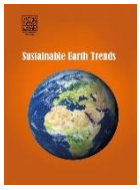
Shahid Beheshti University

Sustainable Earth Trends

Journal homepage: http://sustainearth.sbu.ac.ir



# Evaluation of the socio-economic sustainability of an underground dam: A case study of the Karnaweh Shirin underground dam, Kalat county

Ehsan Tamassoki[a], Javad Momeni Damaneh[a*], Seyed Mohammad Tajbakhsh Fakhrabadi[b], Donya Kheirkhah[a], Ali Akbar Safdari[c]

[a] Department of Natural Resources Engineering, Faculty of Agriculture and Natural Resources, University of Hormozgan, Bandar Abbas, Iran
[b] Department of Watershed Management, Natural Resources Faculty, University of Birjand, Birjand, Iran
[c] Department of Natural Resources Engineering, Natural Resources Faculty, Tehran University, Tehran, Iran

**ABSTRACT**

Underground dams serve as an innovative solution for water resource management in arid and border regions, playing a critical role in aquifer recharge and minimizing water loss. This study evaluates the sustainability of the Karnaweh Shirin underground dam in Kalat County, Razavi Khorasan Province, using structural analysis (MICMAC) and integrating field and documentary data. By identifying 14 indicators across three dimensions—economic (economic yield, income stability), social (community participation, equitable utilization), and environmental (water quality, biodiversity)—the complex relationships among variables were analyzed, and key drivers were identified. The results indicate that income stability, water and food security, equitable utilization, and biodiversity conservation are the primary drivers, while social conflicts and design-implementation inconsistencies pose significant challenges. This research provides an integrated framework for enhancing the sustainability of underground dams and offers a model for similar regions through recommendations such as strengthening community participation, managing conflicts, and implementing engineering improvements. The findings underscore the necessity of systemic approaches in managing water resources in arid border regions.

**ARTICLE INFO**

**Keywords:**
Socio-economic
Environmental
Structural analysis
Water management
Arid regions

**Article history:**
Received: 23 July 2025
Accepted: 19 December 2025

*Corresponding author
E-mail address:
j.momenidamaneh.phd@hormozgan.ac.ir
(J. Momeni Damaneh)

**Citation:**
Tamassoki, E. et al., (2026). Evaluation of the socio-economic sustainability of an underground dam: A case study of the Karnaweh Shirin underground dam, Kalat county, *Sustainable Earth Trends:* 6(4), (146-159).

**DOI**: 10.48308/set.2025.240797.1145

## 1. Introduction

Sustainable water resource management in arid and semi-arid regions, particularly under the pressures of climate change, population growth, and limited water resources, has emerged as a critical challenge of the 21st century (Vörösmarty et al., 2010). This challenge is exacerbated by the global groundwater crisis, particularly in border regions like Karnaweh Shirin, underscoring the need for innovative solutions such as underground dams (Famiglietti, 2014). The depletion of groundwater resources, a growing global concern, necessitates regional strategies that balance exploitation and aquifer sustainability, especially in areas like Karnaweh Shirin, where transboundary water loss is a significant issue (Aeschbach-Hertig and Gleeson, 2012). Underground dams, as innovative structures for storing water in aquifers, reducing surface evaporation, and enhancing groundwater accessibility, play a pivotal role in bolstering water resource sustainability in such regions (Dillon, 2005). Yifru et al. (2019) highlights these structures as sustainable solutions for water storage in arid regions, emphasizing the importance of precise engineering design for the success of projects like the Karnaweh Shirin underground dam. By enhancing artificial aquifer recharge, these structures not only improve water use efficiency but also mitigate surface and groundwater losses, particularly in border areas, thereby contributing to water security and ecosystem sustainability (Angelakis et al., 2018). However, the sustainability of such project's hinges on

Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY). license (https://creativecommons.org/licenses/by/4.0/).

multiple factors, including precise engineering design, social acceptance, local conflict management, and environmental protection (Gleeson et al., 2012). A comprehensive evaluation of their sustainability requires an integrated approach that analyzes the complex interactions among economic, social, and environmental dimensions and identifies key drivers of long-term success (Sivapalan et al., 2012). Community participation, management of social conflicts arising from infrastructure degradation, and regional biodiversity conservation are among the factors that significantly influence the long-term sustainability of such projects (Tamassoki et al., 2025). Previous studies indicate that neglecting these dimensions can reduce the efficiency of similar projects or even lead to their failure (Wheater et al., 2015).

This study employs structural analysis (MICMAC) and integrates field and documentary data to comprehensively evaluate the sustainability of the Karnaweh Shirin underground dam. This approach facilitates the identification of complex relationships among economic (e.g., economic yield, income stability), social (e.g., community participation, equitable utilization), and environmental (e.g., water quality, biodiversity) variables (Godet, 2000). The primary objective is to identify key drivers of the project's sustainability and provide strategic recommendations to enhance its performance and serve as a model for other arid and border regions. This study not only contributes to a deeper understanding of the systemic dynamics of the Karnaweh Shirin underground dam but also offers a scientific and practical framework for policymaking and water resource management in regions facing similar challenges (Loucks et al., 2005).

Numerous studies have explored underground dams and their role in water resource management, yet few have specifically analyzed their sustainability through an integrated, systemic approach in border regions. Angelakis et al. (2018) provide a comprehensive review of the evolution of water management systems, emphasizing the role of underground dams in reducing evaporation and enhancing groundwater storage. Their study highlights the historical use of these structures in arid and semi-arid regions, particularly in the Middle East and North Africa, and notes their enhanced efficiency with modern technologies. Hashemi et al. (2014) review artificial recharge methods in arid and semi-arid regions, underscoring the potential of underground dams to improve water management and reduce resource loss, aligning with the objectives of the Karnaweh Shirin dam. However, these studies pay less attention to the socio-economic dimensions of sustainability.

Dillon (2005) examines the technical and hydrological aspects of managed aquifer recharge, demonstrating that precise design and site selection can enhance aquifer sustainability. Yet, this study gives limited attention to implementation challenges and socio-environmental impacts, emphasizing the need for integrated social and environmental analyses. Similarly, Gleeson et al. (2012) introduce the concept of the "groundwater footprint," highlighting that unsustainable aquifer management can deplete water resources and negatively impact ecosystems. While their study stresses the importance of global water balance, it does not specifically address local projects like underground dams in border regions.

From a social perspective, Shah (2018) explores groundwater governance in irrigated agriculture, emphasizing the importance of community participation and equitable water distribution. This research indicates that neglecting equitable access can lead to social conflicts and reduced project acceptance, a relevant concern for the Karnaweh Shirin dam. Tamassoki et al. (2025) examine water governance in transboundary basins, highlighting how social and political conflicts can jeopardize the sustainability of water projects. These findings underscore the need to address social conflict management in the Karnaweh Shirin project.

In Iran, limited studies have specifically focused on underground dams. Madani (2016) highlights structural challenges in the design and implementation of watershed management projects in Iran, emphasizing the need to consider social and environmental dimensions. Similarly, Biniaz and Tamassoki (2023) examine integrated water resource management in Iran, identifying challenges such as institutional coordination deficits and the need for localized approaches in arid regions, which align with the implementation issues of the Karnaweh Shirin dam. Their study suggests that a lack of community participation and neglect of environmental impacts can undermine project sustainability. Faramarzi et al. (2013)

analyze groundwater resources in Iran, noting the depletion of aquifers in arid and semi-arid regions and advocating for structures like underground dams to support aquifer recharge. However, these studies do not specifically address the systemic sustainability analysis of projects like the Karnaweh Shirin dam.

Overall, the literature suggests that while underground dams hold significant technical and hydrological potential for water resource management, their sustainability depends on factors such as precise design, social participation, conflict management, and environmental protection. The Karnaweh Shirin underground dam was designed and implemented to recharge aquifers, enhance qanat discharge, and prevent transboundary water loss. However, its success extends beyond hydrological achievements. By focusing on the Karnaweh Shirin underground dam and utilizing structural analysis (MICMAC) and field data, this study aims to address gaps in the existing literature. It not only identifies key sustainability drivers but also provides a comprehensive framework for evaluating the socio-economic and environmental sustainability of similar projects in arid and border regions (Loucks et al., 2005).

## 2. Material and methods

### *2.1. Case Study*

The village of Karnaweh Shirin and its watershed are located in the northwest of Razavi Khorasan Province, Kalat Naderi County, Lain District, approximately 13 km west of Lain city, 61 km from Kalat Naderi city, and 113 km from Mashhad city. Politically, the watershed lies at the boundary between Kalat and Dargaz counties. The most suitable access route to the project site is via the paved Mashhad-Kalat-Dargaz road. The underground dam project is situated at the geographical coordinates of 37°13'54.5" N latitude and 59°26'34" E longitude, adjacent to the entrance of the secondary road leading to Karnaweh Shirin village (Fig. 1). The Karnaweh Shirin watershed covers an area of 59.09 km², with elevations ranging from 541 m (minimum) to 2,137 m (maximum) above sea level. The slope of the main watercourse at the gorge entrance and the proposed project site is estimated at approximately 2.5%.

Climatically, based on data from 1998–2018, the average annual precipitation at the Lain No evaporation station, representative of the region, is 295.9 mm. The highest seasonal precipitation (38%) occurs in spring, while the lowest (3%) is recorded in summer. The average annual temperature is 15.8°C. Annual evaporation from the pan is estimated at 1,576 mm, with a potential evapotranspiration of 886.5 mm. Geologically, the region is influenced by the sedimentary-structural zone of the Kopet-Dagh. The Mozduran Formation is the oldest, while the Chehel Kaman Formation is the youngest. The presence of erosion-sensitive formations such as Abtalkh and Abdaraz has resulted in a relatively low slope of the main watercourse and the development of floodplains.

From a socio-economic perspective, Karnaweh Shirin village is recognized as a key livestock hub in Kalat County. Agriculture and livestock rearing play significant roles in the livelihoods of residents. According to the most recent local effectiveness study (Razavi Khorasan Natural Resources and Watershed Management Office, 2021), migration data for the period immediately following dam implementation indicated limited net migration, with two individuals migrating to the village and two leaving in 2019. Over the three-year period from 2018 to 2020, approximately ten individuals were reported to have migrated out of the village.

Overall, the Karnaweh Shirin watershed, located in Kalat County, Razavi Khorasan Province, as a border region with distinct hydrological, climatic, and socio-economic characteristics, provides a suitable context for evaluating the sustainability of underground dams (Razavi Khorasan Natural Resources and Watershed Management Office, 2020). The region faces challenges such as declining aquifer levels, heavy reliance on qanats for agricultural and drinking water supply, and issues related to the transboundary loss of groundwater to neighboring countries (Shah, 2018).

### *2.1. Methodology*

This study is applied research with a descriptive-analytical approach, aimed at evaluating the sustainability of the underground dam in the Karnaweh Shirin watershed, Kalat County. The research process integrates

qualitative and quantitative approaches, drawing on documentary studies, expert-driven analyses, and foresight software tools. Data were collected and analyzed through three main pathways: a review of theoretical literature, field observations (Including physical inspection of the dam, environmental assessment and interaction with the local community), and structural analysis of variable interrelationships. From a systems analysis perspective, Godet (2000) introduced the MICMAC (Matrice d'Impacts Croisés-Multiplication Appliquée à un Classement) structural analysis method as a framework for identifying key drivers and analyzing complex variable interactions. Arcade et al. (1999) demonstrated recent advancements in MICMAC applications for analyzing complex systems, such as water resource management. This method has been applied in various water management studies, including Sivapalan et al. (2012), to analyze socio-hydrological interactions. These studies highlight those systemic approaches can identify leverage points and key dependencies in complex systems, though their application to underground dams in Iran's arid regions remains underexplored. Wheater et al. (2015) emphasized the need to integrate systems analysis with field data to assess project sustainability, noting that design-implementation inconsistencies can reduce project efficiency, a challenge also observed in the Karnaweh Shirin dam.

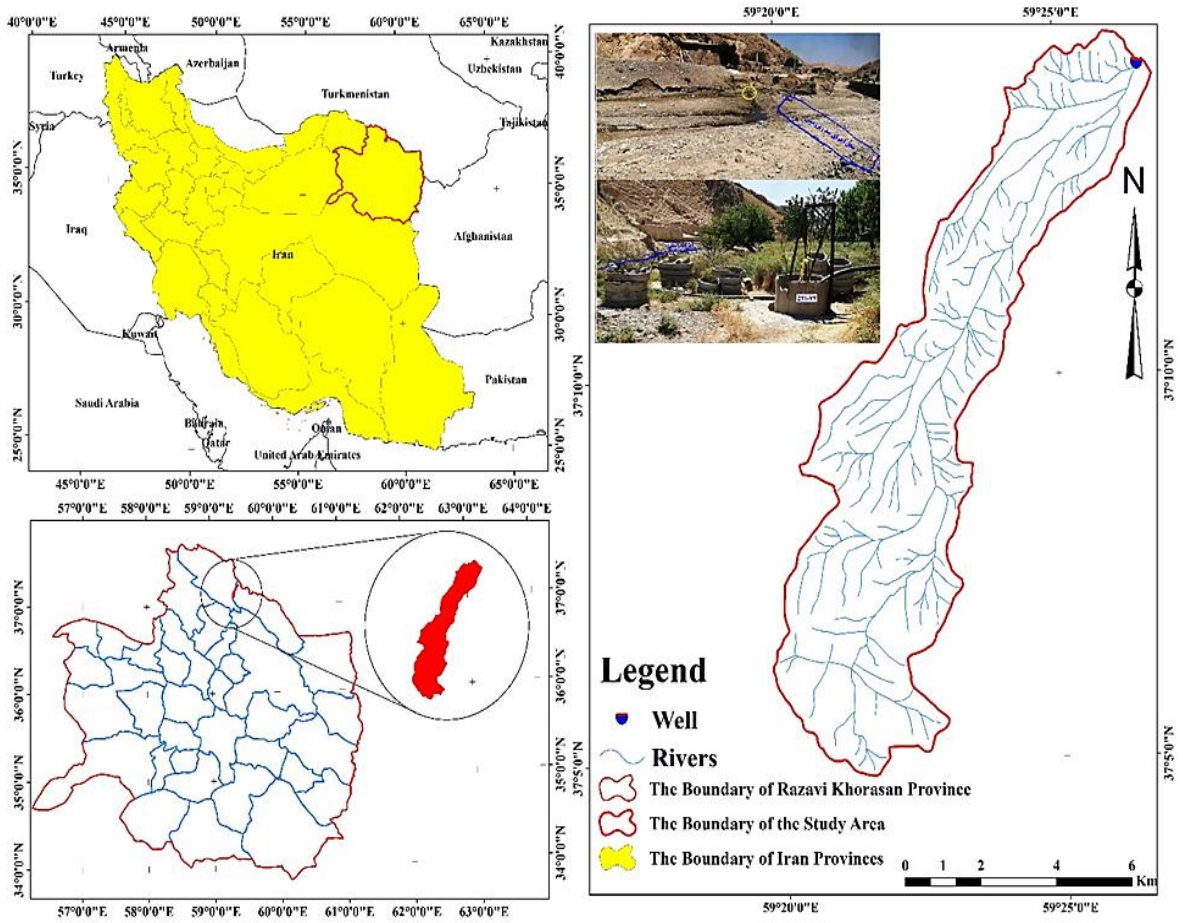



**Fig. 1.** Geographical location of the underground dam in the Karnaweh Shirin watershed.

In the first step, a theoretical framework was developed, and fundamental concepts related to underground dam sustainability were extracted through a literature review of domestic and international scientific sources. Simultaneously, initial indicators and components affecting underground dam sustainability were identified from credible sources, policy documents, and prior research, and categorized preliminarily. To refine and localize these indicators, a field research phase was conducted involving experts. Using the snowball sampling method, 27 experts were selected, comprising 17 water resource management professionals and 10 academic specialists in natural resources and

environmental policy. Data collection tools included semi-structured interviews and specialized questionnaires, designed in two stages based on cross-impact analysis principles.

To analyze the data and evaluate relationships among the identified variables, the cross-impact structural analysis technique was employed. This technique, a cornerstone of foresight studies, enables the identification and measurement of mutual influence and dependency among variables within an N × N matrix. All selected variables were quantified in numerical matrices, and through expert judgment, the direct, indirect, and potential influence of each variable on others was determined. These values ranged from 0 (no effect) to 3 (high effect), with the symbol P indicating potential influence, and were processed using the MICMAC software. The strength of this method lies in its ability to move beyond one-dimensional perspectives, revealing complex networked relationships among variables and extracting key future drivers.

Furthermore, to understand the underground dam system under conditions of uncertainty, structural analysis was applied. This method, with a systemic approach integrating qualitative and quantitative data, examines the internal relationships among variables along influence-dependency axes and visualizes their distribution patterns in a two-dimensional space. The final output of this analysis includes identifying key variables, determining system focal points, and laying the groundwork for designing future scenarios.

## 3. Results and discussion

This study evaluated the sustainability of the Karnaweh Shirin underground dam by identifying 14 key indicators across three dimensions—economic, social, and environmental—and analyzing their complex interrelationships using structural analysis (MICMAC). The economic indicators include economic yield (E1), income stability for beneficiaries (E2), operation and maintenance costs (E3), and employment generation (E4). Social indicators encompass local stakeholder satisfaction (S1), community participation in project management (S2), water and food security in the region (S3), equitable utilization of water resources (S4), and the status of social conflicts (S5). Environmental indicators consist of groundwater quality (Env1), aquifer depletion rate (Env2), changes in regional vegetation cover (Env3), impact on biodiversity (Env4), and control of transboundary water loss (Env5) (Table 1).

### *3.1. Identifying sustainability drivers and leverage points*

The direct Influence matrix (Table 2) and the direct Influence diagram (Fig. 2) revealed that indicators such as biodiversity Influence (Env4) and social indicators including stakeholder satisfaction (S1), community participation (S2), and social conflicts (S5) exert strong direct effects (intensity of 3) on economic indicators such as operation and maintenance costs (E3) and employment generation (E4), as well as other social indicators. The direct influence/dependency map (Fig. 3) delineates the position of each variable based on its degree of influence and dependency.

Key driver variables, characterized by high influence and low dependency, include economic yield (E1), income stability for beneficiaries (E2), control of transboundary water loss (Env5), changes in vegetation cover (Env3), equitable utilization of water resources (S4), and water and food security (S3). These variables demonstrate significant potential to drive systemic change. Leverage/high-risk variables, with both high influence and high dependency, include employment generation (E4), biodiversity Influence (Env4), stakeholder satisfaction (S1), operation and maintenance costs (E3), community participation (S2), and social conflicts (S5). These variables are both highly influential and sensitive, necessitating critical management attention. Groundwater quality (Env1) was classified as an independent variable (low influence and dependency), while aquifer depletion rate (Env2) was identified as a dependent variable (low influence but high dependency).

In the stability analysis of the Karnaweh Shirin underground dam, the distribution of variables in the direct influence/dependence map (Fig. 3) provides critical insights into the system's status. Unlike the "L-shaped" distribution, which, according to MicMac analysis principles, indicates stable systems with distinct roles for influential, independent, and

output variables (Godet, 2000), the observed dispersion in this study is predominantly aligned along the diagonal axis of the chart (from northwest to southeast). This pattern, based on MicMac principles, signifies system instability (Jodlbauer et al., 2022).

**Table 1.** Indicators, dimensions, and descriptions related to the Karnaweh Shirin region.

| Code | Indicator | Dimension | Description related to Karnaweh Shirin |
|---|---|---|---|
| E1 | Economic Yield (ROI) | Economic | Net profit relative to total costs incurred (including income from alfalfa and wheat cultivation, livestock rearing, and ecosystem value). |
| E2 | Income Stability for Beneficiaries | Economic | Continuity and growth of income for residents covered by the dam, particularly farmers and livestock breeders in Karnaweh Shirin village, considering increased qanat discharge and assured wheat production. |
| E3 | Operation and Maintenance Costs | Economic | Actual costs of operation, repairs, and maintenance of the underground dam (currently excluding pumping and labor costs, but these should be included in the future upon project completion). |
| E4 | Employment Generation | Economic | Job opportunities created by the project (including labor during the implementation phase and sustained agricultural and livestock-related jobs). |
| S1 | Local Stakeholder Satisfaction | Social | Qualitative and quantitative perceptions of project performance by villagers, including increased qanat discharge and improved livelihoods. |
| S2 | Community Participation in Project Management | Social | Role of villagers or stakeholders in decision-making, maintenance, and operation (currently, participation is primarily in providing labor and qanat restoration). |
| S3 | Water and Food Security in the Region | Social | Improvement or maintenance of sustainable drinking water supply for livestock and irrigation water, considering increased qanat discharge and availability of water for summer cultivation. |
| S4 | Equitable Utilization of Water Resources | Social | Balanced access to water benefits among different groups (considering water shares for wheat and alfalfa irrigators and challenges related to qanat damage). |
| S5 | Status of Social Conflicts | Social | Impact of the dam on local disputes or conflicts (considering the role of exploitation wells in reducing qanat discharge and damage to some infrastructure). |
| Env1 | Groundwater Quality | Environmental | Changes in salinity, hardness, nitrate, and other parameters (based on chemical analysis of water, characterized as sulfate-calcite type). |
| Env2 | Aquifer Depletion Rate | Environmental | Assessment of groundwater table sustainability (considering increased well and qanat discharge after dam implementation). |
| Env3 | Changes in Regional Vegetation Cover | Environmental | Degradation or restoration of green cover due to the project (considering alfalfa and wheat cultivation and reduced pressure on rangelands). |
| Env4 | Impact on Biodiversity | Environmental | Conservation or threat to plant/animal species (ecosystem valuation of regulatory, habitat, productive, and informational functions). |
| Env5 | Control of Transboundary Water Loss | Environmental | Prevention of subsurface water flow to the neighboring country (Turkmenistan). |

This instability stems from the presence of several "leverage/high-risk" variables that exhibit both high influence and high dependence. Indicators such as "employment generation (E4)," "impact on biodiversity (Env4)," "local stakeholder satisfaction (S1)," "operation and maintenance costs (E3)," "community participation in project management (S2)," and "status of social conflicts (S5)" fall into this category. The strong bidirectional influence of these variables, particularly "social conflicts (S5)," which exerts a significant indirect effect on "income stability for beneficiaries (E2)," increases the complexity and uncertainty in the dam system's dynamics. Additionally, implementation challenges, such as water leakage due to the dam's lack of connection to bedrock, damage to infrastructure, and social conflicts arising from uncompensated damages, further exacerbate this instability. Therefore, despite initial hydrological and economic achievements, the current systemic structure of the Karnaweh Shirin underground dam indicates a condition that requires active intervention and an adaptive management approach to achieve long-term sustainability. In Table 2, the characteristics of the initial matrix based on the opinions of experts and specialists are presented; in Table 4, the matrix of direct and indirect influences of factors affecting the stability of subsurface dams; and in Table 5, the matrix of potential direct and indirect influences of factors affecting the stability of subsurface dams is provided.

**Table 2.** Characteristics of the initial matrix based on expert opinion.

| INDICATOR | VALUE |
|---|---|
| Matrix size | 14 |
| Number of iterations | 2 |
| Number of zeros | 38 |
| Number of ones | 65 |
| Number of twos | 63 |
| Number of threes | 30 |
| Number of P | 0 |
| Total | 158 |
| Fillrate | 80.61224% |

**Table 3.** Structural questionnaire for the study area.

| From → To ↓ | E1 | E2 | E3 | E4 | S1 | S2 | S3 | S4 | S5 | Env1 | Env2 | Env3 | Env4 | Env5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E1 | - | 1 | 3 | 2 | 2 | 3 | 2 | 1 | 3 | 1 | 3 | 1 | 1 | 2 |
| E2 | 2 | - | 3 | 3 | 2 | 3 | 3 | 1 | 3 | 1 | 3 | 1 | 1 | 3 |
| E3 | 2 | 2 | - | 3 | 3 | 3 | 1 | 0 | 3 | 2 | 1 | 0 | 0 | 1 |
| E4 | 2 | 2 | 3 | - | 3 | 2 | 2 | 2 | 3 | 1 | 3 | 1 | 1 | 2 |
| S1 | 2 | 2 | 2 | 3 | - | 2 | 1 | 2 | 3 | 1 | 2 | 1 | 1 | 3 |
| S2 | 1 | 1 | 3 | 3 | 2 | - | 2 | 2 | 3 | 1 | 2 | 1 | 1 | 2 |
| S3 | 1 | 1 | 1 | 1 | 1 | 3 | - | 1 | 2 | 2 | 2 | 1 | 1 | 2 |
| S4 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | - | 3 | 1 | 1 | 1 | 1 | 2 |
| S5 | 1 | 1 | 2 | 2 | 2 | 3 | 2 | 2 | - | 1 | 2 | 1 | 1 | 2 |
| Env1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | 1 | 1 | 1 | 3 |
| Env2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | 1 | 0 | 3 |
| Env3 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | - | 2 | 1 |
| Env4 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | - | 1 |
| Env5 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 0 | - |

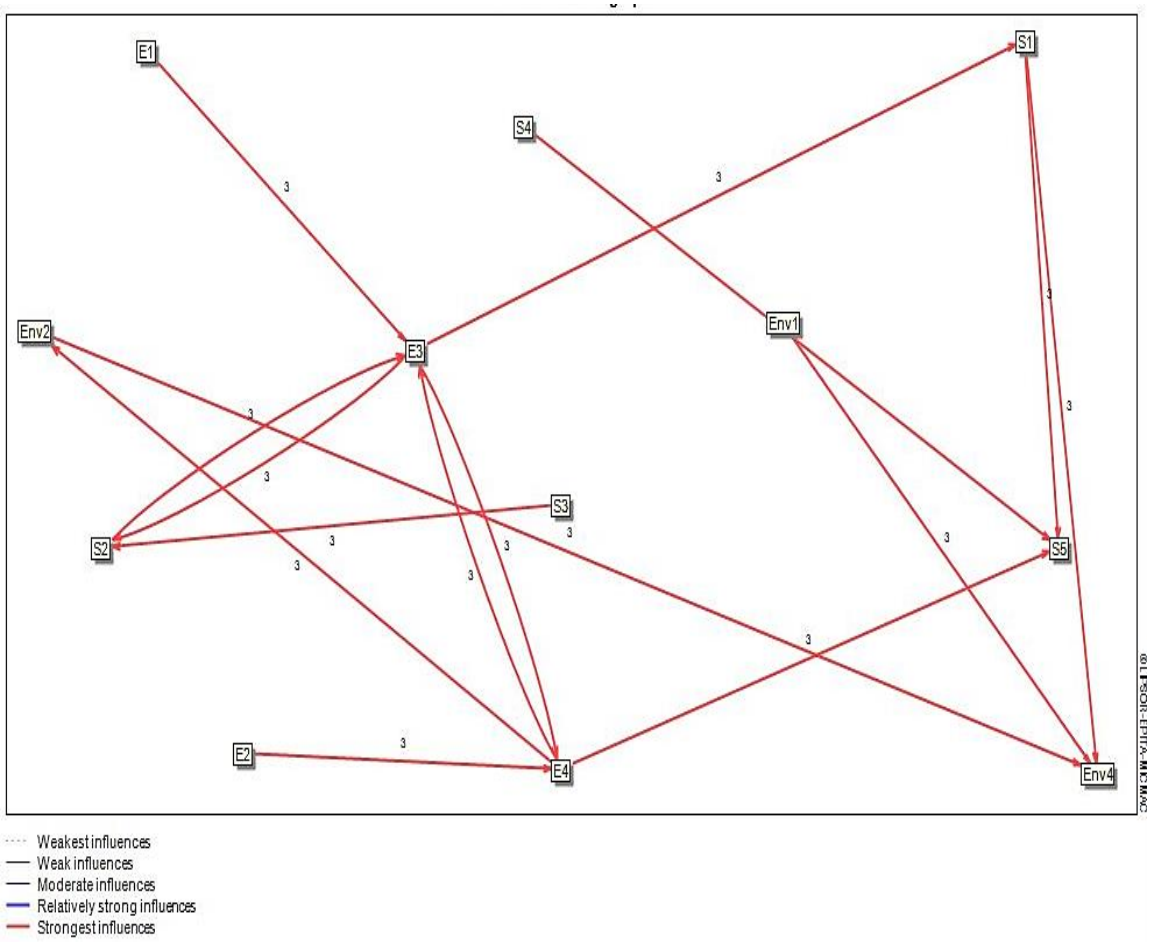



**Fig. 2.** Direct influence.

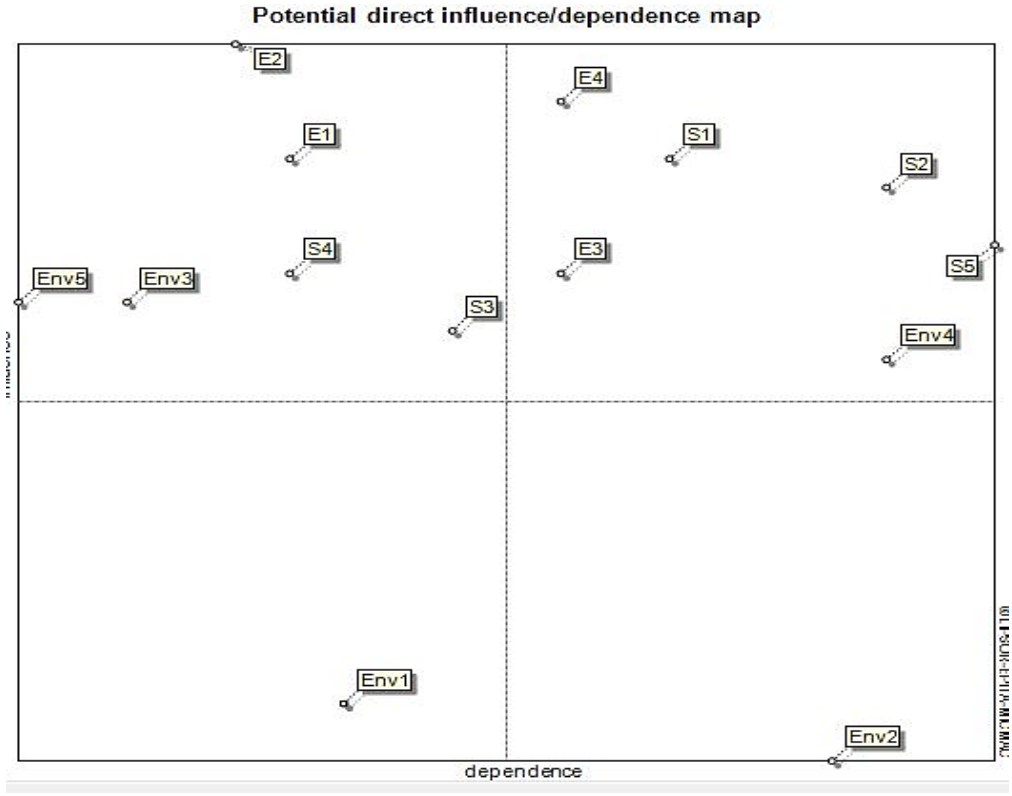



**Fig. 3.** Direct influence/dependence map.

**Table 4.** Matrix of direct and indirect influences on subsurface dam stability.

| RANK | LABEL | DIRECT INFLUENCE | LABEL | DIRECT DEPENDENCE | LABEL | INDIRECT INFLUENCE | LABEL | INDIRECT DEPENDENCE |
|---|---|---|---|---|---|---|---|---|
| 1 | E2 | 1032 | S5 | 1032 | E2 | 1027 | S5 | 1005 |
| 2 | E4 | 960 | S2 | 960 | E4 | 965 | Env4 | 970 |
| 3 | E1 | 889 | Env4 | 960 | S1 | 921 | S2 | 940 |
| 4 | S1 | 889 | Env2 | 925 | E1 | 879 | Env2 | 911 |
| 5 | S2 | 854 | S1 | 818 | S2 | 873 | S1 | 815 |
| 6 | S5 | 782 | E3 | 747 | E3 | 813 | E4 | 774 |
| 7 | E3 | 747 | E4 | 747 | S5 | 796 | E3 | 764 |
| 8 | S4 | 747 | S3 | 676 | S4 | 791 | S3 | 691 |
| 9 | Env3 | 711 | Env1 | 604 | Env3 | 688 | Env1 | 591 |
| 10 | Env5 | 711 | E1 | 569 | Env5 | 688 | S4 | 578 |
| 11 | S3 | 676 | S4 | 569 | S3 | 644 | E1 | 573 |
| 12 | Env4 | 640 | E2 | 533 | Env4 | 615 | E2 | 547 |
| 13 | Env1 | 213 | Env3 | 462 | Env1 | 168 | Env3 | 459 |
| 14 | Env2 | 142 | Env5 | 391 | Env2 | 127 | Env5 | 373 |

**Table 5.** Matrix of potential direct and indirect influences on subsurface dam stability.

| RANK | LABEL | POTENTIAL DIRECT INFLUENCES | LABEL | POTENTIAL DIRECT DEPENDENCE | LABEL | POTENTIAL INDIRECT INFLUENCE | LABEL | POTENTIAL DIRECT DEPENDENCE |
|---|---|---|---|---|---|---|---|---|
| 1 | E2 | 1032 | S5 | 1032 | E2 | 1027 | S5 | 1005 |
| 2 | E4 | 960 | S2 | 960 | E4 | 965 | Env4 | 970 |
| 3 | E1 | 889 | Env4 | 960 | S1 | 921 | S2 | 940 |
| 4 | S1 | 889 | Env2 | 925 | E1 | 879 | Env2 | 911 |
| 5 | S2 | 854 | S1 | 818 | S2 | 873 | S1 | 815 |
| 6 | S5 | 782 | E3 | 747 | E3 | 813 | E4 | 774 |
| 7 | E3 | 747 | E4 | 747 | S5 | 796 | E3 | 764 |
| 8 | S4 | 747 | S3 | 676 | S4 | 791 | S3 | 691 |
| 9 | Env3 | 711 | Env1 | 604 | Env3 | 688 | Env1 | 591 |
| 10 | Env5 | 711 | E1 | 569 | Env5 | 688 | S4 | 578 |
| 11 | S3 | 676 | S4 | 569 | S3 | 644 | E1 | 573 |
| 12 | Env4 | 640 | E2 | 533 | Env4 | 615 | E2 | 547 |
| 13 | Env1 | 213 | Env3 | 462 | Env1 | 168 | Env3 | 459 |
| 14 | Env2 | 142 | Env5 | 391 | Env2 | 127 | Env5 | 373 |

The analysis of the indirect influence diagram (Fig. 4) and the potential indirect influence diagram (Fig. 5) revealed that social conflicts (S5) with a value of 1,142 and biodiversity influence (Env4) with a value of 1,120 exert the strongest indirect influences on income stability for beneficiaries (E2). This analysis indicates that changes in social conflicts and biodiversity influence can significantly affect income stability indirectly through a chain of interconnected factors. Additionally, E2 is most strongly influenced indirectly by Env4 and S5. Overall, the results highlight that income stability (E2), water and food security (S3), equitable utilization of water resources (S4), and biodiversity conservation (Env4) are the primary drivers of the sustainability of the Karnaweh Shirin underground dam. Social conflicts (S5), due to their strong indirect influence on income stability (E2) and their classification as a leverage variable, require particular attention.

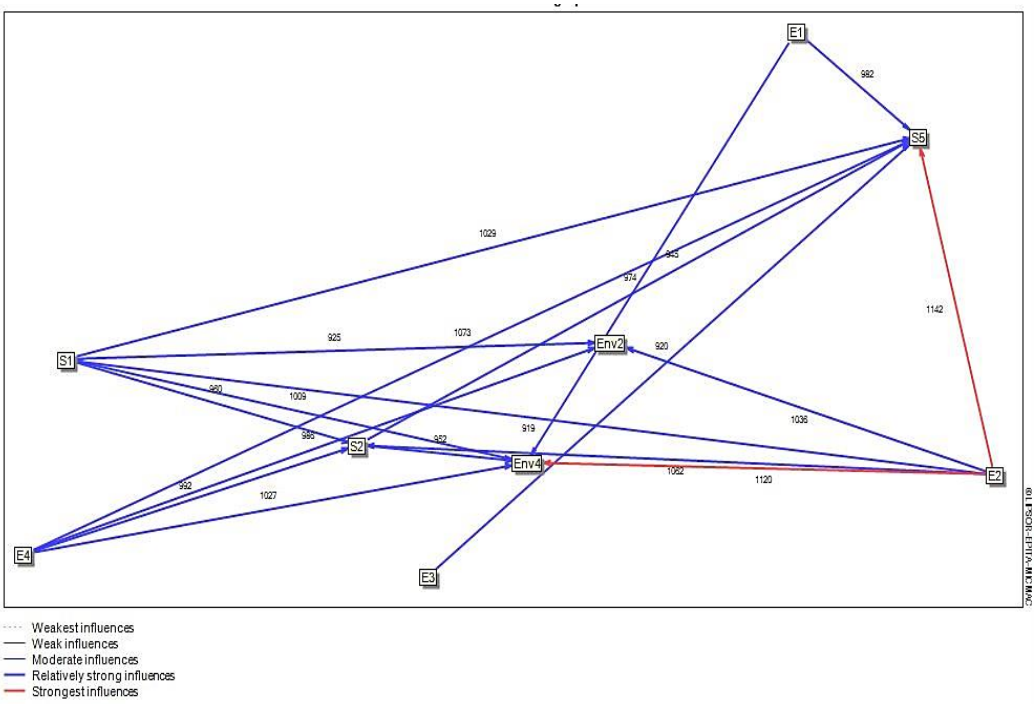



**Fig. 4.** Indirect influences.

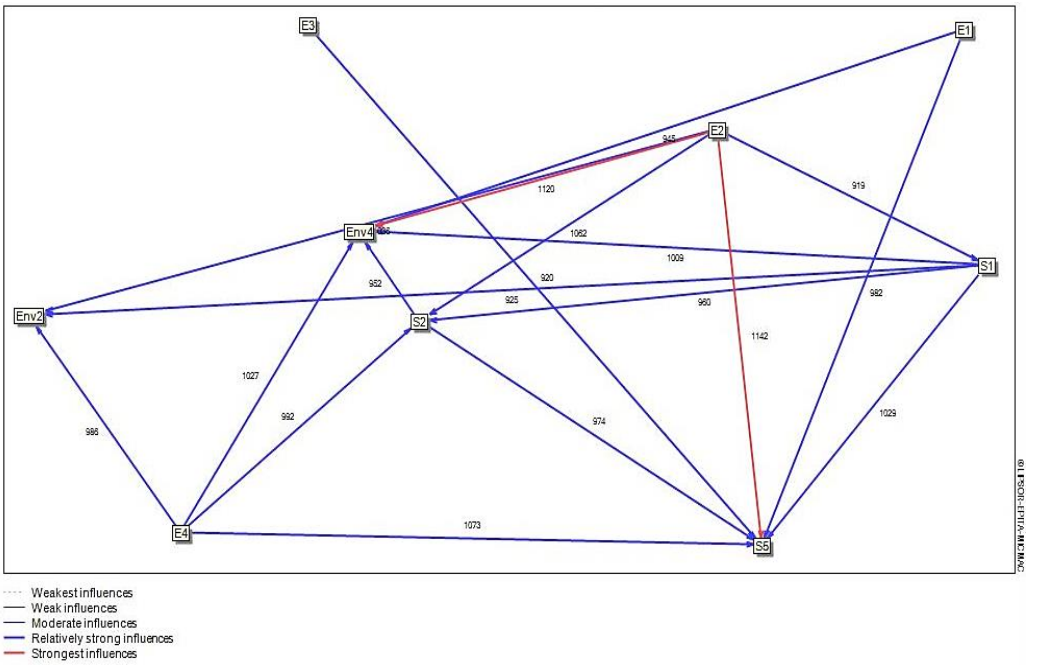



**Fig. 5.** Potential indirect influences.

The potential direct influence diagram (Fig. 6) illustrates direct influences that could become stronger in the future or are currently underperforming relative to their potential. The diagram indicates that groundwater quality (Env1) has the potential to exert a strong influence on E1, E2, E3, E4, S1, S2, S3, S4, S5, and Env2. Additionally, employment generation (E4) could have strong potential influences on S1, S2, S3, and S5, while social conflicts (S5) influence S1 and S3. Biodiversity influence (Env4) also shows potential for strong influence on E3, S3, and S5. These findings highlight potential leverage points in the system that, with appropriate investment and planning, could significantly enhance the overall sustainability of the project. The Potential Direct Influence Diagram (Fig. 6) is derived from the difference between the Direct Influence matrix and the Potential Direct Influence matrix in MICMAC analysis. The Potential matrix represents the maximum intensity of influence that one variable could exert on others over the long term under optimal conditions. Thus, the strong links depicted in this diagram (such as the influence of Env1 on numerous variables, or E4 on social indicators) highlight areas within the system that currently exhibit weak direct impacts but possess inherent potential to become key leverage points in the future. Analyzing these potentials reveals promising avenues for targeted investment and planning to enhance the project's overall sustainability.

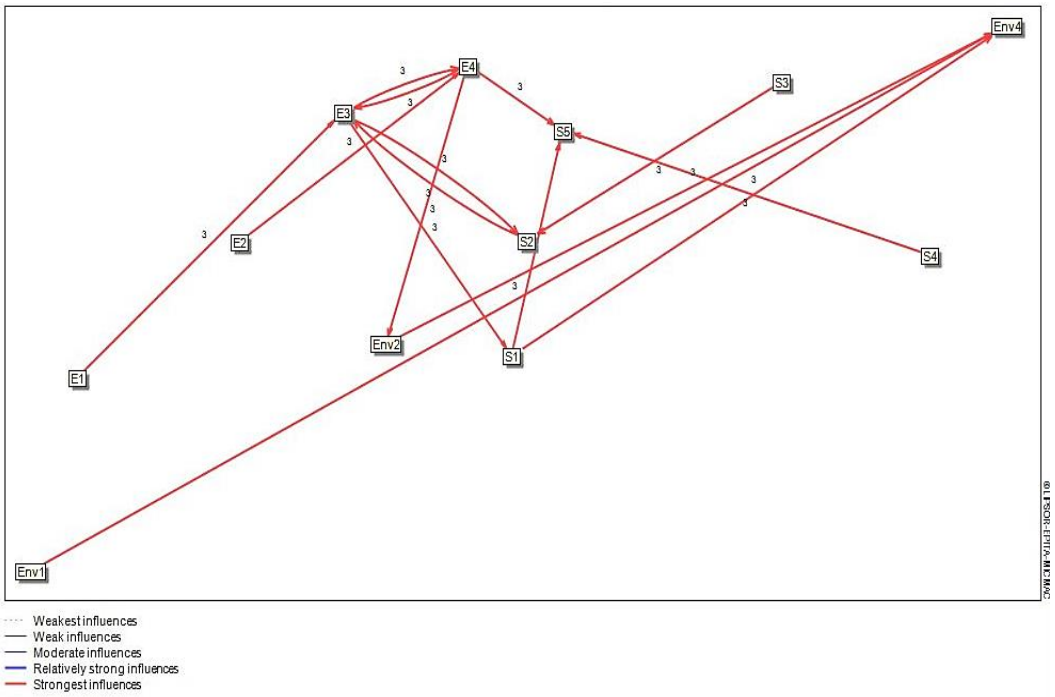



**Fig. 6.** Potential direct influences.

Overall, the results indicate that income stability (E2), water and food security (S3), equitable utilization of water resources (S4), and biodiversity conservation (Env4) are the primary drivers of the sustainability of the Karnaweh Shirin underground dam, while social conflicts (S5) represent a key challenge. The findings emphasize the necessity of systemic approaches in managing water resources in arid border regions. From an ecohydrological perspective, a 7.5-fold increase in qanat discharge (from 2 to 15 liters per second) and improved aquifer recharge (48% reduction in runoff height and 52% reduction in runoff coefficient) are significant achievements of the project. Additionally, direct income generation exceeding 10 billion IRR through alfalfa and wheat cultivation and livestock rearing highlights the project's economic benefits. However, challenges such as water leakage due to the dam's lack of connection to bedrock, damage to 60 meters of the qanat pathway and three well shafts, and the incomplete development of pumping and storage facilities threaten the project's long-term sustainability. Dillon et al. (2009) demonstrated that design-implementation mismatches, such as failure to connect to an

impermeable layer, can reduce the hydrological efficiency of underground dams, a challenge observed in the Karnaweh Shirin dam.

The Karnaweh Shirin underground dam exemplifies developmental projects in arid and semi-arid regions, with its performance dependent on a delicate balance among economic, social, and environmental objectives. Integrated MICMAC analysis and effectiveness studies reveal that, despite positive hydrological and socio-economic outcomes, the project faces significant challenges in design, implementation, and social consequences that jeopardize its long-term sustainability. From an ecohydrological perspective, the dam has achieved notable success in artificial aquifer recharge, evidenced by a 7.5-fold increase in qanat discharge (from 2 to 15 liters per second) and improved aquifer recharge (48% reduction in runoff height and 52% reduction in runoff coefficient) (Razavi Khorasan Natural Resources and Watershed Management Office, 2020). These findings align with Dillon (2005), who emphasized the role of underground dams in enhancing aquifer sustainability. However, design-implementation mismatches, such as the dam's lack of connection to bedrock and water leakage from the left abutment, have reduced hydrological efficiency (Razavi Khorasan Natural Resources and Watershed Management Office, 2020), a problem also noted by Madani (2016) as a factor diminishing the effectiveness of watershed management projects in Iran.

From an environmental perspective, biodiversity conservation (Env4) and changes in vegetation cover (Env3) were identified as key drivers with strong indirect influences on income stability (E2). These results align with Gleeson et al. (2012), who highlighted the importance of ecosystem services in water resource sustainability, but this study's use of MICMAC analysis provides a novel quantitative and networked perspective on indirect relationships. From a social perspective, social conflicts (S5) arising from infrastructure damage (e.g., 60 meters of qanat and a local bridge) and incomplete compensation threaten social sustainability. Sheikhzadeh et al. (2024) demonstrated that participatory qanat management in rural Iran can reduce local conflicts and enhance socio-economic sustainability, a strategy applicable to managing conflicts in Karnaweh Shirin. These findings are consistent with Shah (2018), who noted that inequitable water distribution can lead to local conflicts, though this study, unlike Shah's macro-level governance focus, highlights localized conflicts stemming from implementation issues. Community participation (S2) and stakeholder satisfaction (S1) were identified as leverage variables that can enhance sustainability. Balali et al. (2009) showed that active community participation in water resource management in the Middle East can increase project acceptance and improve social sustainability, a critical factor for strengthening participation in Karnaweh Shirin. This aligns with Tamassoki et al. (2025) on the importance of participatory governance in border regions, but this study's systemic analysis provides a more precise examination of the bidirectional influences of these variables.

From an economic perspective, income stability (E2) and economic yield (E1), driven by over 10 billion IRR in income from alfalfa and wheat cultivation, were identified as primary drivers, aligning with Faramarzi et al. (2013) on the role of water management in enhancing agricultural productivity. However, this study's structural analysis delves deeper into the indirect influence chains among economic, social, and environmental variables. Compared to other studies, this research's systemic approach is more comprehensive than single-dimensional hydrological analyses like Dillon (2005) or social analyses like Shah (2018). Unlike Godet (2000), who applied structural analysis in non-watershed contexts, this study localizes its application to water resource management, filling gaps in Iranian studies like Madani (2016) by providing a practical framework for arid border regions. However, limitations such as the lack of long-term data on biodiversity and aquifer depletion rates (Env2), similar to those reported by Wheater et al. (2015), necessitate continuous monitoring. By integrating field data and systemic analysis, this study not only deepens the understanding of the sustainability dynamics of the Karnaweh Shirin dam but also offers a framework for evaluating similar projects in arid regions.

### *3.2. Strategic recommendations*

The analysis of the Karnaweh Shirin underground dam project yields critical

recommendations essential for its long-term sustainability and effectiveness.

**1. Integrated and participatory water governance:** It is imperative to develop an integrated and participatory water governance model for the Karnaweh Shirin watershed. This model should leverage multilevel water-energy-food nexus frameworks to effectively manage interactions among stakeholders and resources, thereby enhancing the project's social and economic sustainability (Pahl-Wostl, 2017). The model must involve key stakeholders (farmers, livestock breeders, relevant governmental organizations, and experts) in all project phases, from needs assessment and design to implementation, operation, and monitoring. This is particularly critical for managing leverage variables such as S2 (community participation) and S5 (social conflicts).

**2. Engineering revisions based on precise data:** Conducting comprehensive and detailed geotechnical studies, and, if necessary, implementing engineering revisions to ensure the dam's full connection to an impermeable layer (bedrock), is essential to control subsurface flow and prevent water loss. These revisions must be based on thorough field data rather than preliminary assumptions.

**3. Completion of water utilization and transfer infrastructure:** Completing the dam's ancillary facilities, including pumping systems and storage reservoirs, is urgent to effectively utilize extracted groundwater. Additionally, full restoration and reconstruction of the damaged qanat pathway and well shafts, along with establishing sustainable and efficient mechanisms for transferring water from the dam to agricultural lands, are critical to prevent water loss and stakeholder dissatisfaction.

**4. Conflict management and compensation for social damages:** To address the S5 variable (social conflicts), damages to local infrastructure (bridges, coastal walls, and qanat pathways) must be promptly and fully compensated. Establishing a transparent mechanism to address community grievances and concerns and enhance stakeholder satisfaction (S1) is essential.

**5. Systemic monitoring and performance evaluation:** A comprehensive and regular monitoring system for all sustainability indicators, particularly dependent (Env2) and leverage variables, should be implemented. This monitoring must encompass hydrological, economic, social, and environmental indicators. Periodic and long-term evaluations (e.g., every 5 to 10 years) are necessary to provide feedback for management and refine strategies, especially in response to regional climatic and socio-climatic changes.

**6. Emphasis on multifunctional roles and comprehensive valuation:** In justifying future projects, attention should be given not only to direct economic benefits but also to ecosystem functions (e.g., biodiversity conservation [Env4] and climate regulation [Env3]) and indirect social and security benefits (e.g., controlling transboundary water loss [Env5] and preventing migration). Comprehensive valuation of these aspects will enhance decision-makers' understanding of the multifaceted nature of sustainability.

Ultimately, the sustainability of the Karnaweh Shirin underground dam and similar projects in border regions requires an adaptive and intelligent management approach. This approach must address systemic complexities by integrating advanced analytical tools with local and scientific knowledge to develop and implement comprehensive and sustainable solutions.

## 4. Conclusion

The Karnaweh Shirin underground dam represents a notable example of efforts to achieve sustainable water resource management in arid and border regions, with its success contingent on balancing hydrological, ecological, and socio-political functions. Structural analysis (MICMAC) identified key drivers, including income stability for beneficiaries (E2), water and food security (S3), equitable utilization of water resources (S4), biodiversity conservation (Env4), changes in vegetation cover (Env3), and control of transboundary water loss (Env5), which collectively steer the system's dynamics through direct and indirect effects. Hydrological achievements, such as a 7.5-fold increase in qanat discharge and enhanced aquifer recharge, alongside economic benefits like significant income from agriculture and livestock, highlight the dam's high potential to strengthen water security and local livelihoods. However, challenges such as water leakage due to the dam's lack of connection to bedrock, damage to local infrastructure (qanats, bridges, and coastal walls), and social conflicts (S5)

stemming from uncompensated damages threaten long-term sustainability. From an ecohydrological perspective, conserving biodiversity and restoring vegetation cover are critical not only for maintaining ecosystem functions but also for economic sustainability and reducing pressure on natural resources. Taylor et al. (2013) demonstrates that climate change, by reducing aquifer recharge, can threaten biodiversity and ecosystem functions in arid regions like Karnaweh Shirin. From a policy perspective, establishing integrated and participatory governance, with a focus on compensating damages, enhancing community participation (S2), and creating transparent mechanisms for conflict management, is essential. Engineering improvements, such as connecting the dam to an impermeable layer and completing pumping and storage facilities, coupled with continuous monitoring of ecohydrological indicators (e.g., aquifer depletion rates and biodiversity), are vital for optimizing the dam's performance. This study provides an integrated framework that combines quantitative and qualitative analyses with an ecohydrological (balancing water and ecosystems) and policy-oriented (adaptive governance and conflict management) perspective. It not only offers solutions to enhance the sustainability of the Karnaweh Shirin underground dam but also provides a practical model for managing water resources in arid and border regions facing similar climatic and geopolitical challenges. This framework can serve as a foundation for future policymaking and further research on underground dams.

**Acknowledgments**

Ehsan Tamassoki: data collection, sample analysis, performing the model, data analysis, and writing the first draft. Javad Momeni Damaneh: analysis and interpretation of the results, writing (review and editing). Seyed Mohammad Tajbakhsh Fakhrabadi: Roles/Writing - original draft; and Writing - review and editing. All authors reviewed the results and approved the final version of the manuscript. Donya Kheirkhah & Ali Akbar Safdari: Roles/Writing - review and editing. No funding was obtained for this study.

## References

Aeschbach-Hertig, W. & Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience*, 5(12), 853–861.

Angelakis, A. N., Mays, L. W., Koutsoyiannis, D. & Mamassis, N., 2012. Evolution of water supply through the millennia. IWA Publishing.

Arcade, J., Godet, M., Meunier, F. & Roubelat, F., 1999. Structural analysis with the MICMAC method & actor's strategy with MACTOR method. Futures Research Methodology (Version 2.0), 1–69.

Balali, M.R., Keulartz, J. & Korthals, M., 2009. Reflexive water management in arid regions: The case of Iran. *Environmental Values*, 18(1), 91–112.

Biniaz, M. & Tamassoki, E., 2023. Analyzing dimensions of integrity in the Concept of Integrated Watershed Management in Iran. *Integrated Watershed Management*, 3(1), 38–53.

Dillon, P., 2005. Future management of aquifer recharge. *Hydrogeology Journal*, 13(1), 313–316.

Dillon, P., Pavelic, P., Page, D., Beringen, H. & Ward, J., 2009. Managed aquifer recharge: An introduction. Waterlines Report Series No. 13. National Water Commission, Australia.

Famiglietti, J. S., 2014. The global groundwater crisis. *Nature Climate Change*, 4(11), 945–948.

Faramarzi, M., Yang, H., Schulin, R. & Abbaspour, K.C., 2010. Modeling wheat yield and crop water productivity in Iran: Implications of agricultural water management for wheat production. *Agricultural Water Management*, 97(11), 1861–1875.

General Directorate of Natural Resources and Watershed Management of Razavi Khorasan Province, 2021. Study of the effectiveness of watershed management operations (underground dam) in the Karnave Shirin watershed of Kalat County. (Prepared by Scientific Association of Rainwater Harvesting Systems).

Gleeson, T., Wada, Y., Bierkens, M.F.P. & van Beek, L.P.H., 2012. Water balance of global aquifers revealed by groundwater footprint. *Nature*, 488(7410), 197–200.

Godet, M., 2000. The art of scenarios and strategic planning: Tools and pitfalls. *Technological Forecasting and Social Change*, 65(1), 3–22.

Hashemi, H., Berndtsson, R. & Persson, M., 2015. Artificial recharge of groundwater in arid and semi-arid regions: A review of methods and practices. *Hydrological Sciences Journal*, 60(2), 336–350.

Jodlbauer, H., Tripathi, S. & Brunner, M., 2022. Stability of cross impact matrices.

*Technological Forecasting and Social Change*, 182, Article 121822.

Loucks, D. P., van Beek, E., Stedinger, J. R., Dijkman, J. P. M., & Villars, M. T., 2005. Water resources systems planning and management: An introduction to methods, models and applications. UNESCO Publishing.

Madani, K., AghaKouchak, A. & Mirchi, A., 2016. Iran's socio-economic drought: Challenges of a water-bankrupt nation. *Iranian Studies*, 49(6), 997–1016.

Pahl-Wostl, C., 2019. Governance of the water-energy-food security nexus: A multi-level analytical framework. *Environmental Science & Policy*, 92, 356–367.

Shah, T., 2014. Groundwater governance and irrigated agriculture. Global Water Partnership Technical Committee Background Paper, 24, 1–45.

Sheikhzadeh, A., Nakhaei, M. & Ahmadi, A., 2024. Suggested solutions for sustainable management of groundwater at the national level. *Hydrogeology*, 8(2), 115–136.

Sivapalan, M., Savenije, H.H.G. & Blöschl, G., 2012. Socio-hydrology: A new science of people and water. *Hydrological Processes*, 26(8), 1270–1276.

Tamassoki, E., Bahrami Jaf, S., Momeni Damaneh, J. & Tajbakhsh Fakhrabadi, S.M., 2025. Identifying Key Drivers of Watershed Governance within the Hydropolitical Context of the Harirud River. *Journal of Water and Sustainable Development*, 12(2), 77–92.

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y. ... & Treidel, H., 2013. Ground water and climate change. *Nature Climate Change*, 3(4), 322-329.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P. ... & Davies, P., 2010. Global threats to human water security and river biodiversity. *Nature*, 467(7315), 555-561.

Wheater, H.S. & Gober, P., 2015. Water security and the science agenda. *Water Resources Research*, 51(7), 5406–5424.

Yifru, B.A., Kim, M.-G., Lee, J.-W., Kim, I.-H., Chang, S.-W. & Chung, I.-M., 2021. Water storage in dry riverbeds of arid and semi-arid regions: Overview, challenges, and prospects of sand dam technology. *Sustainability*, 13(11), 5905.