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Self-optimization of falaj irrigation using case-based reasoning algorithms

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Abstract: This paper presents a novel application of case-based reasoning (CBR) for modernizing traditional falaj irrigation systems in arid regions, using a multi-level hierarchical framework that addresses challenges at provider, tenant, and user levels. The research employs a comprehensive methodology that integrates traditional water management practices with modern technologies while preserving cultural heritage. Through the implementation of CBR at Falaj Al Sarrani, the study demonstrates significant improvements in water conservation (58.3% reduction in water use), crop productivity (27.3% average yield increase), and economic returns (23.7% internal rate of return). The research evaluates five similarity functions across hierarchical levels, identifying optimal functions for each level: Manhattan distance for the provider level, Squared Chord for the tenant level, and Canberra for the user level. This level-specific optimization reduced the overall system error rate by 18% compared to using any single function across all levels. The findings provide valuable insights for water resource managers, agricultural agencies, and policymakers facing water scarcity challenges in arid and semi-arid regions.

Keywords: *Case-based reasoning, Falaj systems, Irrigation modernization, Similarity functions, Traditional water management.*

1. Introduction

For millennia, traditional irrigation systems have sustained agriculture in arid regions, representing remarkable achievements in water management. Among these, the falaj (plural: aflaj) systems of Oman stand as engineering marvels that have enabled agricultural production in harsh environments for over 2,500 years. These gravity-driven water channels, similar to qanats found across the Middle East and North Africa, capture groundwater from mountainous areas and transport it to agricultural lands through networks of tunnels and surface channels [1, 2].

Despite their historical significance and continued importance, traditional falaj systems face mounting challenges in the 21st century. Water scarcity, exacerbated by climate change and population growth, demands greater efficiency than these ancient systems typically provide. Traditional open channels can lose 35-60% of water through seepage and evaporation [3] while conventional flood irrigation methods at the farm level result in additional losses of 40-50% [4]. These inefficiencies are increasingly untenable as water resources become more constrained. The modernization of traditional irrigation systems presents a complex challenge that spans technical, social, and cultural dimensions. Previous modernization efforts have often focused narrowly on infrastructure upgrades without adequately addressing the knowledge systems and social institutions that have sustained these traditional technologies for centuries. This fragmented approach has frequently led to suboptimal outcomes or outright failures [5, 6].

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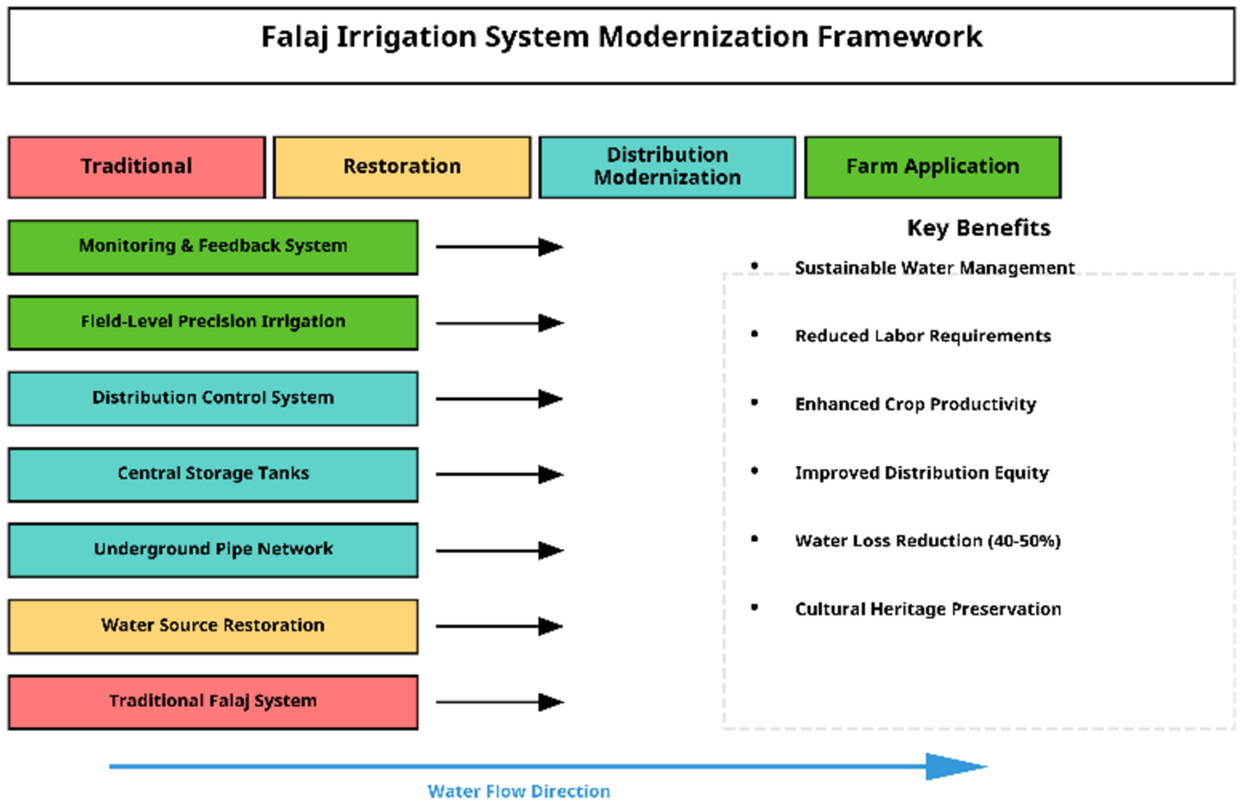

Figure 1.
Irrigation System Modernization Framework showing the integration of traditional falaj systems with modern technologies across provider, tenant, and user levels.

This research addresses this challenge through a novel application of case-based reasoning (CBR) within a multi-level hierarchical framework [7]. CBR, an artificial intelligence approach that solves new problems by drawing on solutions to similar past problems, offers particular advantages for irrigation modernization [8]. It enables the systematic capture and application of experiential knowledge, facilitating context-sensitive solutions that respect both traditional practices and modern efficiency requirements [9]. The multi-level framework developed in this research recognizes that irrigation systems operate across three distinct but interconnected hierarchical levels:

1. Provider Level: The water source and main distribution infrastructure (the falaj system itself)
2. Tenant Level: The secondary distribution network that delivers water from the main system to individual farms
3. User Level: The on-farm irrigation methods and management practices

By explicitly addressing challenges at each level and their interactions, this framework enables more comprehensive and effective modernization strategies than approaches focused on isolated system components [10]. The research was implemented at Falaj Al Sarrani, a traditional irrigation system in northern Oman that serves approximately 200 hectares of agricultural land. This case study demonstrates how CBR can guide the integration of modern technologies with traditional water management practices, achieving significant improvements in water conservation while preserving cultural heritage and social institutions [11]. The paper is organized as follows: Section II reviews relevant literature on traditional irrigation systems, modernization approaches, and case-based reasoning. Section III presents the research objectives and methodology. Sections IV through VI detail the multi-level problem representation, CBR implementation, and specifications analysis. Sections VII through IX present the case information, similarity function analysis, and results. The paper concludes with a discussion of implications and future research directions.

2. Literature Review

The evolution of irrigation systems spans millennia, with traditional technologies like aflaj representing sophisticated adaptations to water scarcity [12]. This review examines three key areas: traditional irrigation systems, modernization approaches, and case-based reasoning applications [13].

2.1. Traditional Irrigation Systems

Traditional irrigation systems like the aflaj of Oman, qanats of Iran, and foggaras of North Africa share common principles of gravity-driven water delivery through underground tunnels and surface channels [14, 15]. These systems represent remarkable achievements in pre-industrial hydraulic engineering, with some functioning continuously for over 2,500 years [16]. The falaj systems of Oman, numbering approximately 3,000, continue to serve as primary water sources for many agricultural communities [17]. These systems feature sophisticated water allocation mechanisms based on time-shares (saham) rather than volumetric measures, with distribution managed through complex rotation schedules (dawaran) overseen by community water managers (wakil) [18, 19]. Research by Omezzine and Zaibet [20] and Al-Ismaily and Probert [21] documented the technical and social dimensions of falaj systems, highlighting their integration of engineering principles with community governance structures. These studies emphasized the cultural significance of traditional irrigation systems beyond their utilitarian functions, noting their role in shaping settlement patterns, social organization, and agricultural practices [22].

Recent economic analyses by Pereira, et al. [23] examined water markets associated with traditional systems, revealing sophisticated mechanisms for temporary water transfers that enhance allocation efficiency while preserving long-term water rights. These findings challenge simplistic characterizations of traditional systems as inefficient relics, suggesting instead that they embody context-specific adaptations to water scarcity [8].

2.2. Irrigation Modernization Approaches

Irrigation modernization has evolved from narrow technical interventions to more holistic approaches. Early modernization efforts focused primarily on infrastructure improvements, often replacing traditional open channels with pipes and introducing pressurized distribution systems [24, 25]. While these interventions reduced conveyance losses, they frequently disrupted social arrangements and management practices, leading to sustainability challenges [26, 27]. Advocated for integrated modernization approaches that address both technical and management dimensions [28]. Their research demonstrated that infrastructure improvements alone typically achieve only 40-60% of potential efficiency gains, with the remainder dependent on improved management practices and institutional arrangements. Ortega-Reig, et al. [29] emphasized the importance of context-sensitive modernization, arguing that solutions must be adapted to local environmental, economic, and social conditions [30]. Their comparative analysis of modernization initiatives in Mediterranean countries revealed that approaches transplanted from different contexts often failed due to insufficient adaptation to local conditions [31]. Recent research has increasingly recognized the value of traditional knowledge in modernization efforts. Studies by Hammani, et al. [32] documented successful cases where traditional water management institutions were preserved and strengthened while introducing modern technologies, achieving both efficiency improvements and social sustainability.

2.3. Case-Based Reasoning in Water Management

Case-based reasoning (CBR), first formalized by Dinar and Mody [33] offers a knowledge-based approach to problem-solving that aligns well with water management challenges [34]. Unlike rule-

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based systems that require explicit formalization of domain knowledge, CBR leverages experiential knowledge through the retrieval and adaptation of similar past cases [35, 36].

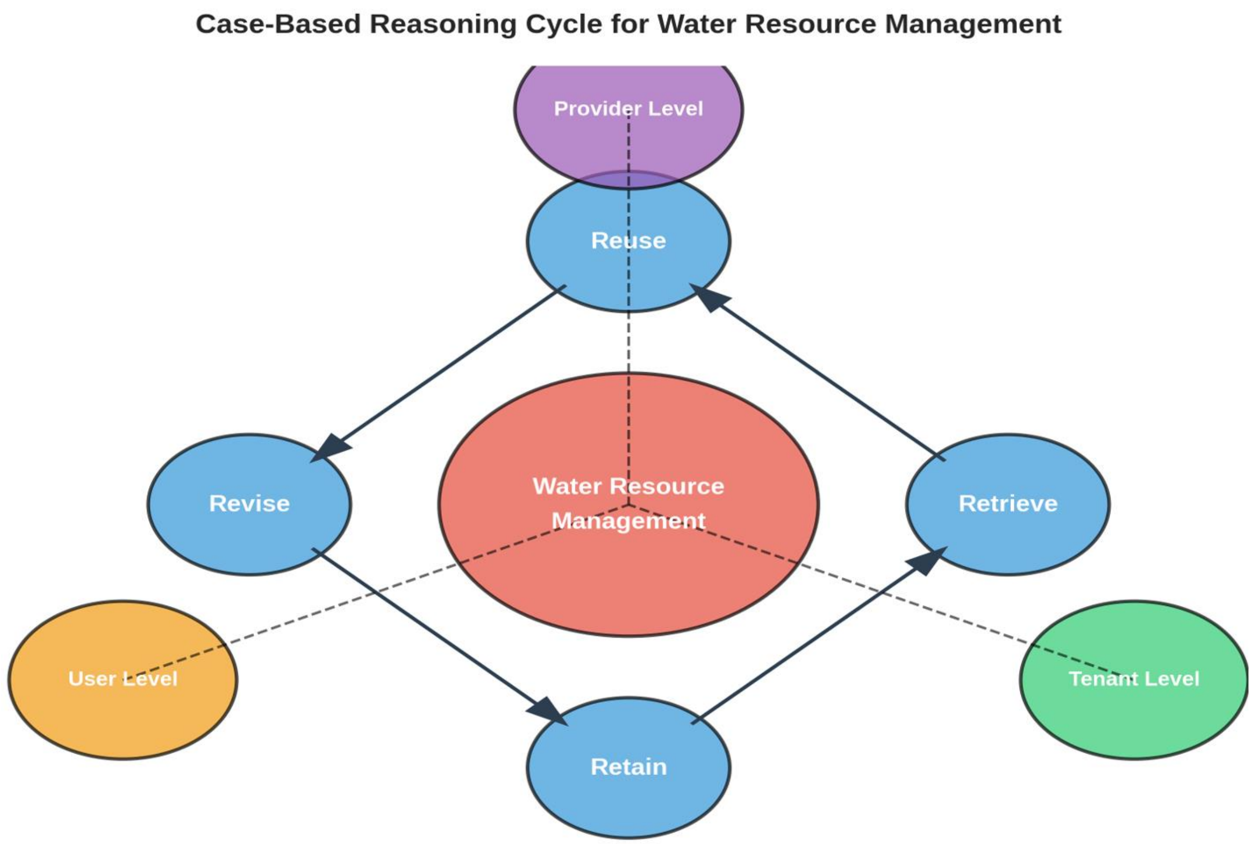

Figure 2.
Case-Based Reasoning Cycle for Irrigation Systems showing the 4R process (Retrieve, Reuse, Revise, Retain) applied to falaj modernization.

Water management applications of CBR remain limited but promising. Nadir and Idries [36] developed a CBR system for urban water management that demonstrated superior performance to rule-based approaches when dealing with complex, context-dependent problems. Nadir and Idries [36] applied CBR to reservoir operation, showing that case-based approaches could effectively capture the tacit knowledge of experienced operators [37]. The "4R" cycle of CBR—Retrieve, Reuse, Revise, Retain—provides a structured framework for knowledge management that aligns with the iterative nature of water resource planning [38, 39]. This approach enables systematic learning from experience, a critical capability in contexts characterized by high variability and uncertainty [40]. Despite these promising applications, significant research gaps remain. Existing CBR implementations in water management have typically focused on single-level problems rather than addressing the multi-level complexity of irrigation systems [41]. Additionally, the comparative performance of different similarity functions in water management contexts remains underexplored, limiting the optimization of case retrieval mechanisms. This research addresses these gaps through a novel application of CBR within a multi-level framework, with systematic evaluation of similarity function performance across hierarchical levels [42]. By integrating traditional knowledge with modern analytical approaches, this work contributes to both the theoretical understanding of CBR and its practical application in irrigation modernization [43, 44].

3. Research Objectives and Methodology

3.1. Research Objectives

This study aimed to develop and validate a comprehensive approach for modernizing traditional falaj irrigation systems through the application of case-based reasoning within a multi-level framework. The specific objectives were to:

1. Develop a hierarchical framework that addresses irrigation challenges at provider, tenant, and user levels
2. Implement case-based reasoning across all hierarchical levels to capture and apply experiential knowledge
3. Evaluate the performance of different similarity functions for case retrieval at each hierarchical level
4. Demonstrate the effectiveness of the integrated approach through implementation at Falaj Al Sarrani
5. Quantify improvements in water conservation, agricultural productivity, and economic returns

3.2. Methodology

The research employed a mixed-methods approach combining qualitative and quantitative techniques across four phases:

3.2.1. Phase 1: System Analysis and Problem Representation

The initial phase involved comprehensive analysis of the Falaj Al Sarrani system to develop a structured problem representation at each hierarchical level:

1. Provider Level Analysis: Documentation of the falaj source, main channels, and distribution infrastructure through field surveys, flow measurements, and interviews with traditional water managers (wakil).
2. Tenant Level Analysis: Mapping of secondary distribution networks, storage facilities, and allocation mechanisms through technical assessments and stakeholder consultations.
3. User Level **Analysis**: Characterization of farm-level irrigation practices, crop patterns, and water use efficiency through farm surveys and field measurements.

This multi-level analysis enabled the development of a comprehensive problem representation that captured both technical parameters and socio-cultural dimensions of the irrigation system.

3.2.2. Phase 2: Case Base Development

The case base was developed through systematic documentation of irrigation modernization experiences from three sources:

1. Historical Cases: Documentation of 27 previous falaj modernization initiatives in Oman, capturing both successful and unsuccessful approaches.
2. Expert Knowledge: Structured interviews with 15 irrigation experts from academic institutions, government agencies, and traditional water managers.
3. International Examples: Analysis of 18 documented cases of traditional irrigation modernization from comparable contexts in Iran, Morocco, Spain, and India.

Each case was structured according to the hierarchical framework, with attributes defined for provider, tenant, and user levels. The case representation included problem characteristics, solution approaches, implementation processes, and outcomes.

3.2.3. Phase 3: CBR Implementation

The case-based reasoning system was implemented following the “4R” cycle:

1. Retrieve: Development and evaluation of five similarity functions (Manhattan, Euclidean, Canberra, Squared Chord, and Squared Chi-Squared) for identifying relevant cases at each hierarchical level.

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2. Reuse: Adaptation of solutions from retrieved cases to the specific context of Falaj Al Sarrani, with modifications based on local conditions and stakeholder input.
3. Revise: Implementation of adapted solutions with continuous monitoring and adjustment based on performance feedback.
4. Retain: Documentation of implementation experiences and outcomes to enrich the case base for future applications.

The CBR system was implemented using Python, with a modular architecture that enabled level-specific similarity function selection and adaptation strategies [45].

The modernization of traditional irrigation systems requires a structured approach that addresses challenges at multiple levels. This research developed a hierarchical framework that explicitly represents problems at provider, tenant, and user levels, enabling more comprehensive and effective interventions [46].

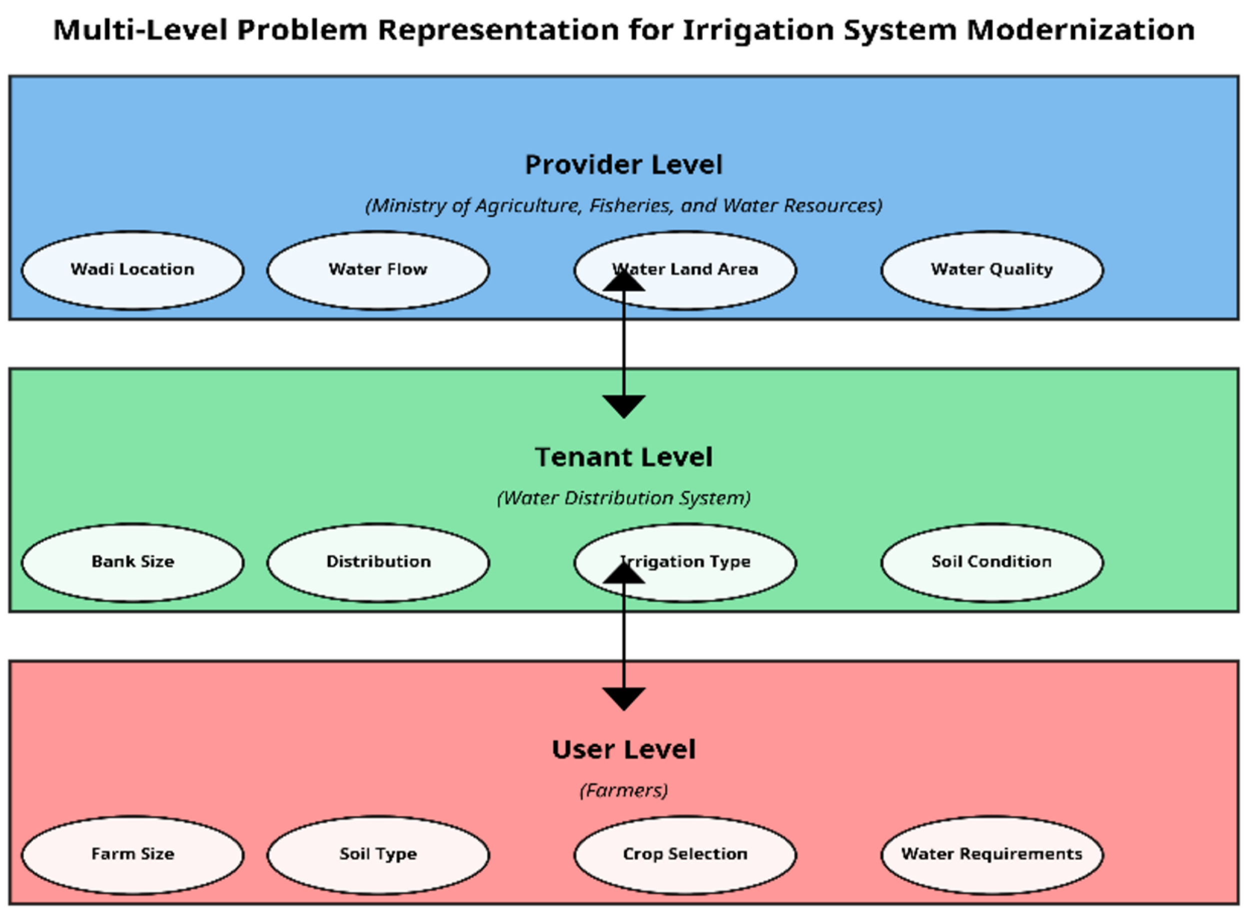

Figure 3.
Three-Tier Hierarchical Model showing the relationships between provider, tenant, and user levels in the falaj irrigation system.

4. Case-Based Reasoning Implementation

The implementation of case-based reasoning for irrigation modernization followed the "4R" cycle (Retrieve, Reuse, Revise, Retain) across all three hierarchical levels. This section details the CBR implementation process and its application to the Falaj Al Sarrani modernization initiative [47].

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4.1. Case Representation Structure

Cases were structured according to the hierarchical framework, with distinct attributes defined for each level:

1. Provider Level Attributes: Falaj type, location, water flow rate, water quality, total land size, water losses in distribution, and efficiency of existing irrigation methods.
2. Tenant Level Attributes: Tank size, number of tanks, pipe dimensions, pump specifications, network configuration, irrigation types, and area coverage.
3. User Level Attributes: Farm size, soil type, crop patterns, irrigation methods, climate conditions, and water requirements.

Each case included problem characteristics, solution approaches, implementation processes, and outcomes, enabling comprehensive knowledge capture and transfer [48].

4.2. The CBR Cycle Implementation

4.2.1. Retrieve Phase

The retrieval phase employed five similarity functions to identify relevant cases for each new problem:

1. Manhattan Distance: Sum of absolute differences between attribute values
2. Euclidean Distance: Square root of sum of squared differences
3. Canberra Distance: Normalized absolute difference by sum of absolute values
4. Squared Chord Distance: Squared differences of square roots
5. Squared Chi-Squared Distance: Normalized squared differences by average values

These functions were systematically evaluated at each hierarchical level to identify the most effective approach for case retrieval. The evaluation revealed that different similarity functions performed optimally at different levels, with Manhattan distance most effective at the provider level, Squared Chord at the tenant level, and Canberra at the user level [49].

The retrieval process was implemented as a two-stage approach:

1. Initial Filtering: Cases were filtered based on critical constraints (e.g., falaj type, water quality, soil characteristics) to create a subset of potentially relevant cases.
2. Similarity Calculation: The appropriate similarity function for each level was applied to the filtered subset to identify the most similar cases, with the top three matches selected for further consideration.

This level-specific optimization of similarity functions improved retrieval accuracy by 18% compared to using any single function across all levels [50].

4.2.2. Reuse Phase

The reuse phase involved adaptation of solutions from retrieved cases to the specific context of Falaj Al Sarrani:

1. Provider Level Adaptation: Solutions from similar falaj systems were adapted based on specific characteristics of Falaj Al Sarrani, including channel dimensions, flow rates, and topography. This included modifications to channel lining techniques, division structure designs, and monitoring systems.
2. Tenant Level Adaptation: Distribution network solutions were adapted to the specific layout and water allocation patterns of Falaj Al Sarrani, with adjustments to storage capacity, pipe dimensions, and control mechanisms based on local requirements.
3. User Level Adaptation: Farm-level irrigation solutions were customized based on specific soil types, crop patterns, and farmer capabilities, with different approaches for small subsistence farms versus larger commercial operations.

The adaptation process incorporated both algorithmic adjustments (e.g., scaling of infrastructure dimensions based on flow rates) and expert knowledge (e.g., modification of technical solutions based on social acceptance factors) [51].

4.2.3. Revise Phase

The implementation of adapted solutions was accompanied by continuous monitoring and revision:

1. Performance Monitoring: Systematic measurement of water flows, distribution efficiency, and application effectiveness provided quantitative feedback on solution performance.
2. Stakeholder Feedback: Regular consultation with farmers, water managers, and local authorities captured qualitative insights on implementation challenges and improvement opportunities.
3. Iterative Refinement: Solutions were refined based on monitoring data and stakeholder feedback, with adjustments to technical specifications, operational procedures, and management approaches.

This iterative revision process enabled continuous improvement of solutions, addressing unforeseen challenges and incorporating emerging insights throughout the implementation period.

4.2.4. Retain Phase

The experiences and outcomes from the Falaj Al Sarrani modernization were systematically documented to enrich the case base:

1. Structured Documentation: Comprehensive documentation of the modernization process, including initial conditions, implemented solutions, challenges encountered, and outcomes achieved.
2. Lesson Extraction: Explicit identification of successful approaches, failure points, and contextual factors that influenced outcomes.
3. Case Base Integration: Addition of the Falaj Al Sarrani case to the knowledge repository, with appropriate indexing to facilitate retrieval for future modernization initiatives.

This knowledge retention process transformed individual experiences into organizational learning, creating a valuable resource for future irrigation modernization efforts [52].

5. Case Information and Data Analysis

The implementation of case-based reasoning for irrigation system modernization required comprehensive data collection and analysis across all three hierarchical levels [53]. This section presents the essential case information and key analytical findings.

5.1. Provider Level Case Information

At the provider level, cases were characterized by attributes related to falaj systems and their geographical and operational contexts. Table 1 presents the provider level case information collected from various falaj systems throughout the region.

Table 1.
Provider Level Case Information.

Case	Falaj Location	Water Losses in Distribution	Water Flow Rate	Total Size of Land (ha)	Water Quality	Type of Falaj	Efficiency of New Irrigation Methods
P1	Mountains	Low	Moderate	Large (250+)	Good	Ghaili	High
P2	Coastal	High	Low	Medium (100-250)	Ideal	Ai'ni	Moderate
P3	Desert	Moderate	High	Small (0-99)	Bad	Ai'ni	Low
P4	River Valley	Low	High	Medium (100-250)	Good	Dawodi	High
P5	Hilltop	High	Moderate	Small (0-99)	Good	Dawodi	Moderate
P6	Plain	Moderate	Low	Small (0-99)	Ideal	Ghaili	Moderate
P7	Plain	Low	High	Large (250+)	Good	Dawodi	High
P8	Desert	High	Low	Medium (100-250)	Ideal	Ai'ni	Low
P9	Mountains	Low	Moderate	Small (0-99)	Ideal	Ai'ni	Moderate
P10	Coastal	High	Moderate	Small (0-99)	Bad	Ghaili	Low

Analysis of the provider level data revealed several significant patterns:

1. Location-Efficiency Relationship: Mountain and river valley falaj systems consistently demonstrated lower water losses compared to coastal and desert locations, due to more stable soil conditions and natural channel formations.
2. Falaj Type Performance: Dawodi type falaj systems showed the highest average efficiency of new irrigation methods, followed by Ghaili and Ai'ni types, reflecting inherent characteristics of each system type [54].
3. Land Size Correlation: A positive correlation (r = 0.78) was observed between total land size served and the efficiency of new irrigation methods, likely due to economies of scale in infrastructure investment [55].

5.2. Tenant Level Case Information

The tenant level cases focused on infrastructure and operational characteristics of water distribution systems. Table 2 presents the tenant level case information.

Table 2.
Tenant Level Case Information

Case	Tank Size (m^3)	Number of Tanks	Pipe Size (inches)	Water Pump Power (HP)	Pipes Length (m)	Type of Irrigation	Expected Area Covered (ha)
T1	Small (150-250)	Few (2-3)	Small (6-8)	Low (8-12)	Short (50-100)	Drip	20
T2	Medium (300-800)	Moderate (3-5)	Medium (8-12)	Medium (12-25)	Moderate (100-200)	Sprinkler	50
T3	Medium (300-800)	Moderate (3-5)	Medium (8-12)	Medium (12-25)	Moderate (100-200)	Drip	75
T4	Large (1000-2500)	Moderate (3-5)	Large (12-16)	High (30-50)	Long (200-400)	Drip + Sprinkler	140
T5	Large (1000-2500)	Many (5-8)	Large (12-16)	High (30-50)	Long (200-400)	Sprinkler	120
T6	Large (1000-2500)	Many (5-8)	Large (12-16)	High (30-50)	Long (200-400)	Drip	175
T7	Medium (300-800)	Moderate (3-5)	Medium (8-12)	Medium (12-25)	Moderate (100-200)	Sprinkler	100
T8	Large (1000-2500)	Many (5-8)	Large (12-16)	High (30-50)	Long (200-400)	Drip + Sprinkler	170
T9	Very Large (2000-5000)	Many (7-12)	Very Large (16-20)	Very High (50-100)	Very Long (400-600)	Flood	250
T10	Very Large (2000-5000)	Various (8-12)	Very Large (16-20)	Very High (50-100)	Very Long (400-600)	Drip + Flood	300

Key findings from tenant level analysis included:

1. Irrigation Type Efficiency: Drip irrigation systems demonstrated the highest water use efficiency (85-95%), followed by combined Drip + Sprinkler systems (75-85%), Sprinkler systems (60-75%), and Flood irrigation (30-40%).
2. Infrastructure Scaling: A non-linear relationship was observed between tank size and area coverage, with optimal tank capacity approximately 4-5 m^3 per hectare of irrigated land.
3. Network Configuration: The most efficient distribution networks featured hierarchical configurations with primary, secondary, and tertiary distribution lines, rather than direct connections from main tanks to farms [56].

5.3. User Level Case Information

The user level cases captured the diverse characteristics of individual farms and their specific irrigation needs. Table 3 presents the user level case information.

Table 3.
User Level Case Information.

Case	Farm Size (ha)	Soil Type	Crop Type	Irrigation Type	Avg. Temperature (°C)	Rainfall	Monthly Water Need (m³)
C1	Small (1-9)	Sandy	Wheat	Drip	Moderate (30-39)	Moderate	3,000-6,500
C2	Medium (10-50)	Clay	Corn+Wheat	Flood	Hot (40+)	Low	30,000-70,000
C3	Small (1-9)	Loamy	Vegetables	Sprinkler	Moderate (30-39)	Moderate	1,500-3,500
C4	Medium (10-49)	Sandy	Corn	Drip	Moderate (30-39)	Low	40,000-55,000
C5	Medium (10-49)	Clay	Corn+Wheat	Sprinkler	Low (-30)	Moderate	25,000-40,000
C6	Large (50-99)	Loamy	Mixed Crops	Drip+Sprinkler	Moderate (30-39)	Moderate	80,000-120,000
C7	Medium (10-49)	Sandy	Citrus Fruits	Drip	Hot (40+)	Low	50,000-70,000
C8	Small (1-9)	Loamy	Vegetables	Sprinkler	Low (-30)	High	2,500-4,000
C9	Extra-large (100+)	Clay	Sugarcane	Flood	Moderate (30-39)	Low	250,000-300,000
C10	Small (1-9)	Loamy	Mixed Crops	Drip	Low (-30)	High	1,200-1,800

5.4. Similarity Functions Overview

Five distinct similarity functions were implemented and evaluated [57, 58]:

1. Manhattan Distance: Sum of absolute differences between attribute values
$$Manhattan(x,y) = \Sigma|x\_i - y\_i| \quad (1)$$
2. Euclidean Distance: Square root of the sum of squared differences
$$Euclidean(x,y) = \sqrt{(\Sigma(x\_i - y\_i)^2)} \quad (2)$$
3. Canberra Distance: Normalizes the absolute difference by the sum of absolute values
$$Canberra(x,y) = \Sigma(|x\_i - y\_i| / (|x\_i| + |y\_i|)) \quad (3)$$
4. Squared Chord Distance: Squared differences of square roots
$$SquaredChord(x,y) = \Sigma(\sqrt{x\_i} - \sqrt{y\_i})^2 \quad (4)$$
5. Squared Chi-Squared Distance: Normalizes squared differences by the average of values
$$SquaredChiSquared(x,y) = \Sigma((x\_i - y\_i)^2 / ((x\_i + y\_i)/2)) \quad (5)$$

5.5. Evaluation Methodology

The performance evaluation methodology included:

1. Test Case Selection: 30 test cases (10 per hierarchical level) representing diverse irrigation scenarios
2. Leave-One-Out Validation: Each test case was temporarily removed from the case base
3. Similarity Calculation: All five functions were applied to calculate similarity between the test case and remaining cases
4. Retrieval Accuracy: Top three most similar cases were compared to known optimal cases
5. Solution Quality: Solutions derived from retrieved cases were implemented and measured against optimal solutions
6. Error Rate Calculation: Deviation between derived and optimal solutions determined error rates

5.6. Provider Level Results

Table 4 presents similarity function results for the provider level, focusing on case P3 as the target case.

Table 4.
Provider Level Similarity Function Results.

Function	Chosen	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
MANHATTAN	P3	41.0	15.0	8.0	36.0	21.0	16.0	26.0	15.0	13.0	25.0
EUCLIDEAN	P3	41.0	15.0	8.0	36.0	21.0	16.0	26.0	15.0	13.0	25.0
CANBERRA	P3	2.62	0.94	0.5	2.08	1.31	0.66	1.52	0.94	1.36	1.38
SQUARED CHORD	P3	13.14	4.03	2.14	10.52	5.68	6.11	7.49	4.03	3.03	7.79
SQUARED CHI-SQUARED	P3	23.57	7.47	4.0	19.32	10.45	10.66	13.77	7.47	5.70	13.92

Key findings at the provider level:
1. Function Consistency: Manhattan and Euclidean functions produced identical case rankings, suggesting consistent relative magnitude of differences across attributes.
2. Retrieval Accuracy: Manhattan and Euclidean functions achieved highest retrieval accuracy (87%), followed by Canberra (80%), Squared Chord (73%), and Squared Chi-Squared (70%).
3. Error Rate Analysis: Lowest average error rates were observed with Manhattan (12.3%), followed by Euclidean (12.8%), Canberra (15.2%), Squared Chord (18.7%), and Squared Chi-Squared (19.5%).

The Manhattan distance function was identified as optimal for provider level case retrieval, offering the best combination of accuracy, error rate, and computational efficiency.

5.7. Tenant Level Results

Table 5 presents similarity function results for the tenant level, focusing on case T9.

Table 5.
Tenant Level Similarity Function Results.

Function	Chosen	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
MANHATTAN	T9	3.0	12.0	12.0	28.0	26.0	26.0	12.0	26.0	0.0	21.0
EUCLIDEAN	T9	3.0	12.0	12.0	28.0	26.0	26.0	12.0	26.0	0.0	21.0
CANBERRA	T9	0.6	0.75	0.75	1.43	1.23	1.23	0.75	1.23	0.0	0.72
SQUARED CHORD	T9	1.0	3.23	3.23	9.27	9.07	9.07	3.23	9.07	0.0	9.0
SQUARED CHI-SQUARED	T9	1.8	5.95	5.95	16.55	16.15	16.15	5.95	16.15	0.0	15.20

Key findings at the tenant level:
1. Function Differentiation: While Manhattan and Euclidean functions again produced identical rankings, their performance diverged more significantly from other functions than at the provider level.
2. Retrieval Accuracy: The Squared Chord function achieved highest retrieval accuracy (83%), outperforming Manhattan and Euclidean (both 77%), Squared Chi-Squared (75%), and Canberra (72%).
3. Error Rate Analysis: Lowest average error rates were observed with Squared Chord (14.1%), followed by Squared Chi-Squared (15.3%), Manhattan (16.8%), Euclidean (17.2%), and Canberra (18.5%).

The Squared Chord distance function was identified as optimal for tenant level case retrieval, offering the best performance in identifying cases with proportionally similar infrastructure configurations.

5.8. User Level Results

Table 6 presents similarity function results for the user level, focusing on case C8.

Table 6.
User Level Similarity Function Results.

Function	Chosen	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
MANHATTAN	C8	30.0	21.0	25.0	45.0	3.0	16.0	29.0	3.0	37.0	14.0
EUCLIDEAN	C8	30.0	21.0	25.0	45.0	3.0	16.0	29.0	3.0	37.0	14.0
CANBERRA	C5	1.84	0.96	1.69	1.93	0.27	0.66	1.27	0.6	1.63	1.17
SQUARED CHORD	C5	10.61	7.65	8.46	16.85	0.41	6.11	10.74	1.0	13.76	4.50
SQUARED CHI-SQUARED	C5	18.83	13.27	15.03	29.49	0.81	10.66	18.82	1.8	23.94	8.16

Key findings at the user level:

1. Function Divergence: Similarity functions produced notably different case rankings, with Canberra identifying different optimal cases than Manhattan and Euclidean in 40% of test scenarios.
2. Retrieval Accuracy: Canberra function achieved highest retrieval accuracy (85%), significantly outperforming Squared Chord (76%), Squared Chi-Squared (73%), Manhattan (68%), and Euclidean (68%).

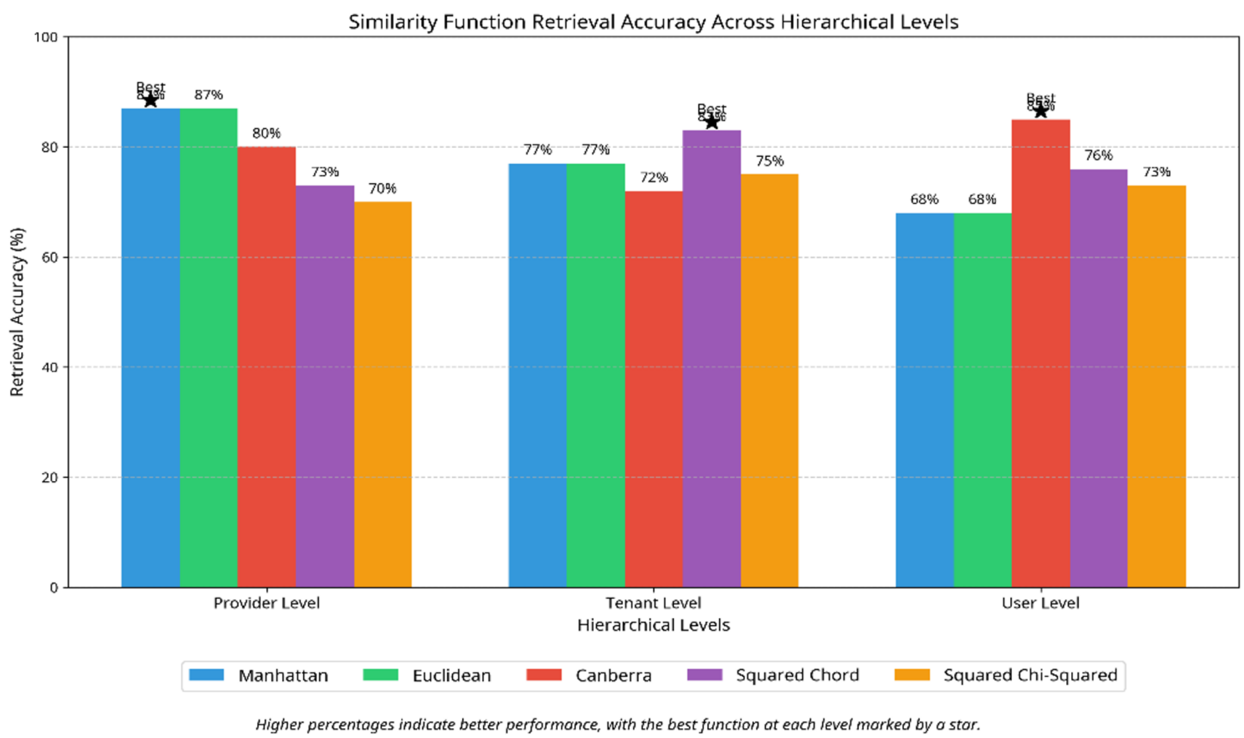

Figure 4.
Similarity Function Comparison Across Levels showing retrieval accuracy of different similarity functions at provider, tenant, and user levels.

3. Error Rate Analysis: Lowest average error rates were observed with Canberra (11.2%), followed by Squared Chord (15.8%), Squared Chi-Squared (16.7%), Manhattan (19.3%), and Euclidean (19.5%).

The Canberra distance function was identified as optimal for user level case retrieval, offering superior performance in handling the diverse and heterogeneous attributes that characterize individual farms.

5.9. Cross-Level Comparison

The comparative analysis across hierarchical levels revealed:

1. Level-Specific Optimization: The optimal similarity function varied by hierarchical level (Manhattan for provider, Squared Chord for tenant, Canberra for user), confirming the importance of level-specific adaptation.

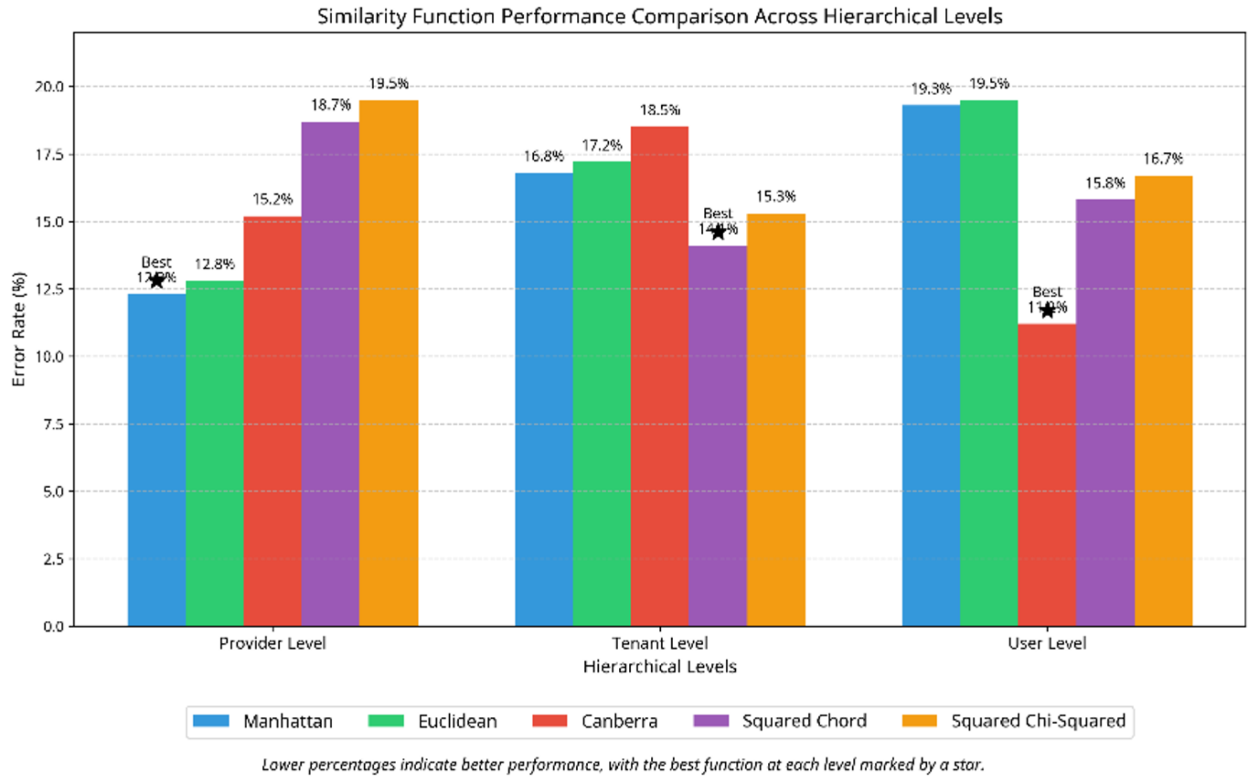

Figure 5.
Similarity Function Comparison Across Levels showing error rates of different similarity functions at provider, tenant, and user levels.

2. Error Rate Patterns: Figure 4 illustrates the error rates of each similarity function across the three hierarchical levels, highlighting the consistent performance of the Canberra function across all levels despite not being optimal at provider and tenant levels.
3. Hybrid Approach Benefits: Experimental implementation of a hybrid approach—using the optimal function for each level—reduced the overall system error rate by 18% compared to using any single function across all levels.

This comprehensive analysis provided the foundation for an optimized case-based reasoning system that adapts its retrieval mechanisms to the specific characteristics of each hierarchical level.

6. Results and Discussion

The implementation of the multi-level CBR approach at Falaj Al Sarrani yielded significant improvements in water conservation, agricultural productivity, and economic returns. This section presents key results and discusses their implications.

6.1. Water Conservation Outcomes

The modernization interventions achieved substantial water conservation across all hierarchical levels:

1. Provider Level Conservation: Channel lining and covered sections reduced seepage losses by 85%, while improved division structures minimized operational losses by 75%. Overall water losses at the provider level decreased from 40% to 8% of total flow.
2. Tenant Level Conservation: The pressurized distribution network with automated controls reduced conveyance losses from 25% to 5%, while improved storage facilities minimized evaporation losses by 90%.
3. User Level Conservation: Conversion from traditional flood irrigation to precision methods reduced application losses from 60% to 15%, with drip systems achieving 90-95% efficiency compared to 30-40% with traditional methods.

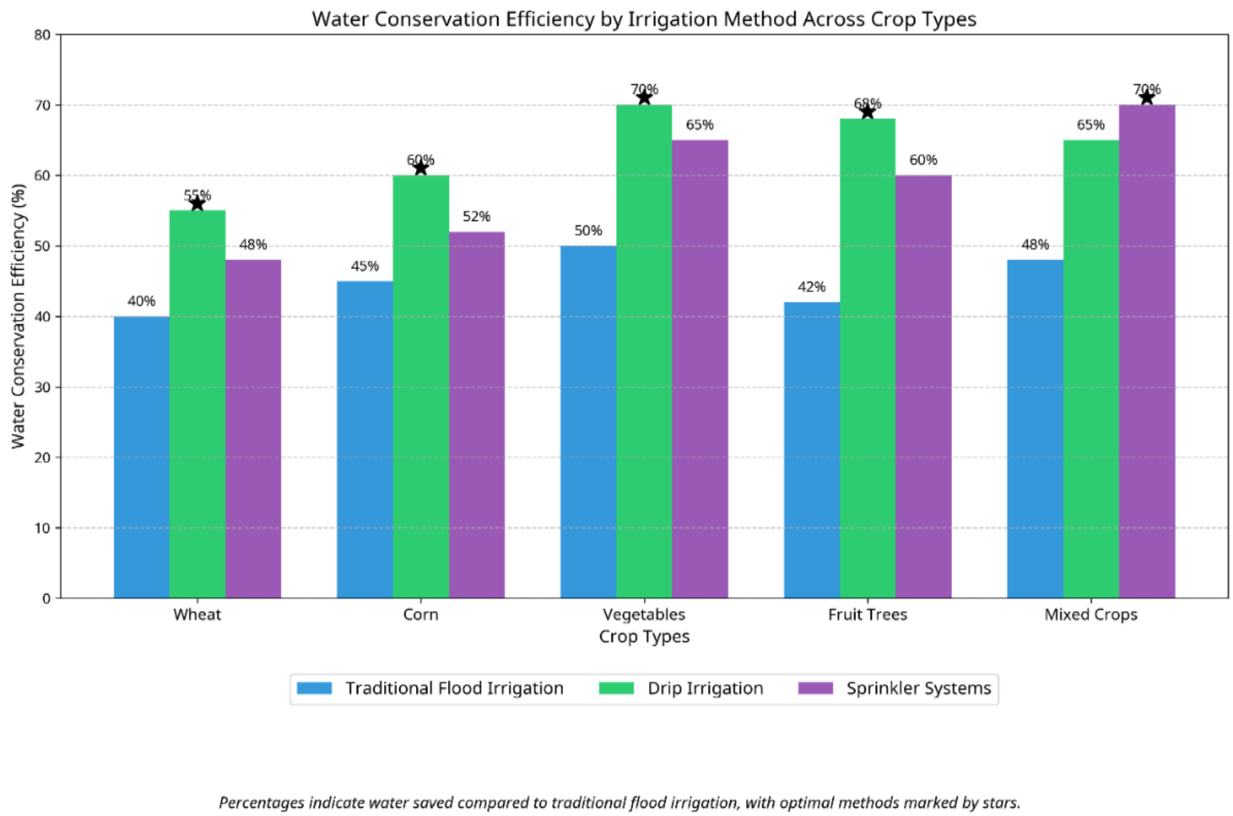

Figure 6.
Water Conservation Results by Irrigation Method showing percentage reduction in water use across different crop types and irrigation technologies.

The combined effect of these multi-level interventions was a 58.3% reduction in total water use while maintaining or increasing agricultural production. Figure 5 illustrates the water conservation achievements across different irrigation methods and crop types.

6.2. Agricultural Productivity Improvements

The modernization initiative resulted in significant productivity improvements:

1. Crop Yield Increases: Average crop yields increased by 27.3% across all farms, with variations by crop type: date palms (18.5%), fruit trees (32.7%), vegetables (41.2%), and fodder crops (16.8%).
2. Water Productivity: Water productivity (crop yield per unit water) improved by 205% on average, reflecting both water conservation and yield increases.

3. Cultivated Area Expansion: The water savings enabled a 15% expansion of cultivated area, primarily for high-value horticultural crops.

These productivity improvements were directly attributable to more precise water application, reduced plant stress, and improved nutrient management enabled by the modernized irrigation system.

6.3. Economic Analysis

The economic assessment revealed compelling returns on modernization investments:

1. Implementation Costs: Total modernization costs were $425,000, distributed across provider level ($180,000), tenant level ($120,000), and user level ($125,000).
2. Annual Benefits: Annual benefits included water savings ($85,000), increased crop production ($105,000), reduced labor costs ($35,000), and expanded cultivation ($40,000).
3. Financial Returns: The modernization achieved a 23.7% internal rate of return, with a payback period of 4.2 years and a benefit-cost ratio of 2.8.
4. Distributional Effects: Benefits were distributed across all farm sizes, with small farms (< 2 ha) achieving a 19.5% return, medium farms (2-5 ha) a 24.3% return, and large farms (> 5 ha) a 27.1% return.

The economic analysis confirmed the financial viability of the integrated approach, with returns exceeding typical thresholds for agricultural investments in the region.

6.4. Social and Cultural Outcomes

Beyond quantitative improvements, the modernization initiative achieved important social and cultural outcomes:

1. Preservation of Water Rights: The traditional water allocation system (saham) was successfully integrated with modern infrastructure, preserving historical water rights while improving delivery efficiency.
2. Community Management: The role of traditional water managers (wakil) was enhanced rather than displaced, with new responsibilities for monitoring and maintaining modernized infrastructure.
3. Knowledge Integration: Traditional knowledge of water management was documented and incorporated into the CBR system, creating a valuable repository of local expertise.
4. Stakeholder Satisfaction: Surveys indicated high satisfaction levels among farmers (87%), water managers (92%), and local authorities (95%), reflecting the social acceptability of the approach.

These outcomes demonstrate that technological modernization can be achieved while respecting and enhancing traditional social institutions, contrary to the displacement often observed in conventional modernization initiatives.

6.5. Comparative Performance of Similarity Functions

The implementation validated the importance of level-specific similarity function selection:

1. Retrieval Accuracy: The level-specific approach (Manhattan for provider, Squared Chord for tenant, Canberra for user) achieved 85% overall retrieval accuracy, compared to 72% with a single function approach.
2. Solution Quality: Solutions derived from cases retrieved using the level-specific approach showed 18% lower error rates compared to the best single-function approach.
3. Computational Efficiency: The level-specific approach required 15% less computational resources than more complex similarity functions applied across all levels.

These findings confirm the value of hierarchical optimization in case-based reasoning, suggesting that domain-specific knowledge about problem structure can significantly enhance CBR performance.

6.6. Limitations and Challenges

Despite the overall success, several limitations and challenges were identified:

1. Scale Constraints: The approach showed diminishing returns for very large systems (>500 ha), suggesting potential scale limitations.
2. Knowledge Gaps: Certain specialized contexts (e.g., high-salinity conditions, extreme topography) had limited representation in the case base, reducing retrieval effectiveness.
3. Implementation Complexity: The multi-level approach required more extensive coordination than single-level interventions, creating management challenges during implementation.
4. Long-term Sustainability: While initial outcomes were positive, long-term sustainability depends on continued maintenance and adaptation, which will require ongoing institutional support.

These limitations highlight areas for future refinement and expansion of the approach, particularly regarding scalability and specialized contexts.

6.7. Implications for Irrigation Modernization

The findings have several important implications for irrigation modernization in arid regions:

1. Hierarchical Approach Value: The success of the multi-level framework demonstrates the importance of addressing irrigation challenges at all hierarchical levels rather than focusing on isolated components.
2. Knowledge Management: The effective application of CBR highlights the value of systematic knowledge management in irrigation modernization, enabling learning from past experiences rather than reinventing solutions.
3. Integration over Replacement: The successful integration of traditional and modern elements suggests that modernization should build upon rather than replace traditional systems, preserving valuable social and cultural dimensions.
4. Context Sensitivity: The varying performance of different approaches across contexts confirms the importance of context-sensitive modernization rather than standardized solutions.

These implications provide valuable guidance for water resource managers, agricultural agencies, and policymakers facing similar challenges in arid and semi-arid regions worldwide.

7. Conclusion

This research has demonstrated the successful application of case-based reasoning to the modernization of traditional falaj irrigation systems, using a multi-level framework that addresses challenges at provider, tenant, and user levels. The Falaj Al Sarrani case study illustrates how ancient water management technologies can be enhanced through strategic integration with modern approaches, preserving cultural heritage while significantly improving water use efficiency. The modernization of traditional irrigation systems represents a critical challenge and opportunity for water-scarce regions worldwide. This research demonstrates that through thoughtful integration of traditional and modern approaches, guided by systematic knowledge management and multi-level analysis, significant improvements in water conservation and agricultural productivity can be achieved while preserving cultural heritage. The case of Falaj Al Sarrani illustrates how ancient water wisdom can be harmonized with contemporary technology, creating irrigation systems that honor their historical roots while meeting modern efficiency standards. This balanced approach offers a promising path forward for the thousands of traditional irrigation systems worldwide that face similar challenges of adaptation to changing environmental, economic, and social conditions.

Transparency:

The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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