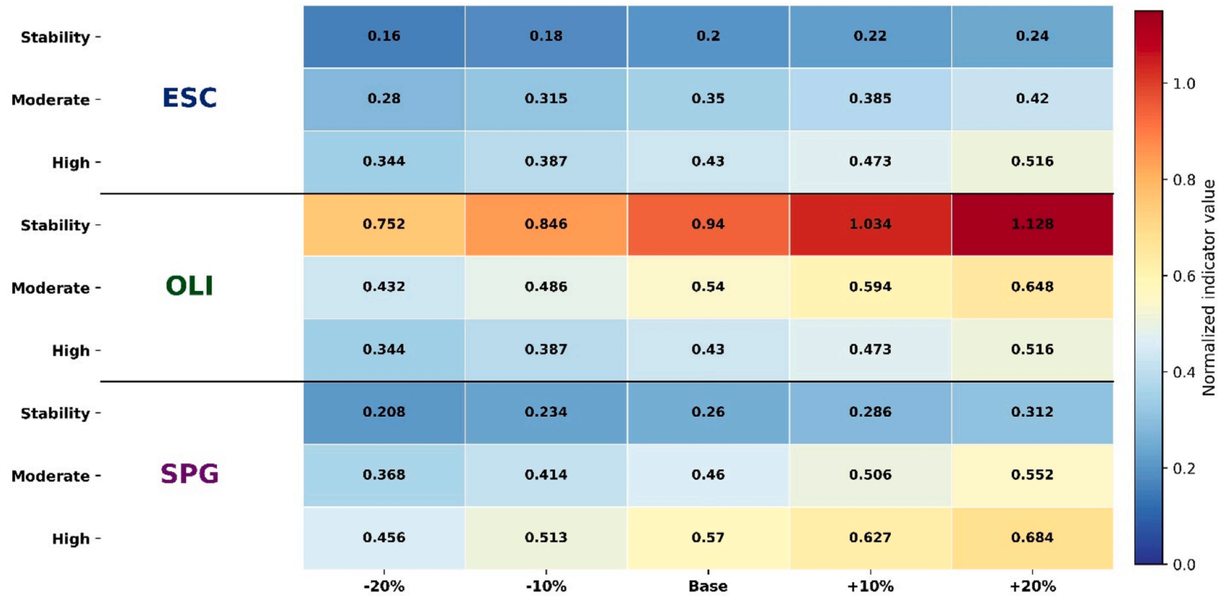

Fig. 10. Sensitivity of ESC, OLI, and SPG to percentage variations relative to their base values under the three prospective scenarios.

Table 42
Quantitative benchmarking of methods (normalized score 0–1).

Scenario	SWOT	AHP	ELECTRE TRI	QSPM	Proposed Framework
Scenario adaptability	0.00	0.30	0.20	0.15	0.92
Uncertainty handling	0.10	0.50	0.80	0.20	0.90
Quantitative rigor	0.20	0.60	0.65	0.75	0.95
Integration capability	0.20	0.50	0.55	0.45	0.95
Decision robustness	0.20	0.60	0.65	0.55	0.92
Overall performance	0.14	0.50	0.57	0.42	0.93

ELECTRE TRI provides a robust sorting mechanism through preference, indifference, veto, and cutting-level parameters, but it does not independently prioritize strategic alternatives or evaluate their future performance. QSPM supports quantitative strategy ranking but does not explicitly incorporate scenario uncertainty or dynamic changes in environmental conditions.

By integrating these methods with the scenario-based ESC, OLI, and SPG indicators, the proposed framework provides a more comprehensive basis for strategic evaluation. Within the adopted benchmarking scheme, it obtained the highest scores for scenario adaptability, integration capability, quantitative rigor, uncertainty handling, and decision robustness, with an overall performance score of 0.93. These results should be interpreted as evidence of methodological complementarity rather than as a replacement for the individual methods, because each component performs a distinct function within the analytical sequence.

Fig. 11 presents the sensitivity of ESC, OLI, and SPG to variations in the principal model parameters. The resulting impacts remain within a narrow range of 0.02 – 0.07. Expert score variability produces the largest effects, with impact values of 0.06 for ESC, 0.05 for OLI, and 0.07 for SPG. Variations in AHP weights have the second largest influence, producing values of 0.05, 0.04, and 0.06, respectively. The effects associated with the ELECTRE TRI cutting level are more limited, while the preference and indifference thresholds show the lowest impacts. In particular, the indifference threshold produces impact values of only 0.02, 0.02, and 0.03 for ESC, OLI, and SPG. The greater influence of expert scores and AHP weights is consistent with their direct role in

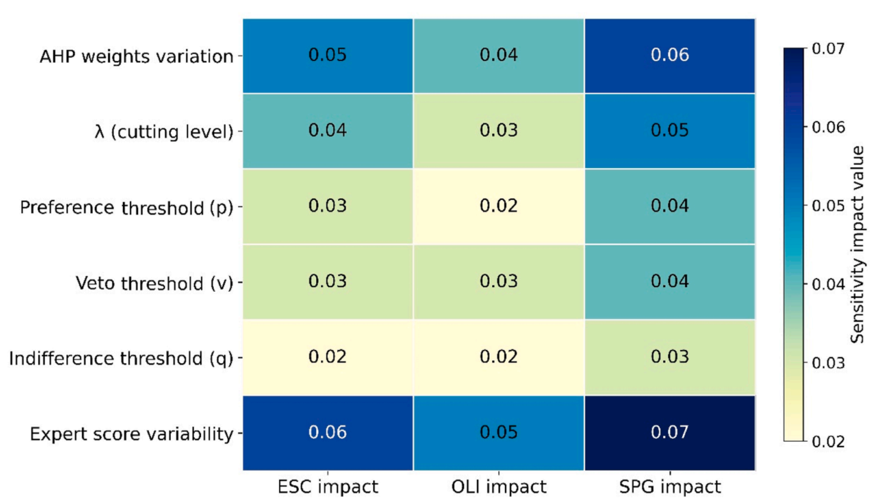

Fig. 11. Sensitivity of ESC, OLI, and SPG to variations in the principal parameters of the integrated decision model.

determining the importance and attractiveness of the strategic factors. In contrast, the comparatively small effects of the ELECTRE TRI thresholds indicate that moderate changes in the sorting parameters do not substantially alter the downstream scenario indicators.

Across all tested parameter configurations, the ranking of the strategic alternatives remained unchanged. WO2 retained the highest STAS value of 13.174, followed by ST1 with 12.290, while WO1, WT1, and ST2 remained in the subsequent positions. The stability of this ranking, together with the preserved scenario ordering of ESC, OLI, and SPG, demonstrates that the selection of WO2 is not dependent on a single parameter setting. WO2 therefore remains the preferred long-term strategy, while the high ranking of ST1 confirms the importance of complementary threat oriented measures under the identified ST-dominant strategic posture. Overall, the sensitivity analysis supports the robustness of both the strategic ranking and the scenario-based interpretation of the refinery's future water-security conditions.

3.7. Practical implications

The findings provide a practical basis for refinery managers to shift from reactive water supply management toward a more structured, anticipatory, and scenario informed planning process. By combining strategic factor identification, expert based weighting, non-compensatory classification, quantitative strategy prioritization, and future scenario assessment, the proposed framework supports decisions that account for both present operational conditions and longer-term uncertainty. This is particularly important in water stressed industrial regions, where source reliability, regulatory restrictions, and competition among users can change rapidly.

The prioritization of WO2 as the preferred strategy (STAS = 13.174) indicates that refinery management should focus on establishing a risk adjusted long-term water supply arrangement rather than relying on a single source or on conventional supply expansion alone. In operational terms, this requires a guaranteed minimum allocation, emergency supply provisions, strategic storage, and physical integration of backup sources. The second-place ranking of ST1 (STAS = 12.290) further indicates that part of the existing well capacity should be preserved as a controlled emergency reserve. WO1 can support this structure where river discharge and treatment feasibility are sufficient, while WT1 and ST2 can contribute through demand prioritization and protection of critical units during supply restrictions.

The scenario indicators provide additional guidance for the timing and intensity of implementation. Under relative resource stability, the low ESC (0.20), low SPG (0.26), and high OLI (0.94) indicate that the refinery has the greatest opportunity to establish contractual, storage, monitoring, and source integration measures at comparatively lower cost and with greater institutional flexibility. Under moderate water stress, ESC and SPG increase to 0.35 and 0.46, while OLI declines to 0.54, showing that implementation becomes more urgent and that delays may increase both technical and financial burdens. Under severe crisis conditions, ESC and SPG reach 0.43 and 0.57, respectively, while OLI falls to 0.43. At this stage, the refinery would have less capacity to exploit new opportunities and would depend more heavily on measures already established in advance.

These results have direct implications for investment planning. Capital allocation should prioritize interventions that improve flexibility across several scenarios rather than projects optimized for only one expected condition. Strategic storage, monitoring systems, source interconnection, selective treatment capacity, and emergency demand management infrastructure are therefore more valuable when evaluated as components of an integrated supply architecture. The framework also helps managers distinguish between measures that should be implemented immediately and investments that can be phased according to hydrological and institutional conditions. From a policy perspective, the results emphasize the importance of coordination between the refinery, the Regional Water Authority, the municipal water utility, and environmental regulators. Long-term agreements should clearly define minimum allocations, emergency priorities, operational responsibilities, and restrictions applicable during drought or regional shortages. Such coordination is essential because the risks represented by Tdn1 and Tdn2 cannot be removed solely through internal refinery actions. The framework can also support regulatory agencies by providing a transparent basis for assessing industrial water allocation requests, emergency supply arrangements, and proposed infrastructure investments.

The sensitivity analysis strengthens the practical relevance of the results by showing that the principal scenario relationships and strategy ranking remain stable under moderate variation in model inputs. Expert score variability and AHP weights have a greater influence than the ELECTRE TRI threshold parameters, but the observed changes remain limited and do not alter the strategic ordering. This suggests that the recommended implementation pathway is not dependent on a single parameter setting and can therefore be used as a reasonably robust planning reference.

Several limitations should nevertheless be acknowledged. The reliability of the results depends on the quality and completeness of the input data, including expert judgments and operational records. Although expert elicitation was structured through AHP, ELECTRE TRI, and QSPM, some degree of subjectivity remains unavoidable. Broader participation by operational personnel, policymakers, and regional water managers could improve the representativeness of future applications. In addition, ESC, OLI, and SPG provide interpretable comparative indicators but do not reproduce all dynamic interactions within the refinery and regional water system. Their application could therefore be strengthened through integration with real-time monitoring, hydraulic simulation, system dynamics modelling, or optimization under uncertainty. The framework was developed for a specific refinery and should not be transferred directly to other industrial settings without recalibration. Factor definitions, weights, thresholds, scenario coefficients, and feasible strategies may differ according to local hydrology, regulation, infrastructure, and industrial demand. Nevertheless, the overall analytical structure is transferable and can be adapted to other water-intensive industries facing similar uncertainty.

Overall, the proposed framework provides refinery managers with a practical mechanism for linking strategic priorities to operational actions, investment sequencing, and institutional coordination. Its main contribution is not limited to identifying WO2 as the preferred strategy; it also clarifies when the strategy should be implemented, which complementary measures are required, and how increasing water stress changes the balance between available opportunities and unresolved performance gaps. The proposed framework serves as a practical decision support tool that enables managers to transition from reactive to proactive and scenario informed decision making, thereby strengthening the long-term sustainability and resilience of refinery water systems.

3.8. Engineering applications

The proposed framework has direct applicability in engineering practice, particularly for water resource management in industrial facilities operating under water stress conditions. Unlike purely analytical approaches, the integration of SWOT, AHP, ELECTRE TRI, and QSPM provides a structured pathway for translating strategic evaluation into actionable engineering decisions. From an operational perspective, the identification of WO2 as the preferred strategy suggests a shift toward reducing dependency on vulnerable water sources while enhancing the use of more reliable and adaptable alternatives. In practical terms, this can be implemented through diversification of water supply systems, including increased utilization of surface water sources, integration with regional water distribution networks, and development of flexible allocation mechanisms to respond to fluctuations in availability.

The framework also supports infrastructure-level decision-making. For example, investments in pipeline connectivity, storage systems, and adaptive treatment units can be prioritized based on their contribution to reducing environmental stress (ESC) and improving opportunity utilization (OLI). In addition, the reduction of system performance gaps (SPG) can guide the optimization of operational parameters and capacity planning.

A key engineering advantage of the proposed approach is its ability to incorporate future uncertainty into decision-making. The scenario-based indicators enable engineers and managers to evaluate how system performance evolves under different stress conditions, thereby supporting robust design and long-term planning. This is particularly relevant in regions where water availability is subject to significant variability due to climatic and regulatory factors. Furthermore, the framework can be integrated into digital monitoring and decision-support systems. By linking real-time operational data with the defined indicators, it becomes possible to develop adaptive management strategies that respond dynamically to changes in water demand, supply conditions, and system performance.

Overall, the proposed framework provides a bridge between strategic planning and engineering implementation, offering a practical tool for improving water security, enhancing system resilience, and supporting sustainable industrial operations.

Although the present study is based on a specific refinery case, the proposed decision-making framework is inherently transferable to other industrial contexts. The modular structure of the framework allows its core components—SWOT, AHP, ELECTRE TRI, and QSPM—to be adapted to different operational environments by recalibrating input data, criteria weights, and decision parameters. In particular, the defined indicators (ESC, OLI, and SPG) are not site-dependent and can be recalculated under varying hydrological, regulatory, and technological conditions. This enables the framework to capture system behavior under different stress levels and future scenarios across diverse industrial settings.

The applicability of the framework extends beyond oil refineries to other water-intensive sectors, including petrochemical complexes, thermal power plants, and large-scale manufacturing industries, where water resource security is a critical operational constraint. However, successful implementation in other contexts requires careful localization, including the selection of relevant criteria, expert elicitation, and scenario definition. These adaptations ensure that the framework remains both robust and context-sensitive. This adaptability highlights the framework's potential as a generic decision-support tool for industrial water resource management under uncertainty.

The results obtained in this study are consistent with previous research, indicating the increasing influence of external pressures on industrial water systems. For instance, recent studies on water resource management have highlighted the growing role of climate variability and regulatory constraints in shaping system performance. However, unlike conventional approaches that primarily focus on static evaluations, the proposed framework integrates scenario-based indicators (ESC, OLI, SPG), enabling a dynamic assessment of system resilience. This represents a significant advancement over previous MCDM applications, which often lack explicit mechanisms for evaluating future uncertainty.

Moreover, while earlier studies applying SWOT–AHP or QSPM frameworks have provided useful prioritization tools, they typically rely on qualitative or semi-quantitative assessments. In contrast, the present study introduces a fully quantified and integrated decision-support system, linking strategic evaluation with scenario-based performance metrics. These differences demonstrate that the proposed framework not only confirms existing insights but also extends them by providing a more comprehensive and forward-looking analytical structure.

3.9. Limitations and future research directions

Despite the robustness of the proposed integrated framework, several limitations should be acknowledged:

1. The ELECTRE TRI method, while effective in handling uncertainty and non-compensatory decision logic, requires the definition of boundary profiles and threshold parameters. These parameters may introduce sensitivity to model configuration, especially when empirical calibration data are limited.
2. The QSPM approach assumes linear aggregation of attractiveness scores, which may not fully capture complex interdependencies among strategic factors. This simplification could affect the accuracy of strategy prioritization in highly dynamic systems.
3. The framework is dependent on the availability and quality of input data, including operational, environmental, and economic information. Inaccurate or incomplete data may propagate through the decision-making process and influence the outcomes.
4. The scenario definitions used in this study represent plausible but simplified representations of future conditions. While they provide valuable insights into system behavior, real-world uncertainties may involve more complex and unforeseen interactions.

Future research should focus on integrating probabilistic and data-driven approaches, such as stochastic modeling or machine learning techniques, to enhance the predictive capability of the framework. Additionally, expanding the framework to include dynamic feedback mechanisms and real-time data integration could further improve its applicability in complex industrial environments.

These limitations do not undermine the validity of the results but rather define the scope within which the findings should be interpreted.

4. Conclusion

This study developed and implemented an integrated, multi-criteria, and forward-looking strategic assessment framework to evaluate the refinery's water supply alternatives under internal and external constraints. The novelty of this work lies in its combined use of SWOT, AHP-based weighting, ELECTRE TRI multi-criteria sorting, and QSPM quantitative strategy evaluation, enabling an evidence driven prioritization of water supply strategies for an industrial facility operating in a water stressed region. The approach transforms qualitative managerial judgments into a structured and reproducible decision-support system tailored to long-term resource security in oil refining operations.

The KOR was evaluated as a case study. The IFEM and EFEM analyses produced total weighted scores of 2.641 and 3.322, respectively. However, the strategic position was determined from the normalized internal and external SWOT coordinates rather than directly from these aggregate scores. The resulting coordinates, $X = 0.082$ and $Y = -0.080$, placed the refinery's water supply system in the ST quadrant, indicating that existing internal strengths should primarily be used to address external threats. Through ELECTRE TRI, the strengths, weaknesses, opportunities, and threats were categorized and weighted, providing an evidence based foundation for strategy development. The reconstructed SWOT matrix generated five feasible alternatives from the ST, WO, and WT strategy families. The QSPM results identified WO2 as the highest ranked strategy, with an STAS of 13.174, followed by ST1 with 12.290, WO1 with 10.738, WT1 with 10.085, and ST2 with 9.245. Thus, although the overall strategic posture is ST-dominant, WO2 represents the most attractive individual strategy based on its performance across the complete set of internal and external factors.

In addition to strategic prioritization, the study introduced three quantitative indicators to assess future water supply conditions under alternative scenarios. The ESC, OLI, and SPG were calculated for relative resource stability, moderate water stress, and severe water crisis scenarios to represent hydro-environmental stress, the extent to which external opportunities remain exploitable, and the gap between current and desired strategic performance. The ESC increased from 0.20 under relative resource stability to 0.35 under moderate stress and 0.43 under severe crisis conditions, indicating progressively greater environmental and institutional pressure. Over the same scenarios, the OLI declined from 0.94 to 0.54 and 0.43, showing that the capacity to exploit external opportunities decreases as water stress intensifies. The SPG increased from 0.26 to 0.46 and 0.57, demonstrating a widening difference between existing system capabilities and the performance required for resilient operation.

These quantitative findings complement the strategic results derived from the SWOT – AHP – ELECTRE TRI – QSPM framework. The relatively favorable stability scenario provides the greatest opportunity for early implementation of contractual, storage, treatment, and source integration measures, whereas moderate and severe stress progressively reduce implementation flexibility and increase the need for contingency measures. WO2 remains the preferred long-term strategy because it combines a risk adjusted supply agreement with a guaranteed minimum allocation, emergency supply provisions, strategic storage, and backup source integration. Its attractiveness is strongly supported by factors such as Sdn1, Sri5, Wwe1, Wri1, Owe3, Ori2, and Odn1. Nevertheless, the nonzero but moderate attractiveness scores assigned to Tdn1 and Tdn2 show that municipal supply interruption and restrictive industrial water policies can be mitigated but not fully eliminated. Therefore, the effectiveness of WO2 under severe conditions depends on its integration with complementary measures, particularly the controlled emergency well capacity represented by ST1 and the demand management provisions associated with WT1.

Overall, this integrated decision framework provides a replicable model for strategic water resource planning in industrial environments facing hydrological and institutional uncertainty. The prioritization of WO2 offers a coherent pathway for strengthening water security through contractual safeguards, strategic storage, source diversification, and proactive risk mitigation. At the same time, the second place ranking of ST1 confirms the importance of threat oriented measures under the identified ST-dominant posture. The sensitivity analysis showed that the ordering of the three scenarios and the ranking of the strategic alternatives remained stable under the tested parameter variations, supporting the robustness of the principal conclusions. The findings therefore demonstrate the potential of structured multi-criteria and scenario-based approaches to support sustainable industrial water management, particularly in regions where environmental pressure, regulatory restrictions, and declining water availability increase the need for adaptive and quantitatively supported strategic planning.

Key findings of this study can be summarized as follows:

- The integrated SWOT – AHP – ELECTRE TRI – QSPM framework enabled structured identification, classification, weighting, and quantitative prioritization of water supply strategies under complex internal and external conditions.
- The IFEM and EFEM total weighted scores were 2.641 and 3.322, respectively, while the normalized coordinates $X = 0.082$ and $Y = -0.080$ placed the refinery's water supply system in the ST quadrant.
- The QSPM identified WO2 as the preferred strategy with an STAS of 13.174, followed by ST1 with 12.290, WO1 with 10.738, WT1 with 10.085, and ST2 with 9.245.
- Scenario analysis showed increasing environmental stress (ESC: 0.20 → 0.35 → 0.43), declining opportunity leverage (OLI: 0.94 → 0.54 → 0.43), and a widening strategic performance gap (SPG: 0.26 → 0.46 → 0.57).
- WO2 is the preferred long-term strategy, but its effectiveness under severe conditions depends on enforceable contractual provisions, strategic storage, backup source integration, and complementary ST and contingency measures.
- The preservation of scenario ordering and strategic ranking under sensitivity testing supports the robustness of the analytical results.
- The proposed framework advances existing practice by integrating strategic positioning, multi-criteria classification, quantitative strategy evaluation, and scenario based resilience indicators into a practical and transferable decision support structure.

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During the preparation of this work, the authors used ChatGPT and Grammarly to improve language clarity and readability. The authors critically reviewed and edited the content and take full responsibility for the final version of the manuscript.

CRediT authorship contribution statement

Kamran Mohammadi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mehrdad Shemshadi:** Writing – review & editing, Resources, Project administration, Investigation, Data curation. **Nemat Ali-mohammadi:** Writing – review & editing, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2026.112344.

Data availability

Data will be made available on request.

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