

HISTORICAL EVOLUTION OF IRRIGATION AND DRAINAGE SYSTEMS IN WORLD IRRIGATION ENGINEERING HERITAGE AND PATHS FOR ENHANCING CONTEMPORARY AGRICULTURAL ECOLOGICAL RESILIENCE

ÉVOLUTION HISTORIQUE DES SYSTÈMES D'IRRIGATION ET DE DRAINAGE DANS LE PATRIMOINE MONDIAL DU GÉNIE D'IRRIGATION ET VOIES POUR RENFORCER LA RÉSISTANCE ÉCOLOGIQUE AGRICOLE CONTEMPORAINE

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ABSTRACT

This paper analyzes the coordinated circulation mode between Turpan Karez's three-dimensional irrigation and drainage system of "vertical shaft — underground channel — open channel — reservoir" and oasis agricultural ecology, interprets the key processes by which ancient people adapted to the arid and high-evaporation climate characteristics of the Turpan Basin, reduced water loss through underground channel water conveyance, and realized efficient utilization of water resources relying on groundwater circulation, confirming the benign interaction between the heritage irrigation and drainage system and the agricultural ecology in arid areas, and highlighting its ecological value of integrated protection of mountains, rivers, forests, farmland, lakes, grasslands and deserts.

At the same time, from the multi-levels of farm, region, industry and food system, it extracts the core resilience characteristics of irrigation and drainage-type agricultural ecosystems in world irrigation engineering heritage, explores the ecological wisdom of "complying with nature and adapting to local conditions" contained in Karez, and focuses on highlighting the in-depth integration of heritage value and contemporary practice: transforming the traditional wisdom of "underground channel water conveyance and water-saving irrigation" of Turpan Karez into a regulation scheme for precision irrigation in contemporary arid and semi-arid agricultural areas to promote the development of regional water-saving agriculture; drawing on its "groundwater-oasis" coordinated symbiosis mode to provide a replicable technical path for agricultural ecological transition in northwest arid areas; relying on the application and protection mechanism of Karez heritage to promote the regional popularization of the concept of irrigation and drainage ecological transition, and realize the living inheritance of heritage techniques through intangible cultural heritage inheritance and technological empowerment.

On this basis, combined with the background of contemporary climate change, it explores practical methods to support agricultural ecological transition, deeply integrates the historical technical experience and management wisdom carried by Karez with the needs of modern ecological transition, provides actionable historical reference and practical guidance for promoting irrigation and drainage systems to empower agricultural ecological transition and enhance the resilience of agriculture in response to climate change, and highlights the contemporary value of world irrigation engineering heritage in contemporary ecological governance.

Keywords : irrigation and drainage system; water loss; ecological value; semi-arid agricultural areas; modern ecological transition.

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RESUME

Cet article analyse le mode de circulation coordonné entre le système d'irrigation et de drainage tridimensionnel de Turpan Karez, le «puits vertical - canal souterrain - canal ouvert - réservoir», et l'écologie agricole des oasis; interprète les processus clés par lesquels les peuples anciens se sont adaptés aux caractéristiques climatiques arides et à forte évaporation du bassin du Turpan, ont réduit la perte d'eau grâce au transport d'eau via des canaux souterrains et ont réalisé une utilisation efficace des ressources en eau reposant sur la circulation des eaux souterraines, confirmant l'interaction bienfaisante entre le système patrimonial d'irrigation et de drainage et l'écologie agricole dans les zones arides tout en soulignant sa valeur écologique de protection intégrée des montagnes, des rivières, des forêts, des terres agricoles, des lacs, des prairies et des déserts.

En même temps, à partir des multiples niveaux de l'exploitation agricole, de la région, de l'industrie et du système alimentaire, il extrait les caractéristiques fondamentales de résistance des écosystèmes agricoles de type irrigation et drainage du patrimoine mondial du génie d'irrigation, explore la sagesse écologique de «respecter la nature et s'adapter aux conditions locales» selon Karez, et met l'accent sur l'intégration approfondie de la valeur patrimoniale et des pratiques contemporaines: transformer la sagesse traditionnelle «du transport d'eau via des canaux souterrains et de l'irrigation économe en eau» de Turpan Karez dans un programme de régulation pour l'irrigation de précision dans les zones agricoles arides et semi-arides contemporaines afin de promouvoir le développement d'une agriculture régionale économe en eau; en s'appuyant sur son modèle de symbiose coordonnée «eaux souterraines-oasis» pour fournir une voie technique reproductible pour la transition écologique agricole dans les zones arides du nord-ouest; en s'appuyant sur le mécanisme d'application et de protection du patrimoine Karez pour promouvoir la vulgarisation régionale du concept de transition écologique de l'irrigation et du drainage, assurant ainsi le patrimoine vivant des techniques du patrimoine grâce au patrimoine culturel immatériel et à l'autonomisation technologique.

Sur cette base, en tenant compte du contexte du changement climatique contemporain, il explore des méthodes pratiques pour soutenir la transition agro-écologique, intègre fortement l'expérience technique historique et la sagesse de gestion portées par Karez avec les exigences de la transition écologique moderne, fournit des références historiques exploitables et des conseils pratiques pour promouvoir les systèmes d'irrigation et de drainage afin de favoriser la transition écologique agricole et d'améliorer la résistance de l'agriculture face au changement climatique, et met en évidence la pertinence actuelle du patrimoine mondial du génie d'irrigation dans la gouvernance écologique contemporaine.

Mots clés : Système d'irrigation et de drainage; Perte d'eau; Valeur écologique; Zones agricoles semi-arides; Transition écologique moderne.

1. Introduction

1.1 Research Background and Significance

The intensification of global climate extremes, with frequent occurrences of disasters such as droughts, high temperatures, and sandstorms, coupled with weak disturbance resistance and insufficient self-repair capacity of agricultural ecosystems, makes building agricultural ecological resilience a core task for ensuring regional food security, ecological security, and rural revitalization. The Turpan Basin has an average annual precipitation of only 16mm and an average annual evaporation of up to 3000mm. The extreme arid climate makes surface water retention difficult, and traditional surface canal systems suffer significant water conveyance losses.

As a unique underground hydraulic engineering system in arid regions, the Karez, through its complete system comprising vertical shafts, underground conduits, open channels, and terminal reservoirs (laoba), achieves gravity-fed water conveyance and subsurface drainage without external power, drastically reducing evaporation losses. It also effectively regulates farmland groundwater levels and controls soil salt accumulation, representing one of the optimal hydraulic models adapted to the natural

endowments of arid regions. The inscription of the Karez as a World Heritage Irrigation Structure in 2024 has made its dynamic conservation, ecological revitalization, and modern transformation and utilization a current research hotspot and a task of the times.

Existing research mostly focuses on the historical investigation, engineering structure, and cultural preservation of the Karez, with few studies deeply integrating its integrated irrigation and drainage functions with the theory of agricultural ecological resilience. This paper systematically reviews the millennium-long evolution of the Karez, deconstructs the intrinsic coupling mechanism between traditional hydraulic engineering and the resilience of agricultural ecosystems in arid regions, enriches the theoretical system of ecological hydraulics, sustainable agricultural development, and cultural heritage revitalization in arid regions, and fills the research gap on how traditional hydraulic wisdom empowers modern agricultural ecological resilience.

Addressing the contemporary development dilemmas of the Karez, this paper proposes targeted and actionable pathways for revitalization and upgrading. It aims to resolve the contradiction between traditional hydraulic heritage preservation and modern agricultural development, enabling the synergistic release of the Karez's multiple values—water-saving irrigation, soil and water management, ecological conservation, and cultural empowerment. This will contribute to stable agricultural production and increased income, saline-alkali land improvement, and oasis ecological restoration in arid regions, providing a practical paradigm for the revitalization of hydraulic heritage and the enhancement of agricultural ecological resilience in Northwest China's arid regions.

1.2 Current Research Status at Home and Abroad

Domestic research on the Karez started relatively early, with achievements concentrated in three dimensions: first, historical tracing and technical studies, investigating the origin and westward transmission of well-and-channel techniques during the Han Dynasty, and sorting out the history of large-scale construction during the Qing Dynasty and the development of Uyghur traditional excavation techniques; second, engineering protection and hazard management, focusing on analyzing the causes of Karez siltation, collapse, and water volume decline, and proposing engineering restoration measures such as dredging, reinforcement, and seepage prevention; third, research on ecological and cultural values, preliminarily exploring the Karez's role in water conservation, salt control, and oasis ecological maintenance, as well as its intangible cultural heritage and tourism value. Overall, domestic research emphasizes historical investigation, engineering repair, and static preservation, lacking systematic and structured research centered on agricultural ecological resilience, with insufficient in-depth exploration of integration paths between traditional engineering and modern agriculture and digital water conservancy.

Foreign research primarily focuses on similar underground Karez (Qanat) systems in regions like Persia and Central Asia, emphasizing the water-saving mechanisms, regional adaptability, and modernization transformation models of underground conduits, confirming the unique advantages of traditional underground hydraulic engineering in efficient water resource utilization and ecological maintenance in arid regions. However, foreign research lacks regional specificity for China's Xinjiang Turpan Basin and does not integrate China's oasis agricultural development models, water rights systems, and ecological protection policies, making it difficult to directly address the practical needs of Karez revitalization and utilization in China.

This paper constructs a coupled research framework of "hydraulic engineering—ecosystem—agricultural development"; systematically explains the intrinsic mechanisms by which the Karez irrigation and drainage system enhances agricultural ecological resilience; integrates five dimensions—engineering, digital technology, ecology, institutions, and industry—to form a comprehensive and actionable revitalization and upgrading system; and innovates in practical value by aligning with the requirements of water conservancy development in arid regions in the new era, creating a replicable model of "traditional hydraulic wisdom + modern digital water-saving."

2. Structure, Principles, and Historical Evolution of the Karez Irrigation and Drainage System

2.1 System Structure and Irrigation-Drainage Operational Principles

The core advantage of the Karez, distinguishing it from single-purpose irrigation canal systems, lies in its integrated and coordinated irrigation-drainage operation. The underground conduits intercept subsurface flows formed by the infiltration of Tianshan Mountain snowmelt and convey water via gravity flow to farmlands for irrigation. Simultaneously, the crisscrossing network of underground conduits continuously drains groundwater from farmland areas, stabilizing the water table below the critical depth of 1.5-2.0m, effectively preventing the upward migration and accumulation of soil salts via capillary action, thereby controlling secondary soil salinization at its source. Irrigation water supplementation, subsurface drainage, and soil salt control proceed synchronously, forming a virtuous cycle system for soil and water ecology adapted to arid regions.

Vertical Shafts: Spaced 20-50 meters apart along the underground conduit alignment, with depths ranging from several meters to tens of meters depending on terrain and groundwater level, primarily used for soil removal during construction, shaft ventilation, and later-stage dredging and maintenance. Shaft openings are equipped with sand prevention facilities to avoid windblown sand filling the conduits.

Underground Conduits: The core unit of the system, buried 1-3 meters underground, relying on natural topography to form a gentle gradient of 0.5‰-1‰ for gravity-fed water conveyance. Being completely isolated from surface high temperatures and windblown sand, the conduits drastically reduce evaporation losses, with conveyance losses less than 5%, only 1/10 to 1/40 of traditional open channels. They also serve the core function of subsurface drainage and groundwater level regulation.

Open Channels: Surface channels connecting the outlet of the underground conduits to the farmland irrigation areas, equipped with water control gates to achieve zonal water distribution and precise irrigation for farmlands.

Terminal Reservoirs (Laoba): End-point regulating and storage ponds that can store channel water, regulate diurnal and seasonal water fluctuations, stabilize water temperature, settle silt, ensure irrigation stability, and also function as small ecological wetlands, conserving local soil and water ecology.

2.2 Historical Evolution Process

The Karez in Turpan has a long history, but so far, consensus on its origin has not been reached. The earliest Karez that can be definitively identified were excavated in the early 15th century. From then until the early 19th century, the development of Karez in Turpan was slow. From the mid-19th century to the 1960s, it was a period of rapid development for the Turpan Karez, experiencing three major development peaks: the first after Lin Zexu was exiled to Xinjiang during the Daoguang reign of the Qing Dynasty, the second during Yang Zengxin's governance of Xinjiang in the early Republic of China, and the third from the 1950s to the 1960s. During the Daoguang reign, Lin Zexu, while stationed in Xinjiang, oversaw the repair and construction of over 60 Karez, reclaiming over 110,000 mu of wasteland, and was revered by the local people as "Lord Lin's Wells." During the Guangxu reign, after Zuo Zongtang recovered Xinjiang, he vigorously promoted Karez construction, with the total number of systems in the region exceeding 800. In 1957, the number of Karez in Turpan reached 1,237, with a total channel length exceeding 5,000 kilometers, irrigating an area of 19,300 hectares and a total flow of 20.95 m³/s, becoming the lifeline for oasis agricultural survival and development. During this period, Karez excavation, repair, and management techniques became fully standardized, forming a multi-ethnic co-construction and sharing hydraulic system. In 2014, the Karez excavation technique was inscribed on the National Intangible Cultural Heritage List.

After the 1970s, the excavation of new Karez basically ceased, and Karez development showed a declining trend. In the past decade, Turpan's cultural relics and water conservancy departments have conducted multiple systematic surveys and organized reinforcement and protection of Karez. Existing Karez have been effectively protected, and their historical and cultural value has gradually gained recognition.

Throughout its millennium-long development, the Karez exhibits three major evolutionary patterns: first, technological localization and adaptation, gradually iterating and optimizing into a dedicated hydraulic technology system adapted to the arid region's climate, hydrology, and soil conditions; second, functional ecological upgrading, expanding from a single function of military settlement and farmland irrigation to composite ecological functions including water-saving conveyance, soil and water management, ecological conservation, and oasis maintenance; third, dynamic adaptation to the times, iterating and transforming with societal development needs—ancient adaptation to land reclamation and development, modern adaptation to scaled agriculture, and contemporary adaptation to ecological protection and high-quality development—demonstrating environmental adaptability and developmental resilience.

3. The Value of Karez in Supporting Agricultural Ecological Resilience and Existing Problems

3.1 Multidimensional Value of Karez in Enhancing Agricultural Ecological Resilience

Water Resource Resilience: Stable Water Supply and Water Saving, Resisting Extreme Drought Disturbances

The underground conduit water conveyance mode of the Karez completely avoids interference from surface high temperatures, windblown sand, and drought on water conveyance, resulting in water conveyance stability. Even in extreme drought years, it can guarantee basic irrigation water for farmlands. The extremely low evaporation loss enables highly efficient water resource utilization. Compared to the 50%-70% loss rate of traditional open channels, it saves significant scarce water resources in arid regions. Furthermore, the system relies on gravity-fed conveyance of subsurface flows, requiring no mechanical power, zero energy consumption, and zero carbon emissions, aligning with the goals of water-saving agriculture and carbon neutrality in arid regions, providing stable and sustainable water supply support for agricultural production.

Soil and Water Ecological Resilience: Salt Control and Soil Stabilization, Improving Cultivated Land Ecology

The core function of integrated irrigation and drainage allows precise regulation of farmland groundwater levels, blocking the upward migration and accumulation of soil salts, and continuously leaching salts from the topsoil. Data shows that soil salt content in Karez irrigation areas is 30%-50% lower than in surrounding areas without such systems, making it a core ecological means for saline-alkali land improvement and cultivated land quality maintenance in Turpan. Additionally, stable groundwater levels prevent over-extraction leading to groundwater funnels, reducing risks of soil desertification and erosion. The soil erosion modulus in irrigation areas is 68% lower than in surrounding areas, effectively curbing oasis desertification and maintaining soil and water ecological stability in cultivated lands.

System Disturbance Resistance Resilience: Distributed Layout, Outstanding Risk Resilience The Karez is a distributed, networked hydraulic system, with multiple conduits and terminal reservoirs operating in coordination, possessing the disturbance resistance advantage of "single-point failure, overall unaffected." Compared to centralized reservoir and pumping station systems, it has stronger resistance to drought, windblown sand, and hydrological fluctuations, with higher system self-healing capability and stability. Moreover, the underground conduits are deeply buried, less affected by surface disasters and human damage, with low operation and maintenance costs and long life cycles, enabling long-term stable performance of hydraulic and ecological functions.

Biological Ecological Resilience: Conserving Oases, Maintaining Biodiversity The flowing corridors of Karez and the water bodies of terminal reservoirs form scarce humid ecological belts in arid regions, nourishing native sand-fixing vegetation such as populus euphratica, tamarisk, and saxaul, providing habitats and movement corridors for various waterbirds like egrets and swans, as well as multiple nationally protected animals, effectively maintaining oasis biodiversity. Furthermore, stable and clean water sources support the protection of Turpan's characteristic grape germplasm resources, maintaining a gene bank of over 550 grape varieties, aiding the ecological protection of characteristic agricultural germplasm resources. In some areas, relying on Karez for winter ecological water supplementation has effectively restored wetland ecology in regions like the Ayding Lake, improving the regional microclimate.

Socio-economic Resilience: Cost Reduction and Efficiency Increase, Empowering Rural Development The gravity-fed water conveyance of Karez significantly reduces agricultural irrigation energy consumption and operation costs. Combined with modern drip irrigation technology transformation, it can save over 40% of water per mu and reduce irrigation costs by about 300 yuan per mu, markedly improving agricultural production efficiency.

The stable and mild water source is suitable for planting characteristic fruits like grapes and Hami melons, supporting the development of Turpan's characteristic and advantageous agricultural industries. Simultaneously, as a World Heritage Irrigation Structure and national intangible cultural heritage, the Karez can be linked with cultural tourism and study tour industries, realizing the synergistic transformation of ecological, cultural, and economic values, empowering rural revitalization.

3.2 Core Existing Problems in Contemporary Karez Development

Engineering Level: Aging and Damaged Infrastructure, Declining Irrigation-Drainage Function

Long-term natural erosion and lack of maintenance have led to severe aging of most Karez facilities. Over 60% of operating conduits suffer from problems like siltation in underground conduits, wall collapse, and leakage damage. Cracks and filling of vertical shafts are common, leading to a significant decline in water conveyance and drainage efficiency. Most terminal reservoirs lack anti-seepage and purification modifications, with prominent issues of siltation and water leakage, resulting in insufficient water storage regulation and water quality assurance capacity, and an overall weakening of the integrated irrigation-drainage function.

Resource Level: Groundwater Over-extraction, Insufficient Water Source Recharge

During the large-scale development of modern agriculture, the disorderly drilling of numerous motor-pumped wells for groundwater extraction has led to a continuous decline in regional groundwater levels. This has significantly reduced the subsurface flow recharge upon which the Karez depends for survival, causing sharp decreases in water volume or even complete drying up of many Karez. Additionally, degradation of water conservation vegetation in mountainous areas and fluctuations in glacial meltwater further exacerbate water source shortages, forming a vicious cycle of "over-extraction—declining water levels—drying conduits—ecological degradation."

Technical Level: Extensive Operation and Maintenance Models, Insufficient Adaptation to Modern Agriculture

Traditional Karez rely on manual underground dredging and repair, with high operational risks and extremely low efficiency. Furthermore, traditional excavation and maintenance techniques face the problem of lack in inheritors. Existing conduit systems lack intelligent monitoring and precise water distribution facilities, resulting in rough water regulation that cannot meet the development needs of modern agriculture, such as integrated water and fertilizer management, precision irrigation, and smart agriculture. There is an insufficient adaptation between traditional hydraulic models and modern agricultural systems.

4. Optimization Pathways for the Karez System to Enhance Contemporary Agricultural Ecological Resilience

4.1 *Engineering Revitalization and Restoration, Consolidating the Hardware Foundation for Ecological Resilience*

Adhering to the principles of "repairing the old as it was, prioritizing function, and adapting to ecology," promote the protective restoration and modernization transformation of traditional Karez engineering. Combine traditional techniques with modern machinery to carry out dredging of underground conduits, repair of collapsed sections, and reinforcement of vertical shafts, clean up conduit siltation, seal leakage points, and restore the functions of water conveyance, drainage, and salt control. Implement ecological transformation of old terminal reservoirs, adding anti-seepage layers and aquatic plant purification zones to optimize water storage regulation, water quality purification, and ecological conservation capacity. Simultaneously, promote the integrated transformation of "underground conduits + buried pipelines + efficient drip irrigation," combining traditional gravity-fed conveyance with modern precision irrigation technology to address issues of high loss and low precision in traditional irrigation, significantly improving water resource use efficiency and adapting to modern agricultural planting models.

4.2 *Digital Technology Empowerment, Building a Smart Hydraulic Management and Control System*

Establish a digital smart management and maintenance platform for Karez. Deploy intelligent sensors for water level, flow, water quality, and water temperature at key vertical shafts, underground conduit nodes, and terminal reservoirs to achieve 24-hour real-time monitoring and anomaly warning of water conveyance status and groundwater dynamics. Complete the "one-well-one-file" digital archiving for all Karez, accurately recording information such as conduit location, structural parameters, operational status, and maintenance records to achieve refined and visual management and maintenance. Relying on GIS geographic information systems, integrate meteorological data, soil moisture, and crop water requirements to build intelligent water distribution scheduling models, dynamically optimize irrigation water allocation, achieve on-demand water supply and precision irrigation, and promote the transformation from traditional hydraulics to smart ecological hydraulics.

4.3 *Ecological Collaborative Governance, Constructing a Virtuous Soil and Water Circulation System*

Deepen the integrated irrigation-drainage comprehensive management of saline-alkali lands. Rely on the subsurface drainage and waterlogging reduction function of underground conduits, combined with periodic salt leaching via open channels and biological salt control using salt-tolerant vegetation, to structure a composite saline-alkali land Governance System of "engineering salt control + biological improvement," continuously improving cultivated land quality. Rely on the Karez conduit layout to create continuous ecological corridors. Plant native drought-tolerant and sand-fixing vegetation such as *populus euphratica*, sea-buckthorn, and tamarisk around vertical shafts and along conduit lines to structure an integrated oasis ecological protection network of "water—forest—farmland" for windbreak and sand fixation, soil and water conservation, and habitat restoration. Strictly implement the "dual control" of groundwater quantity and level. Delineate core protection zones and buffer control zones for Karez, strictly prohibit new motor-pumped wells and high water-consumption planting projects within protection zones, utilize floodwater and reclaimed water for ecological water supplementation during flood seasons, and maintain the dynamic balance of groundwater.

4.4 *Integrating Multiple Values, Empowering Long-term Resilient Development*

Rely on the stable and high-quality water source of Karez to develop green and organic grapes, characteristic fruits and other advantageous industries, promote ecological planting models, enhance the added value of agricultural products, and create ecological agricultural brands in arid regions. Promote the deep integration of hydraulic heritage with cultural tourism and study tour industries, create Karez hydraulic study bases, ecological and folk culture tourism routes, and link with cultural tourism resources such as the Flaming Mountains and the Ruins of Jiaohe to achieve synergistic transformation of ecological, cultural, and economic values. Summarize and refine the revitalization model of "traditional

Karez + modern water-saving + ecological governance," and promote it to similar arid regions in Northwest China such as Gansu, Ningxia, Inner Mongolia, and Central Asia, exporting Chinese traditional hydraulic ecological wisdom and paradigms for agricultural resilient development in arid regions.

5. Conclusion and Outlook

The Karez irrigation and drainage system has formed an ecological hydraulic model that adapts to local conditions and coexists harmoniously with nature. Its core functions of integrated irrigation and drainage, low consumption and water saving, and salt control and soil stabilization are well-suited to extreme arid regions. Against the backdrop of frequent extreme climate events and intensified ecological constraints in contemporary times, the Karez supports the construction of agricultural ecological resilience in arid regions comprehensively across five dimensions: water resource supply, soil and water stability, system disturbance resistance, biological conservation, and socio-economic aspects. It serves as a core ecological stabilizer for the sustainable development of oasis agriculture.

Currently, the Karez system faces multiple challenges, including aging and failing infrastructure, declining water source recharge, insufficient technological adaptation, fragmented ecological corridors, and lagging management mechanisms, leading to the continuously weakening of its ecological resilience functions. Addressing these issues through engineering revitalization and restoration to consolidate the hardware foundation, digital technology empowerment to improve management precision, ecological collaborative governance to optimize soil and water cycles, institutional system improvement to fortify long-term safeguards, and integration of multiple values to achieve quality and efficiency enhancement can systematically crack the development bottlenecks of Karez, effectively enhance agricultural ecological resilience in arid regions, and realize a win-win situation of dynamic heritage preservation and high-quality development of modern agricultural ecology.

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