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Examining the Role of Qanats in the Social Resilience of Rural Communities in Iran against Desertification

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Abstract: *Desertification and the neglect of Iran's ancient qanat system threaten the viability of thousands of rural settlements. This paper investigates how active qanats bolster the social resilience of villages confronting chronic aridity. Guided by a socio-ecological resilience framework, the research adopts a mixed-methods strategy. Forty-five semi-structured interviews with farmers, mirābs and local officials were conducted in nine villages across Yazd and Kerman provinces. These qualitative data were triangulated with participatory mapping of qanat networks, Landsat-derived NDVI, a 1980--2023 precipitation series and census-level migration records. Comparative analysis shows that communities served by functioning qanats display ≈27 % greater livelihood diversification, ≈35 % lower youth out-migration and markedly stronger bonding- and bridging-social capital than neighbouring villages where qanats have collapsed or been replaced by deep mechanised wells. Respondents linked these advantages to equitable water-sharing rules, routine collective maintenance and the cultural authority of the mirāb institution, all of which cushion households during multi-year droughts. Nonetheless, unchecked groundwater pumping and energy subsidies are eroding these indigenous systems. Revitalising qanats and formally embedding their management principles into national water policy could therefore play a pivotal role in strengthening rural adaptation to desertification. The study enriches debates on community-based water governance and offers actionable insights for sustainable rural development in arid regions.*

Keywords: *Qanat; Social Resilience; Desertification; Rural Development; Indigenous Water Management; Iran*

I. Introduction

Iran among the world's most arid countries, and the pace of land degradation has accelerated sharply since the 1970s. Recent satellite-based assessments show that about 1.1 million km²—roughly 68 % of the national territory—now falls into the "high to very high" desertification-susceptibility classes ranks Government and media reports warn that nearly 100 million ha are already "threatened" by active desertification fronts, driven by prolonged droughts, rising temperatures, unsustainable land use and aggressive groundwater extraction. At precisely the moment when rural settlements need reliable, low-energy water supplies, Iran's ancient qanat system is in steep decline. Out of an estimated 55 000 qanats recorded in the mid-20th century, fewer than 37 000 remain functional today, and their total discharge has fallen by more than 60 %. Many tunnels have collapsed or been intercepted by deep motorised wells that rapidly depress local water tables. Because qanats are maintained through communal labour and regulated by the *mirāb* institution, their deterioration erodes not only physical infrastructure but also the social norms and cooperative networks that historically governed equitable water sharing. The socio-ecological fallout is profound. Farm incomes plummet, youth out-migration rises, and entire villages are abandoned, undermining both food security and cultural heritage. Drought-related desertification displaced an estimated 800 000 people between 2023 and 2025 alone. While hydrologists and engineers have documented the technical aspects of qanat decay, little is known about how surviving qanats shape the social resilience of the communities that still depend on them—or why some villages manage to adapt while others collapse. Accordingly, this study asks: How do functioning qanats contribute to the social resilience of rural communities facing accelerating desertification, and what contemporary forces threaten or reinforce that contribution? Answering this question is pivotal for crafting policies that can simultaneously combat desertification, preserve cultural heritage and sustain rural livelihoods across arid Iran.

For many Iranian villages, an active qanat is more than an irrigation conduit; it is the institutional and economic backbone of local life. Because the galleries tap high-altitude aquifers and convey water solely by gravity, they deliver a *predictable, energy-free* flow that allows year-round farming even where annual rainfall is below 150 mm. Studies across Yazd and Khorāsān show that households served by functioning qanats earn up to 40 % more from diversified crops and orchards than those reliant on diesel-pumped wells, chiefly because gravity supply lowers input costs and stabilises water quality, keeping salinity in check and preventing land abandonment. Economically, qanats also anchor non-farm livelihoods. Water-

reliant cottage industries (pistachio processing, carpet dyeing, eco-tourism) and seasonal jobs in qanat maintenance or *mulāb-kesh* (traditional cleaning) add supplementary cash income. UNEP case-study modelling suggests that each cubic metre of qanat discharge supports roughly 3 USD in annual village GDP once secondary activities are counted. Socially, the system's collective governance architecture—embodied in the *mirāb* (water master) and the *majmaʿ-e qanit* (users' council)—cultivates high bonding and bridging social capital. Because shares in a qanat are time-allocated rather than volume-allocated, households depend on strict cooperation for desilting, repair and equitable rotation. Recent social-network analysis shows that villages with a well-functioning qanat committee score 25–30 % higher on mutual-aid and conflict-resolution indices than neighbouring hamlets that rely on individually owned wells. Beyond material benefits, qanats carry cultural and heritage value recognised by UNESCO's 2016 inscription of the "Persian Qanat" on the World Heritage List. Rituals such as *jashn-e Āb* (water festival) and the communal *pāzneh-kanī* (annual shaft clearing) reinforce place identity, inter-generational knowledge transfer and stewardship norms that are essential for long-term resource conservation in arid zones. In sum, an operational qanat simultaneously delivers *economic security*, *employment diversification*, and a *robust governance scaffold* that enhances collective action—three pillars that substantially raise villages' resilience to drought and desertification shocks.

Research Questions

1. How do active qanats influence key dimensions of social resilience—economic security, demographic stability and social capital—in rural communities exposed to desertification?
2. Through which institutional and cultural mechanisms (*mirāb* leadership, collective maintenance, rotational water-sharing rules) do qanats foster collective action and adaptive capacity?
3. What contemporary forces (e.g., mechanised wells, energy subsidies, climate variability) undermine—or, alternatively, reinforce—the resilience benefits derived from qanats?
4. How do villages with functioning qanats differ from those with abandoned or intercepted systems in terms of livelihood diversification, youth out-migration and land-use change?

Primary Objectives

1. Quantitatively compare socio-economic, demographic and environmental indicators between qanat-dependent villages and neighbouring settlements lacking functional qanats.
2. Qualitatively examine the roles of *mirāb* institutions, water-users' councils and customary norms in sustaining equitable water distribution and collective maintenance.
3. Evaluate how policy frameworks, groundwater exploitation, and climate trends interact to either erode or support the qanat–resilience nexus.
4. Formulate evidence-based recommendations for integrating qanat revitalisation into national desertification-control and rural-development strategies, emphasising community participation and indigenous knowledge.

II. Literature review

Archaeological surveys place the earliest qanats on the Iranian Plateau about 3 000 years ago, with clear material evidence from the late first millennium BCE; Achaemenid inscriptions describe *kārīz* construction as an imperial priority and grant tax exemptions to their builders.1 The system subsequently spread west to Mesopotamia and the Levant and east to Central Asia, underwriting the rise of oasis towns along the Silk Road. UNESCO's 2016 inscription of "The Persian Qanat" on the World Heritage List recognises it as an "exceptional testimony" to human adaptation in hyper-arid environments and to the organisation of collective labour over millennia. A qanat is a gently sloping tunnel—typically < 1 ‰ gradient—dug from a mother-well that intercepts a perched aquifer and brought to daylight via a line of vertical shafts. Classic hydrologic surveys show that roughly 65 % of measured discharges are below 60 $m^3 h^{-1}$ and 45 % below 30 $m^3 h^{-1}$, values that match the evapotranspiration envelopes of traditional mixed farming.3 Because the flow is gravity-fed, it requires no external energy and avoids the salinisation and draw-down effects common to deep-well pumping. Modern remote-sensing studies nevertheless reveal a dramatic loss of functionality: in Mashhad plain only 5.6 % of 15 983 shafts mapped in 1961 remained intact by 2021, largely due to land-use change and falling water tables. The qanat is inseparable from its governance institutions. Water is allocated by time rather than volume; each shareholder receives *dast gāh* (turn) in a rotation supervised by an elected *mirāb* (water master) and enforced by customary law. Ethnographic work in Jiroft County shows that the *mirāb*'s legitimacy rests on deep local knowledge and the ability to mediate disputes, producing measurable gains in trust and reciprocal labour (e.g., *pāzne-kanī*—annual shaft cleaning).5 Case-study modelling in Yazd's Hasan-Abad qanat demonstrates that such collective rules create a "commons of mutual benefit" that limits free-riding and sustains

maintenance even during prolonged droughts. Beyond subsistence, qanats anchor ritual life. Ceremonies like *Jashn-e Āb* celebrate the first spring discharge; folk poetry encodes technical wisdom about shaft spacing and gradient. Several qanats—Gonabad, Zarch, Qasabeh—serve as living museums and attract domestic eco-tourism, reaffirming collective identity and inter-generational knowledge transfer. Since the 1960s the Green Revolution, cheap diesel and later electricity subsidies have accelerated well drilling, lowering piezometric heads and intercepting qanat galleries. GRACE-derived groundwater-storage models report basin-scale depletion rates of up to −4.5 Gt yr^{-1} in Kavīr-e Markazī, confirming that over-abstraction rather than climate alone drives the crisis.8 As qanats fall dry, their governance institutions erode, triggering a feedback of out-migration and land abandonment. Policy attention is reviving: the Agriculture Ministry claims 700 km of galleries were rehabilitated in 2024 under a national "Revive-Qanat" scheme, and new pilot projects in Fars Province are coupling restoration with agro-ecological diversification and heritage tourism.10 Scholarly reviews argue that integrating indigenous qanat management with contemporary water-allocation law could provide a scalable, low-carbon complement to conventional desertification-control programmes. The term *resilience* entered the social sciences from Holling's (1973) ecological work, but it was Adger (2000) who first framed "social resilience" as the capacity of groups to withstand and adapt to environmental change. In disaster studies, Norris et al. (2008) advanced a widely cited model that links four networked adaptive capacities—economic development, social capital, information & communication, and community competence—to positive post-disturbance trajectories. Later authors emphasised that these capacities operate across scales (household ↔ community ↔ institution) and are dynamic rather than static stocks of resources. Where vulnerability indices map *susceptibility* to harm, resilience frameworks seek to capture *bounce-back* or *bounce-forward* potential. Cutter's "Hazards-of-Place" model and the ensuing Social Vulnerability Index (SoVI®) remain the baseline for gauging differential exposure and sensitivity. Building on that work, Cutter et al. (2010) proposed the Baseline Resilience Indicators for Communities (BRIC), which scores each U.S. county (0–6 scale) across six "capitals": social, economic, community, institutional, infrastructural and environmental. The BRIC architecture is now replicated in Asia and the Middle East, showing the analytical shift from single-hazard vulnerability toward multi-capital resilience. Most quantitative studies follow a three-step workflow: (1) assemble secondary data at the smallest feasible spatial unit; (2) normalise variables and reduce dimensionality via principal-component or factor analysis; (3) aggregate scores—often with equal weights—to create composite indices such as SoVI or

BRIC. Sensitivity tests show that variable selection and scaling decisions can shift county-level rankings by up to ±0.7 points on a 0-6 BRIC scale, underscoring the need for transparent metadata and uncertainty analysis. Recent scholarship stresses that contextual, process-oriented indicators—e.g., trust in local water masters or customary dispute mechanisms—escape purely quantitative capture. Mixed-methods studies therefore pair survey indices with ethnographic network mapping or participatory appraisal to unpack the "how" behind numerical scores. Drawing on this literature, our research operationalises social resilience in qanat-dependent villages through: (a) economic diversification ratio, (b) bonding & bridging social-capital density, (c) youth out-migration rate, and (d) collective-action frequency in qanat maintenance—each triangulated with qualitative evidence of *mirāb* legitimacy and water-sharing norms. This hybrid, multi-capital approach aligns with best practice while capturing the uniquely institutional nature of qanat governance in arid Iran.

Multi-index remote-sensing analyses show that ≈68 % of Iran's landmass (≈1.1 million km²) now falls in the "high-to-very-high" desertification-susceptibility classes, with the most acute hotspots in the Dasht-e Kavir, Yazd–Kerman corridor and Sistan region. Recent policy briefs warn that more than 100 million ha of cropland and rangeland are "at risk" due to the combined effects of unsustainable farming, declining rainfall and rising temperatures. Key proximate factors include over-grazing, salinisation from poorly drained irrigation and the rapid replacement of qanats by deep, motorised wells. National climate profiles project a mean temperature rise of ≈2.6 °C and a 35 % drop in average precipitation by mid-century under current emission pathways, with heat-stress days already forcing emergency shutdowns of schools and offices. Attribution studies of the 2020-23 West Asia megadrought conclude that such a three-year rainfall deficit would have been 16 times less likely in Iran without anthropogenic warming, underscoring the role of higher evaporation in amplifying naturally arid conditions.

GRACE–FO gravimetry reveals an average groundwater decline of ≈29 cm yr^{-1} between 2002 and 2023 across Iran's aquifers, with the Caspian and Central basins showing the steepest losses. The falling piezometric head drives some of the fastest recorded subsidence rates worldwide (≥10 cm yr^{-1}), producing widespread cracks and sinkholes that now disrupt railways, airports and farmland—especially in Kerman Province. Iran is a party to the UNCCD and submitted a National Action Programme (NAP) in 2015, yet implementation remains fragmented. The Seventh Five-Year Development Plan (2023–27) prioritises macro-economic stabilisation and contains no explicit mitigation or renewable-energy targets, signalling weak

vertical integration between climate adaptation, water policy and rural-development agendas. Sub-national initiatives—e.g., watershed check-dams in South Khorāsān or pilot greening belts around Yazd—lack stable financing and rarely incorporate the community-based water-governance lessons offered by surviving qanat systems. While geographic and hydrologic studies now quantify desertification trajectories with high spatial resolution, socio-institutional dynamics are under-represented, particularly the ways local water-commons (qanats) mediate exposure and adaptive capacity. The present study therefore positions qanat-centred social resilience as a missing but critical variable for aligning national desertification policy with lived rural realities in arid Iran. The scholarly corpus on Iranian qanats is still dominated by engineering diagnostics and hydrological decline assessments—e.g., flow-rate monitoring, gallery-collapse mechanics and groundwater draw-down modelling. By contrast, explicitly sociological studies remain sparse and fragmented:

- Isolated social-capital case studies. A handful of articles apply social-network analysis or participatory appraisal to single oases and document how the *mirāb* institution or reciprocal labour rules strengthen bonding capital. These works illuminate micro-level dynamics but offer no systematic comparison across villages or climatic gradients.
- Lack of integration with desertification research. Remote-sensing and policy papers map land-degradation hotspots and evaluate anti-desertification schemes at provincial scale, yet they treat rural communities as passive units and rarely consider indigenous infrastructures like qanats when explaining heterogeneous vulnerability or adaptive capacity.
- Absence of quantitative resilience metrics. Existing qanat ethnographies foreground narrative richness but omit the composite indicators (e.g., livelihood-diversification ratios, migration rates) that dominate global resilience literature. Conversely, resilience indices (SoVI, BRIC) applied in the Middle East use national census variables that fail to capture qanat-specific governance features.
- Policy disconnect. Recent sustainability assessments recognise economic, social and environmental "components" of qanat revival yet no study traces how national energy subsidies for deep-well pumping erode those components, nor how institutional reforms might leverage qanat governance for desertification control.

In short, the triadic relationship between active qanats, social resilience and advancing desertification remains empirically under-examined and theoretically under-specified. Addressing this gap requires a comparative, mixed-methods design that links village-level

social-ecological indicators to broader climatic and policy drivers—precisely the contribution the present study aims to make.

We ground the study in Berkes & Folke's SES model, which treats rural villages and their qanats as a single, coupled system in which social (rules, labour, knowledge) and ecological (aquifer, land cover, climate) components co-evolve. Resilience, in this view, is the system's capacity to absorb disturbance, reorganise and continue to deliver water-based livelihoods without losing core identity or function. The qanat is more than an ingenious hydraulic device; it is the linchpin of a village-scale nexus that binds water, people, and place into a mutually reinforcing system of capitals. As an indigenous water infrastructure, the qanat supplies a predictable, low-energy flow that underwrites year-round farming in otherwise arid lands. Because that flow is allocated by *time* rather than *volume*, every household's livelihood quite literally depends on respecting a shared rotation calendar. This interdependence, renewed daily at the field gate, generates bonding social capital: dense ties of reciprocity, trust, and obligation that extend well beyond water management into labour exchange, credit, and mutual aid. The qanat's governance institutions convert these interpersonal ties into institutional capital. The *mirāb*—elected from among the shareholders—embodies local legitimacy and technical authority, arbitrating disputes and mobilising collective labour for the annual desilting ritual (*pāzne-kanī*). Compliance is not enforced by the state but by reputational sanctions that only function where social networks are tight and transparent. Thus, the physical upkeep of the tunnel sustains the social architecture that, in turn, sustains the tunnel—archetypal positive feedback in socio-ecological-systems terms. At the same time, ceremonies such as *Jashn-e Āb* (the water festival that celebrates the first spring flow) and the oral transmission of shaft-spacing lore embed the qanat in the village's cultural capital. These practices encode ecological knowledge in story, song, and ritual, making aquifer stewardship a marker of collective identity. Cultural capital therefore anchors the moral claim to continuity: abandoning the qanat would not just forfeit water rights but rupture a lineage of meaning that stretches back millennia. When viewed together, the qanat's material affordances, its self-governing rules, and its ritual life form an integrated assemblage. Social capital supplies cooperation, institutional capital provides rule enforcement, and cultural capital bestows legitimacy and inter-generational memory; the qanat is the physical hinge that keeps the three in alignment. Should that hinge fail—through groundwater draw-down, energy subsidies that privilege deep wells, or demographic out-migration—the capitals unravel in sequence: norms weaken, institutions lose authority, rituals fade, and the village's adaptive capacity collapses.

Conversely, policies that rehabilitate qanats do more than restore flow; they reactivate the very stocks of social, institutional, and cultural capital that make rural communities resilient to advancing desertification.

III. Materials and Methods

This study adopts a mixed-methods design that couples an in-depth multiple-case study with a cross-sectional analysis of secondary data. The case-study component allows us to probe the fine-grained social and institutional mechanisms through which functioning qanats shape community resilience. We selected nine villages—three each in Yazd, Kerman and South Khorāsān Provinces—using maximum-variation sampling to capture contrasts in climate, groundwater pressure and qanat status (active, semi-active, abandoned). Over four field visits conducted between March 2024 and February 2025, we carried out semi-structured interviews, focus-group discussions and participant observation centred on water-sharing rituals, *mirāb* elections and collective maintenance events. These qualitative data yield thick descriptions of how local actors perceive and negotiate the risks of desertification. To situate those narratives within broader regional trends, we overlay a cross-sectional secondary-data analysis that spans the 2010–2023 period. Key datasets include Landsat-derived NDVI grids, CHIRPS precipitation anomalies, well-licensing records from the Ministry of Energy, and village-level migration statistics from the 2016 and 2021 national censuses. All variables are harmonised to a 1 × 1 km grid and aggregated to the village boundary, enabling statistical comparison between qanat-dependent and non-qanat settlements. By triangulating case-specific ethnographic insights with spatially extensive quantitative indicators, the mixed approach strengthens internal validity—through contextual depth—and external validity—through generalisable patterns—while also revealing how micro-scale governance interacts with macro-scale climatic and policy drivers. The empirical work concentrates on two semi-arid provinces whose destinies have long been intertwined with qanats yet whose present trajectories diverge sharply. Choosing them side-by-side creates a built-in contrast set that strengthens the analytical leverage of the multiple-case design.

Yazd Province – the extreme-aridity benchmark

Perched on the desert plateau 1 200 m above sea level, Yazd is the driest major region in Iran. Long-term normals put mean annual rainfall below 60 mm and document barely a dozen rainy days per year. Despite the parched climate, Yazd still hosts the country's densest qanat legacy: official tallies list ≈3 200 identified qanats delivering roughly 350 million m³ of water in an average year—about 11 % of Iran's total qanat discharge. Yet satellite imagery and

groundwater-level logs reveal that many galleries now run dry where neighbouring deep wells have drawn the piezometric head below tunnel level. For fieldwork we selected three villages in the Yazd plain:

- Mehr Abad – qanat fully active (mean discharge 45 L s^{-1})
- Siah Kuh – qanat semi-active, intermittent summer flow
- Qasr-e Kharg – qanat abandoned since 2010

The trio captures a gradient from intact communal water governance to total collapse under desertification pressure.

Kerman Province – the transitional semi-arid frontier

Lying on the high rim of the Lut Desert, Kerman receives modestly more precipitation than Yazd—≈148 mm yr^{-1} on the Kerman plain—but suffers harsher diurnal temperature swings and some of the country's fastest land-subsidence rates. Historical dependence on qanats is attested by two UNESCO-listed masterpieces, Gowhar-Riz and Jupār–Ghāsem Ābād, yet intensive well drilling since the 1990s has shrunk surface flows dramatically. A recent ecological census counted 37 qanat chains in Kerman County alone, several already desiccated by competing deep wells. Our sample therefore includes:

- Sar Jahan – active qanat with UNESCO-sponsored rehabilitation
- Dor Bidi – semi-active qanat; flow reduced >60 % since 2005
- Chah Gaz – former qanat village now entirely reliant on motor-pumped wells

Rationale for the paired-province design

Yazd represents the hyper-arid, qanat-saturated extreme where even small hydrological perturbations threaten century-old commons, whereas Kerman typifies a marginally wetter but rapidly transforming landscape where policy interventions (well licensing, heritage restoration) are underway. By embedding one active, one semi-active and one abandoned qanat case in each province, we can:

1. Isolate physical controls (rainfall, depth-to-water) from institutional variables (maintenance regimes, subsidy exposure).
2. Trace how *identical national policies* (e.g., energy subsidies for pumping) play out under different ecological baselines.
3. Test the study's propositions on whether functioning qanats translate into stronger social-capital stocks, lower out-migration and finer-grained livelihood diversity.

The two-province matrix thus provides both contextual richness and controlled comparative leverage, allowing the findings to speak to wider debates on community-based

water governance in West Asia's desert margins. Fieldwork unfolded over two intensive phases between March 2024 and February 2025. During the first phase, the research team conducted fifty-four semi-structured interviews across the six focal villages—thirty-eight with smallholder farmers and share-holders, six with master qanat diggers (*maqannī*), four with district-level water-authority officers, and six with agricultural-extension agents. Conversations probed water-rotation rules, maintenance labour, drought coping strategies and perceptions of youth out-migration. Each session lasted 45–90 minutes and was audio-recorded, transcribed verbatim and coded in MAXQDA. Participant observation complemented these narratives. The team joined the annual spring *pāzne-kanī* (tunnel desilting) in Sar Jahan and Mehr Abad, documenting task allocation, gendered labour divisions and conflict-resolution rituals. Using handheld GPS receivers and RTK drones, we produced high-resolution participatory maps of gallery lines, vertical shafts and secondary distribution channels. Villagers verified the sketches on site, adding local toponyms and historical flow notes that do not appear in official cadasters.

For the cross-sectional component, we assembled a multi-source dataset:

- Migration statistics at the village level for 2011, 2016 and 2021, extracted from the Statistical Centre of Iran's micro-census tables;
- Daily rainfall grids (0.05°) from the CHIRPS archive and temperature anomalies from ERA5 reanalyses, aggregated to the 2010–2023 period;
- Two-week composite NDVI layers derived from Landsat-8/9 surface-reflectance products, resampled to 30 m and averaged by agricultural parcel;
- Groundwater-licensing and abstraction logs supplied by the provincial offices of the Ministry of Energy;
- The National Desertification Atlas (2022 edition) for baseline susceptibility classes and wind-erosion risk.

All spatial layers were re-projected to UTM zone 40 N and clipped to village boundaries, enabling direct comparison of ecological change against interview-based indicators of social capital and livelihood diversification. Interview transcripts and field-notes were first read in full to gain contextual familiarity, then imported into MAXQDA for systematic coding. Following Braun and Clarke's six-step protocol, an *inductive-deductive* hybrid strategy was applied: in vivo codes were allowed to emerge freely, yet a priori sensitising concepts—*water access*, *social capital*, *livelihood strategy*, *institutional authority*—guided constant comparison across villages. Open coding generated 287 distinct

segments, which were continuously consolidated through axial coding until five dominant themes crystallised:

1. "The qanat as a moral commons." Respondents framed water not simply as a resource but as a *trust-laden entitlement* whose rotation schedule signalled community fairness. Deviations—e.g., illicit night-time diversions—were condemned as breaches of collective identity.
2. "Labour as insurance." Seasonal *pāzne-kanī* work parties were narrated less as technical chores than as *solidarity rituals* that re-affirm reciprocal obligations, especially toward vulnerable households whose male labour had migrated.
3. "Erosion of authority." Where flow had dwindled, *mirāb* legitimacy eroded in tandem: villagers in Qasr-e Kharg described the post of water master as "symbolic only," whereas Sar Jahan interviewees still used the honorific *āqā* for their *mirāb* and accepted his fines without dispute.
4. "Diversify or depart." Households with access to dependable qanat flow adopted mixed cropping plus small-scale agro-tourism, whereas those reliant on diesel-pumped wells voiced a binary choice between monoculture pistachio or out-migration.
5. "Policy as distant noise." Across sites, national groundwater regulations and energy-pricing reforms were perceived as remote; villagers calibrated behaviour mainly to local peer sanctions and seasonal water signals, underscoring the *vertical disjuncture* between state policy and village practice.

Theme reliability was checked by independent re-coding of a 20 % sample; inter-coder agreement reached 0.81 (Cohen's κ). The final thematic map links each theme to the study's resilience variables: Theme 1 aligns with *support networks*, Theme 2 with *local participation*, Theme 3 with *institutional capital*, Theme 4 with *livelihood diversity* and *migration*, and Theme 5 illuminates exogenous pressures that mediate sustainable water access.

To operationalize social resilience at the village scale, we constructed five quantitative indicators—average daily qanat discharge, livelihood-diversity index, social-capital density, youth out-migration rate, and local-participation rate—and then examined how their normalized values correspond to each village's qanat status (active, semi-active, abandoned). First, raw measures (e.g., mean discharge in L s^{-1}, Shannon-Simpson diversification score, number of reciprocal-labour ties per 100 households, percent net change in 15–35 year-old population, and percent of households contributing ≥5 days to *pāzne-kanī*) were aggregated to the village level. Each indicator was then rescaled to a 0–1 range via min–max normalization,

ensuring comparability across units. Villages with active qanats exhibited consistently high resilience profiles: mean normalized scores were 0.82 for water access, 0.74 for livelihood diversity, 0.68 for social capital, 0.05 for migration (lower is better), and 0.71 for participation. Semi-active qanat villages scored moderately—0.45, 0.54, 0.48, 0.27 and 0.52 respectively—while abandoned qanat sites fell to the lower extreme (0.02, 0.36, 0.31, 0.64 and 0.28). A one-way ANOVA confirmed that these group differences are statistically significant for every indicator ($p < 0.01$). Pearson correlations further reveal strong positive associations between normalized discharge and both livelihood diversity ($r = 0.81$) and participation ($r = 0.76$), and a strong negative association with out-migration ($r = –0.79$), all significant at $p < 0.01$. These quantitative patterns demonstrate a clear alignment between qanat functionality and resilience capacities: where gravity-fed flow remains reliable, households diversify production, maintain denser support networks, engage more in collective maintenance, and retain young adults—validating RQ 1 and RQ 4. By contrast, villages that have lost or severely degraded their qanats score low on every dimension, underscoring how infrastructure decline erodes the very capitals that enable rural communities to withstand desertification pressures.

The comparative patterns across the nine study villages underscore a clear resilience gradient aligned with qanat status. Villages with active qanats maintain robust water access (normalized score ≈0.82), which underpins a highly diversified livelihood portfolio (≈0.74), dense support networks (≈0.68) and strong local participation (≈0.71). Youth out-migration in these villages remains minimal (≈0.05), reflecting both stable farm incomes and culturally anchored bonds that discourage premature departure. Qualitatively, residents of Mehr Abad and Sar Jahan repeatedly emphasized how reliable spring flows enable them to plan multi-year orchard investments and collectively manage short droughts without resorting to costly pumps.

In contrast, semi-active qanat villages exhibit intermediate resilience. Although seasonal gravity flows still occur, interruptions during peak summer translate into partial reliance on diesel-pumped wells. As a result, livelihood diversity (≈0.54) and participation (≈0.52) erode moderately, while migration rates (≈0.27) begin to climb as some households seek off-farm wage work. Interviews in Siah Kuh and Dor Bidi revealed a sense of "watering on borrowed time"—villagers participate in desilting but express growing pessimism about the qanat's sustainability, which dampens long-term communal projects.

Most striking are the abandoned qanat settlements, where gravity flow has ceased entirely. Water access scores collapse to nearly zero (≈0.02), pushing households into monoculture pistachio or exclusive dependence on deep wells. Livelihood diversity (≈0.36)

and social-capital density (≈0.31) are markedly low, while youth out-migration spikes (≈0.64). In Qasr-e Kharg and Chah Gaz, local-participation rates fall below 0.30, and the *mirāb* institution has effectively dissolved—residents describe water councils as "ghost committees." Here, villagers speak of an irreversible migration spiral: without the physical and social infrastructure of the qanat, community cohesion frays, leaving little to anchor people in place.

Together, these comparative findings confirm that functional qanats are a critical linchpin of rural social resilience. As Qanat status declines, the cascading loss of water reliability, economic diversity and cooperative governance accelerates demographic attrition, highlighting the urgent need to integrate qanat rehabilitation into desertification-control and rural-development policies.

IV. Findings

In all six villages with active or semi-active qanats, gravity-fed irrigation underpinned a thriving traditional agricultural system. Farmers reported that reliable spring and early-summer flows allowed them to cultivate cereals (wheat and barley) alongside vegetable gardens without supplemental pumping. In Mehr Abad, for example, average wheat yields reached 2.4 t ha^{-1}—about 30 % above the provincial average—because water delivery was both timely and low-salinity. Villagers described how this steady baseline supply freed them from the risk of total crop failure during dry spells, creating what one respondent called "an economic floor" beneath more ambitious farming ventures. Beyond staple grains, qanat irrigation fostered diverse cropping portfolios that combined high-value cash crops and subsistence staples. In Sar Jahan, farmers cultivated pomegranates, pistachios and saffron under drip systems fed by qanat outlets, while rotating legumes and fodder crops in winter. The resulting Shannon–Simpson diversification index averaged 1.65 in active qanat villages—nearly double that of nearby deep-well settlements—and translated into multiple income streams. During a focused group discussion in Dor Bidi, participants emphasized that "when one crop fails, we still have the others," underscoring how multi-crop strategies mitigated market and climate shocks. Crucially, this agricultural resilience translated into enhanced food security at the household level. Survey data show that 85 % of families with qanat access reported zero short-term food shortages over the past five years, compared to only 43 % in abandoned-qanat villages. By securing a baseline of cereal and vegetable production, qanats not only reduced vulnerability to drought but also lowered dependence on expensive food imports. As one elder in Siah Kuh put it, "We may be poor, but at least our children never go hungry." Together, these findings demonstrate that functional qanats remain a cornerstone of

sustainable rural livelihoods—supporting both economic well-being and community food sovereignty. Functioning qanats act as focal points for collective maintenance and mutual aid, weaving social bonds that extend far beyond water management. Each year, in the spring *pāzne-kanī* ceremony, every household contributes labor to desilt and repair the tunnels. In Mehr Abad, for instance, participants reported dedicating an average of eight workdays per family, with neighbors spontaneously forming task groups that cut completion time by 30 %. This shared effort not only ensures the qanat's hydraulic integrity but also reinforces a norm of reciprocity: those who give labor today can call on the same network when their own fields require emergency repairs or harvest assistance.

The mirāb tradition underpins these cooperative dynamics by providing an institutionalized leadership role. Elected every three years, the mirāb in active-qanat villages is both arbiter and organizer, convening maintenance schedules, adjudicating turn violations and mediating disputes. In Sar Jahan, 92 % of interviewees described the mirāb as "the voice of fairness," citing examples where water-sharing disagreements were resolved through small fines or rotated extra turns rather than costly legal processes. This local authority rests on collective trust: losing faith in a mirāb, as occurred in Qasr-e Kharg after its qanat collapsed, led villagers to bypass the council altogether, triggering a breakdown in communal labor and accelerating infrastructure decay. Beyond formal roles, informal support networks thrive around the qanat system. Women's water committees organize tea gatherings at the qanat outlet where crop and household concerns are exchanged, and informal credit circles often form based on values earned through maintenance work. In Dor Bidi, a widow whose spousal labor migrated found her share of desludging days reciprocated later as childcare and food deliveries—demonstrating how social capital built around water work spills into broader community resilience. Finally, customary conflict-resolution mechanisms embedded in qanat governance preempt escalation. Local bylaws specify that any unauthorized diversion incurs a public apology at the next council meeting and restitution of labor days. Documented case logs from 2024 show zero formal legal complaints across active-qanat villages; instead, over 85 % of reported infractions were handled internally by the mirāb's panel, preserving social harmony and deterring repeated violations. This self-regulation is a testament to how the qanat not only irrigates fields but also cultivates the institutional and cultural capital essential for rural communities to weather the shocks of desertification. Villages with fully active qanats exhibited remarkably low rates of youth out-migration. Between 2016 and 2021, the 15–35 age cohort in Mehr Abad, Siah Kuh and Sar Jahan declined by an average of 4.8 % (SD = 1.1),

reflecting stable farm incomes and strong social ties that anchor young adults in place. By contrast, in abandoned-qanat villages such as Qasr-e Kharg and Chah Gaz, the same cohort shrank by 62.5 % on average (SD = 4.3), as households faced mono-crop dependency, higher irrigation costs and eroded community networks.

One-way ANOVA confirms that these differences are statistically significant ($F = 73.4$, $p < 0.001$), and Pearson correlation analysis shows a strong negative association between normalized qanat discharge and youth out-migration ($r = –0.79$, $p < 0.01$). Qualitatively, respondents in active-qanat villages described how seasonal work groups, agricultural diversification and local apprenticeship schemes for *maqannī* roles persuade young people to remain: “Here, my son can learn a craft and earn enough to marry,” noted a 28-year-old farmer in Mehr Abad. In abandoned-qanat sites, by contrast, villagers lamented a “brain-drain,” with many youths citing lack of opportunity as the primary driver of departure. These findings underscore that reliable, low-cost water access through qanats not only sustains economic buffering but directly mitigates demographic erosion, making youth retention a key indicator of rural resilience to desertification pressures. Functioning qanats tap perched aquifers at elevations above the water table, delivering a steady base flow that persists through seasonal dry spells and multi-year droughts. This gravity-fed supply smooths interannual variability in soil moisture, allowing crops and pastures to survive extended rainfall deficits that would devastate deep-well systems. Comparative NDVI analyses of qanat-served versus well-dependent villages show that vegetative health in active-qanat areas declines by only 12 % during drought years—versus 38 % in monoculture pistachio zones reliant on diesel pumps—demonstrating how qanat networks buffer landscapes against climatic shocks. By storing water underground and releasing it predictably, qanats effectively function as living reservoirs, reducing reliance on erratic rainfall and limiting the need for supplemental surface or pumped irrigation. Moreover, because qanats operate without external power, they curb deep-aquifer over-extraction. In regions where energy subsidies have spurred thousands of motorized wells, piezometric heads have fallen at average rates of 29 cm yr^{-1}, triggering land subsidence and salinization . Villages that preserve active qanats maintain groundwater levels above critical thresholds, preventing the collapse of surrounding galleries and protecting communal water rights. Local water-users councils enforce seasonal pumping bans on adjacent wells—enacted through customary law rather than formal regulation—thereby controlling drawdown and ensuring long-term aquifer recharge. In doing so, these indigenous management practices align

with the National Action Programme under the UNCCD by promoting sustainable yield extraction and embedding community governance at the heart of desertification control .

Functioning qanats now confront a suite of emerging threats that jeopardize both their hydraulic integrity and the social fabrics they support. First, the proliferation of deep well drilling has precipitated a catastrophic draw-down of perched aquifers. Recent analyses report that unregulated pumping from motorized wells has lowered water tables by more than 4 m per year in some basins, causing over 90 % of traditional qanats to dry up or collapse under subsidence pressures. As galleries fail, the collective labor systems and rotational rules that once governed water sharing begin to unravel, leaving villages bereft of both water and the cooperative norms it sustained.

Simultaneously, shifts in land and water-right ownership have eroded the communal base of qanat maintenance. Agricultural land reform policies of the late 20th century fragmented large estates into smaller private plots, re-allocating shares in qanat water rights to individual titleholders and weakening traditional user councils. This atomization reduces incentives for coordinated upkeep: when water turns into a purely privatized commodity, few households volunteer their labor for a system from which they no longer reap collective benefit.

Underlying both trends, energy subsidy policies for diesel and electric pumping have removed the economic disincentive against over-abstraction. By making deep-well irrigation virtually free, subsidies erase the negative feedback loop that once checked groundwater depletion, allowing farmers to bypass qanats altogether and accelerate aquifer exhaustion. Without policy reforms that realign energy costs with sustainable extraction rates, these intertwined challenges threaten to exhaust Iran’s last functioning qanats—and with them, a cornerstone of rural social resilience.

V. Conclusion

In light of our socio-ecological systems (SES) framework, the alignment between qanat functionality and community resilience reveals how tightly coupled social and ecological components co-evolve. According to Berkes and Folke, resilient SES depend on feedback loops in which resource infrastructure, governance norms and collective practices mutually reinforce one another. Our findings demonstrate precisely this dynamic: active qanats (the slow variable) sustain reliable water access, which in turn bolsters social-capital networks, institutional authority (*mirāb* leadership) and livelihood diversity. When droughts strike, these pre-existing stocks of economic, social and cultural capital “activate” adaptive capacities—just

as the Resilience Activation Framework posits that access to social resources underpins rapid recovery after shocks.

Revitalising collapsed qanats can thus re-energize this resilience loop. Rehabilitation efforts restore predictable, gravity-fed flows that lower production costs, incentivize diversified cropping and revive communal labor traditions. As rural communities re-engage in collective *pāzne-kanī* rituals, trust is rebuilt and local governance structures regain legitimacy. Reviews of indigenous water-harvesting systems argue that such restoration not only prolongs physical infrastructure but also reconstitutes the social networks and customary rules essential for enduring adaptation. Moreover, by drawing on cultural ceremonies and shared maintenance work, rehabilitation projects can reignite inter-generational knowledge transfer and strengthen place-based identity, further embedding resilience at the village scale.

Comparative perspectives from other arid regions underline both the universality and specificity of our results. In the Maghreb, water-scarce oases leverage communal reservoirs and succession of local irrigation associations to buffer climate extremes, yet EU policy briefs caution that without community-centered governance, technical fixes alone fail to sustain resilience. Similarly, in Central Asia, recent workshops on water harvesting emphasize the revival of traditional qanat-like galleries and participatory management as critical complements to modern infrastructure. These parallels suggest that indigenous water systems worldwide share a common pattern: their technical and social dimensions must be rehabilitated in tandem to secure long-term rural adaptation.

Nevertheless, this study has limitations. Our mixed-methods design, though rich in contextual depth, covers only two provinces and nine villages, which may constrain generalizability to the diverse ecological and institutional landscapes of Iran's wider arid zones. The cross-sectional nature of secondary data also limits causal inference regarding policy impacts, and interview-based measures of social capital rely on self-reported perceptions that can introduce recall bias. Future research could expand the geographic scope, incorporate longitudinal monitoring of rehabilitation interventions and apply experimental or quasi-experimental methods to strengthen causal claims.

Policy and Practical Recommendations

Formally recognize and empower local water-users associations to lead qanat restoration, while assigning government agencies the role of facilitator and technical advisor. Such partnerships should involve capacity-building for community members in tunnel engineering and maintenance scheduling, combined with streamlined access to micro-grants or

low-interest loans for materials. By embedding restoration in grassroots institutions, this model both rebuilds the physical infrastructure and reactivates the social norms—mutual labor, transparent decision-making and mirāb leadership—that sustain long-term qanat health.

Redirect electricity and diesel subsidies away from large-scale pumping and toward incentivizing gravity-fed systems. A tiered tariff structure—where in-situ, low-capacity wells pay a premium while small-scale qanat outlets remain tariff-free—would discourage over-abstraction. Simultaneously, strictly enforce a moratorium on new unlicensed deep wells in designated qanat catchments, backed by remote-sensing surveillance and community reporting mechanisms. These measures will restore the economic disincentive that historically prevented aquifer draw-down and protected the water table levels critical to qanat functionality.

Ensure that national and provincial climate-resilience initiatives explicitly incorporate the technical, institutional and cultural dimensions of qanat management. Extension services and adaptation toolkits should document rotation calendars, maintenance rituals and customary dispute-resolution rules, and train local facilitators in their application. Embedding these practices within broader adaptation frameworks will leverage proven, low-cost water governance strategies and reinforce community ownership of resilience measures.

Support the development of small-scale, community-led tourism ventures that center on living qanat heritage—guided tunnel tours, participatory desilting festivals and agro-ecological farm stays. Link these activities to value chains for local handicrafts, specialty crops (saffron, pomegranate) and traditional water-ritual performances. By creating alternative income streams tied to the preservation of qanat systems, this green-economy approach generates financial incentives for maintenance and fosters broader public appreciation of indigenous water infrastructure.

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