https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

A review of Jinci Springs discharge in China: millennia utilization, decadal dry-up, and recent resurgence

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Abstract. Jinci Springs, a historically significant karst spring system in the semi-arid region of northern China, has served as a critical water source and cultural landmark for millennia. This review synthesizes the socio-hydrological evolution of the springs, tracing transformations in water use, governance, and resilience from ancient times to the present. Early hydraulic interventions were primarily military-driven, later expanding to agricultural irrigation and ritual-based water governance. Over centuries, a hybrid governance system emerged that blended spiritual traditions, including water deity worship, with local institutions to mediate conflicts and allocate resources. In the modern era, intensified groundwater extraction—driven by technological advances and insufficient regulatory oversight—led to aquifer depletion and the cessation of spring flow in April 1994. The ensuing water crisis triggered a societal and institutional pivot toward conservation, culminating in a suite of restoration efforts and policy reforms. Intermittent spring resurgence began in May 2023, with continuous flow observed since September. This case underscores the importance of social adaptability, cultural continuity, and governance reform in maintaining spring systems under stress. By examining the long-term dynamics of Jinci Springs, this review contributes to broader discussions on socio-hydrological resilience and sustainable groundwater management in water-scarce regions.

1 Introduction

Water has long served as a cornerstone of human civilization(Mithen, 2012; Schaik & Willems, 2015; C. Li et al., 2023; Isendahl, 2004), enabling agricultural development, supporting urbanization, and shaping socio-political structures across time(Harrower, 2009; Smith, 2020; Zhuang et al., 2018). Ancient societies—from the irrigation networks of India(Jana & Tamang, 2023; Singh et al., 2020) and Egypt(Ahmed et al., 2020; Barnes, 2017) to the qanat systems of Persia (karez in China)(Q. Li et al., 2023; Salek, 2019)—developed sophisticated hydraulic infrastructures to manage water scarcity in arid and semi-arid environments. These early innovations have not only laid the foundation for modern water engineering but also reveal how water management was deeply intertwined with governance, territorial expansion, and cultural identity(Alba et al., 2025; Yates et al., 2017). The Roman Empire's aqueducts reinforced imperial control and urban prosperity(Sánchez López, 2023), while the Venetian Republic and Umayyad Caliphate similarly leveraged hydraulic expertise to sustain socio-economic growth(Bozorg-Haddad, 2021). In ancient China, large-scale, state-led irrigation projects played a critical role in grain security and political legitimacy(Storozum et al., 2018; Zhuang, 2017). Water has also carried strong symbolic and spiritual meanings, as reflected in rituals, divination, and religious practices, underscoring its dual role as both material resource and cultural asset(Glowacki & Malpass, 2003; Oestigaard, 2017). Maintaining balanced human–water relationships has long been regarded as essential for societal stability and prosperity(Shi et al., 2019; Wang-Erlandsson et al., 2022; Yang et al., 2021).

Today, karst regions—home to over 1.18 billion people globally(Goldscheider et al., 2020)—play a vital role in water security(Hartmann et al., 2014), agriculture(Shoemaker, 2022), ecosystem functioning(Vilhar et al., 2022), and socio-economic development(de Sena et al., 2022; Q. Zhou et al., 2025). China, with the world's largest karst area (2.55 million km², ~26.5% of its territory), relies heavily on karst groundwater, especially in its semi-arid north(Nico Goldscheider et al., 2020). However, the inherent hydrogeological complexity of karst systems—characterized by high heterogeneity in recharge, flow, and discharge—renders them particularly sensitive to climatic variability and anthropogenic stress(Çallı et al., 2025; G. Jiang et al., 2025; Luo et al., 2022). In recent decades, intensified groundwater extraction and climate-induced shifts have resulted in the severe decline of major karst springs in northern China, with some experiencing complete flow cessation(Keqiang et al., 2021; Z. Zhang et al., 2020). Jinci Springs, located in Taiyuan, Shanxi Province, exemplifies this transformation. As one of northern China's most culturally and hydrologically significant karst springs, its long history of human reliance spans millennia. Yet since the 1950s, unsustainable groundwater exploitation has led to a progressive decline, culminating in a complete dry-up in April 1994(Z. Zhang et al., 2020). This triggered ecological degradation, economic recession, and tourism contraction. In response, the local government launched a comprehensive restoration campaign, leading to intermittent flow recovery in May 2023 and continuous spring discharge since September 2023.

While hydrological studies have explored the causes of spring depletion, water quality degradation, and the physical conditions for resurgence(C. Li et al., 2021, 2024a; Lu et al., 2020; Wang Z. et al., 2020; Z. Zhang et al., 2020), there remains a significant gap in understanding the long-term socio-hydrological dynamics of Jinci Springs. This review addresses that gap by tracing the historical evolution of water use, governance strategies, and cultural values associated with the spring. It examines how hybrid systems of governance—including deity worship, customary water-sharing institutions, and state-led interventions—contributed to both the resilience and vulnerability of the spring. By reconstructing the socio-hydrological history of Jinci Springs, this study aims to offer broader insights into the governance of groundwater systems in arid and semi-arid regions. The findings contribute to a growing discourse on spring restoration, highlighting the relevance of historical practices and public engagement in developing adaptive, culturally grounded strategies for sustainable water management.

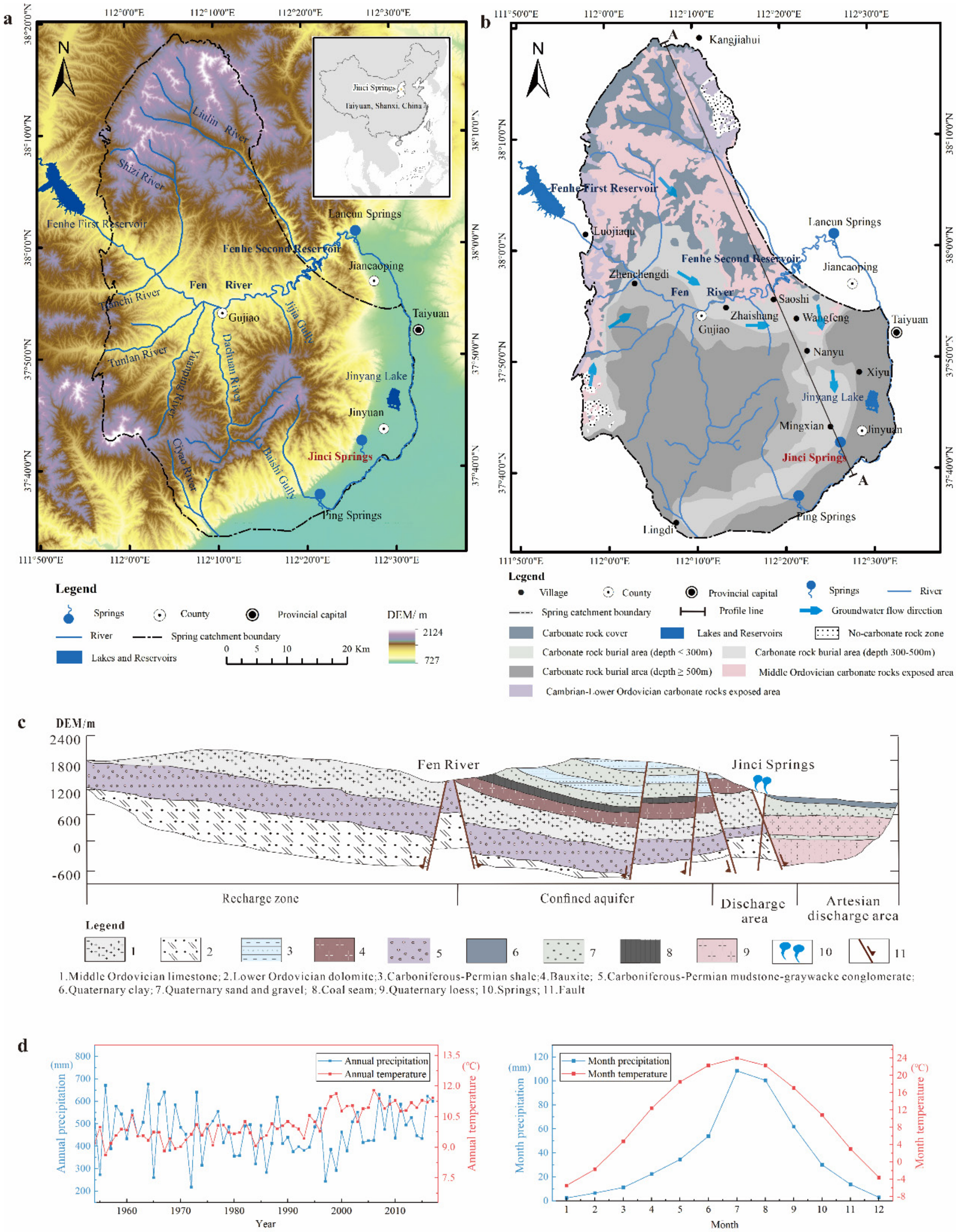
https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

2 Study Area & Methodology

2.1 Hydrogeological Conditions of the Jinci Springs Catchment

Jinci Springs, located in Taiyuan, the capital city of Shanxi Province, China (Figure 1a), is fed by a karst groundwater system covering a catchment area of approximately 2,713 km². The terrain slopes from northwest (2,124 m above mean sea level) towards southeast (780 m amsl) (Liang et al., 2019). Geologically, the Paleozoic era's marine sedimentation generated extensive limestone, shale and sandstone layers. Subsequent tectonic events, including the Mesozoic Yanshan Movement and Cenozoic differential uplift and subsidence, exposed deeply buried limestone formations, forming a highly permeable karst aquifer characterized by abundant conduits and fractures(Y. Li et al., 2019; Ma T. et al., 2012). Recharge to the karst aquifer primarily originates from atmospheric precipitation and surface water infiltration. The geological stratigraphy of the area is relatively complete, comprising Cambrian-Ordovician carbonate rocks, Carboniferous-Permian sandstone, shale, and coal seams, Triassic clastic deposits, and Quaternary unconsolidated sediments from bottom to top(C. Li et al., 2021, 2024a) (Figures 1b, 1c). Impermeable Cambrian carbonate rocks constitute the lower boundary of the aquifer, while the Middle Ordovician carbonate formations, intermittently exposed in the northern catchment and buried towards the south, form the main groundwater-bearing unit. Overlying strata of sandstones, shales, coal seams, clastic rocks, and unconsolidated sediments restrict vertical water movement(Duan et al., 2025; Z. Zhang et al., 2022). Recharge predominantly occurs in the northern and western catchment areas, directing groundwater flow towards the southeast. Upon encountering low-permeability geological barriers, groundwater resurfaces, giving rise to the Jinci Springs complex(Hao et al., 2009; Sun et al., 2016) (Figures 1b, 1c).

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026



https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

Figure 1. Overview of the Jinci Springs region: (a) Elevation map of the springs region; (b) Distribution and burial types of carbonate rocks; (c) Geological cross-section along line A-A in Figure 1b; (d) Temperature and precipitation fluctuations in the Jinci Springs catchment.

Jinci Springs exhibit substantial and stable flow, with measured data and historical records prior to 1950 estimating the flow rate ranging between 2.0 m^3/s and 3.0 m^3/s(Su, 2018). The region receives an average annual precipitation of about 460 mm, with an average evapotranspiration of approximately 1800 mm(C. Li et al., 2024b). The climate is classified as warm temperate semi-arid continental monsoon, characterized by significant seasonal variations with precipitation concentrated in the summer months (June to September) and uneven distribution both annually and seasonally(R. Ma et al., 2011). The multi-year average temperature is 10.01°C, with the highest temperatures of 23.73°C in July and the lowest of -5.75°C in January, coinciding with concurrent rain and heat periods (Figure 1d)(Liang et al., 2024).

2.2 Data Sources and Processing Methods

2.2.1 Literature Compilation and Thematic Data Extraction

This study synthesized information from a wide range of peer-reviewed academic sources to investigate the historical and hydrological evolution of Jinci Springs. Literature was retrieved from major academic databases, including Web of Science, Google Scholar, and the China National Knowledge Infrastructure (CNKI), using keywords such as “Jinci Springs,” “spring re-flow,” and “water culture.” A total of 35 peer-reviewed publications were identified and reviewed, focusing on the historical development, water resource management, and the impacts of anthropogenic activities and environmental change on spring flow interruption and recovery. Supplementary context was derived from academic monographs, which provided theoretical and empirical support for the socio-hydrological analysis. Additionally, climate data, land use trends, and flow regulation measures were compiled from relevant studies and systematically cross-referenced to ensure consistency and reliability.

2.2.2 Geospatial Data Acquisition and Processing

Geospatial datasets were integrated using standard Geographic Information System (GIS) methodologies. A 12.5-meter resolution Digital Elevation Model (DEM) was obtained from the ALOS Global Digital Surface Model via the Google Earth Engine (GEE) platform. Hydrological features were sourced from OpenStreetMap (OSM), with refinement and validation based on authoritative academic references. Key spatial features were extracted by georeferencing and vectorizing the Jinci Springs map and its associated information as published in Liang et al. Historical irrigation zones of the Jinci aqueduct during the Qing Dynasty were digitized based on published sources. All point, line, and polygon features were initially extracted using Google Earth Pro and subsequently compiled into final map outputs (e.g., Figure 2) using ArcGIS 10.8 and vector editing software.

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

2.2.3 Data Validation and Integration Framework

All spatial and thematic data were processed within a unified spatial framework to facilitate robust analysis of the human–water relationship in the Jinci Springs region. Cross-validation was conducted between multiple sources to ensure methodological rigor and data consistency. The integrated dataset provided a comprehensive basis for interpreting long-term changes in groundwater use, socio-cultural adaptation, and sustainability pathways for spring ecosystem recovery.

3 Ancient Development and Utilization of Jinci Springs

3.1 Utilizing Jinci Springs Discharge from Military to Agricultural Purposes

The Jinci Springs catchment is characterized by a well-developed river system and abundant groundwater resources, since the Fen River, the second-largest tributary of the Yellow River, flows through adjacent area and delivers a large amount of surface water. Early people in ancient Taiyuan City, where Jinci Springs are situated, developed complex social structures and large settlements thanks to the rich water resources. In the late Spring and Autumn period (circa 479 BCE), the ancient city of Jinyang (renamed Taiyuan in 590 CE) was established at the confluence regions of Jinci Springs with the Fen River(Shen & Yuan, 2009). Surrounded by mountains on three sides and traversed by the Fen River to the north, Taiyuan's geographical setting provided natural military defenses and a stable environment conducive to social development. Additionally, the flourishing river transport on the Fen River and the fertile lands of the Jinci Springs region enabled ancient Taiyuan to gradually become a military stronghold (Zhao S., 2019; J. Zheng & Wang, 2014). Over various dynasties, it also developed into a regional economic and political hub (Figure 2)(X. Zhang et al., 2022).

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

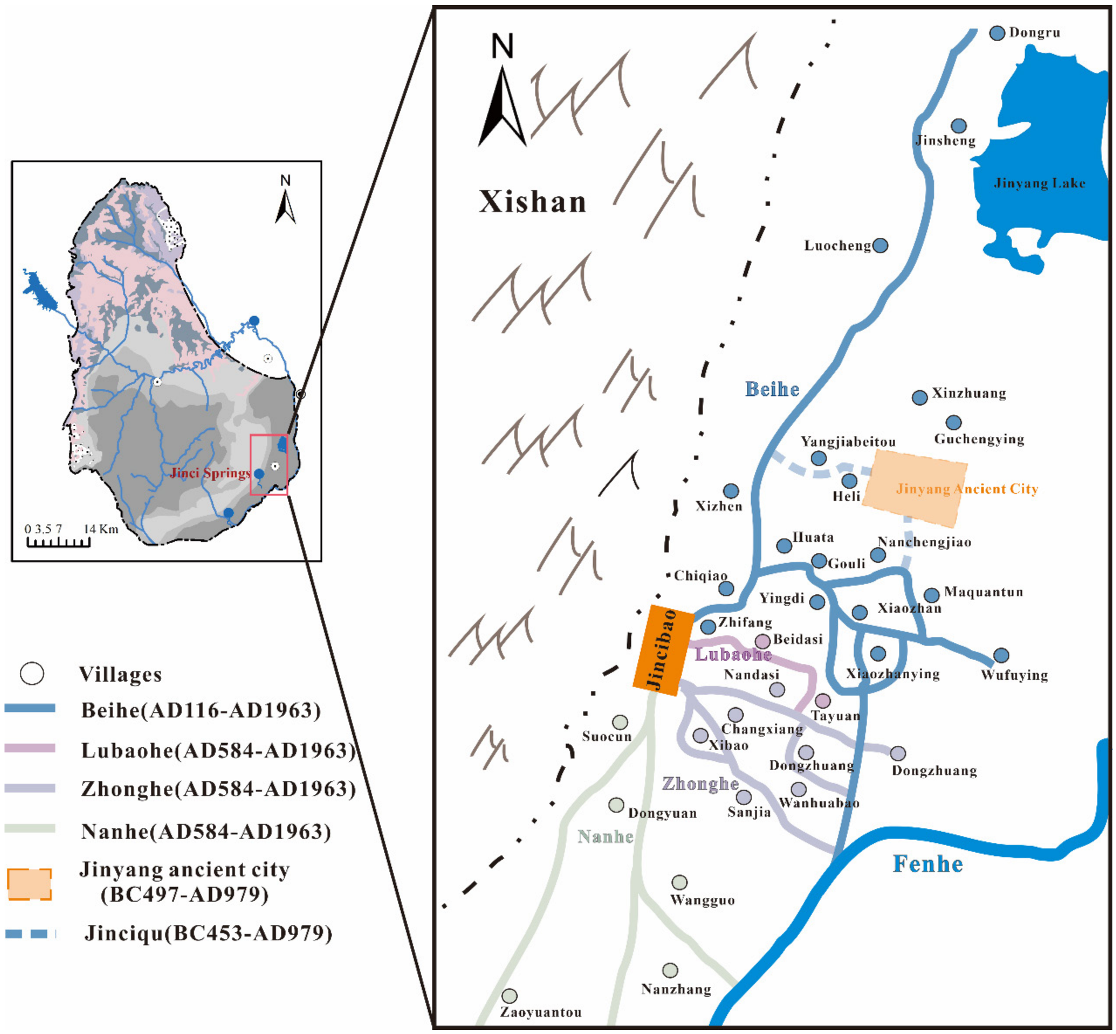


Figure 2. Irrigation extent of the Jinci Canal during the Qing Dynasty

The origin of hydraulic engineering at Jinci Springs can be traced back to around 453 BC(Miller, 2004). In a bid to seize territory, the minister Zhibo of the Jin State excavated the Zhibo Canal (later known as Jinci Canal) to divert the spring water and flood ancient Taiyuan city. Initially constructed as a military siege facility during wartime, the Jinci Canal represents one of China's earliest hydraulic engineering projects, predating the large-scale Dujiangyan irrigation system(X. Zheng et al., 2020). After the war, during a period of peace, the Jinci Canal was gradually repurposed by local residents for farmland irrigation, marking the beginning of a new phase in the utilization of Jinci Springs discharge for agricultural irrigation.

As Taiyuan became a regional political and economic center, water demand increased. During the subsequent millennium, hydraulic facilities surrounding Jinci Springs expanded gradually to enhance agricultural irrigation efficiency. In the Han Dynasty (116 CE), the Zhibo Canal (now known as the North River) was dredged to direct water from Nanlao Spring (one

https://doi.org/10.5194/egusphere-2025-5309
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outlet of Jinci Springs) to surrounding Guchengying and Jinsheng villages, for agricultural irrigation (Figure 2). During the Sui Dynasty (circa 584 CE), three new main canals—the Middle River, South River, and Lubao River—were constructed, extending the irrigation radius to 20 kilometers. During the Tang Dynasty, two aqueducts were constructed across the ancient Fen River (in 639 CE and 780 CE) for delivering water from Jinci Springs to mitigate soil salinization in the eastern parts of ancient Taiyuan and at the same time expand irrigation to approximately 7.47 square kilometers of farmland. During that period, Jinci Springs became the essential water source for the ancient Taiyuan City, providing water for irrigation and domestic use.

By the Song Dynasty (cirac 1060 CE), the irrigation area of Jinci Springs reached its peak, covering approximately 23 square kilometers, marking a period of highest irrigation efficiency in ancient times(Su, 2020). During the Ming and Qing Dynasties (circa 1368-1912 CE), the population of the Taiyuan region grew significantly, leading to frequent conflicts over water use in the spring region(Xing, 2005). This period was also characterized by the development and gradual refinement of the irrigation management system for Jinci Springs. Over several dynasties, the management of Jinci irrigation channels and hydraulic infrastructure gradually evolved into a relatively fixed set of procedures, ensuring the efficient utilization of water resources for agricultural purposes.

3.2 Water Rights Conflicts

In the water-scarce semi-arid regions, conflicts over water resources often stemmed from unequal distribution and disputes over water rights. Political instability could further exacerbate these conflicts(Angelakis et al., 2021). During the Song and Yuan dynasties, Taiyuan, as a military stronghold, experienced numerous wars and turmoil. In the Ming and Qing dynasties, population growth and an increase in irrigated farmland intensified water resource conflicts in the Jinci Springs region. Amidst this backdrop, water distribution and management systems were continually proposed and refined. These developments were accompanied by shifting beliefs related to water rights.

3.2.1 Management Systems

During the Sui and Tang dynasties, hydraulic engineering efforts at Jinci Springs focused primarily on water diversion to ensure a stable supply. By the Song dynasty, the emphasis shifted towards expanding irrigation areas and improving efficiency of using Jinci Springs water. Between 1056 and 1063, the government constructed water distribution facilities at the source of Jinci Springs. These facilities divided the spring water into ten parts (Fig. 3a). Seven parts were allocated to the North River, one and a half parts to the South River, one part to the Middle River, and a half part to the Lubao River(Editorial Committee of 'Records of Water' Conservancy in Jin River, 2002). The establishment of this system reflected the society's significant emphasis on water resource management at that time, ensuring that the irrigation needs of various regions were met. The precise allocation method not only improved the efficiency of water use, but also reduced social conflicts arising from unequal water distribution. This distribution system continued until 1950s. Despite multiple dynastic changes and social

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

transformations, the water distribution system of Jinci Springs was preserved and maintained. This indicates that ancient engineers fully considered the sustainable use and long-term management of water resources when designing hydraulic engineering.

In the early Ming dynasty, the Jinci Springs region became a crucial site for military garrisons. Military households accounted for one-third of the total cultivated land and population in Taiyuan at the time. The irrigation water distribution adopted the "half for military, half for civilians" rule, exacerbating tensions over Jinci Springs' water resources(Xing, 2005). By the Qing dynasty, irrigation water was meticulously allocated by days among villages, with specific arrangements each year for the number of water use cycles and their duration (Editorial Committee of 'Records of Water' Conservancy in Jin River, 2002). As water resources became increasingly scarce, the spring water allocation system evolved to become more precise, reflecting society's ongoing adaptation and advancements in water resource management.

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

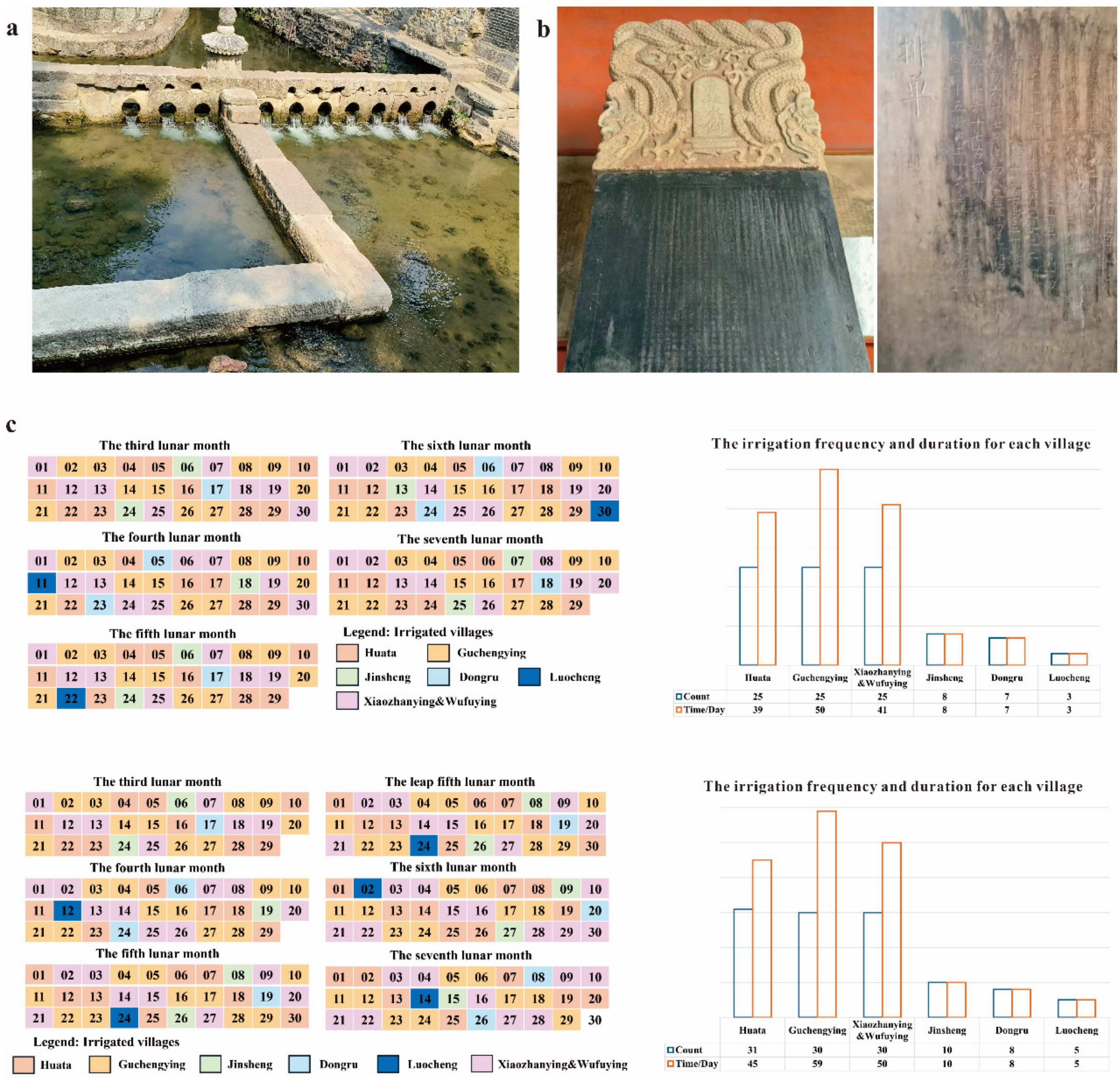

Figure 3. Hydraulic infrastructure and water management systems of the Jinci Springs. a) The Three-Seven Water Distribution Facility; b) The North River Spring and Autumn Hydraulic Inscription; c) Allocation of irrigation water based on historical inscriptions. According to the Spring and Autumn Hydraulic Inscription of the North River (1853), Huata (including villages such as Xizhen, Nanchengjiao, Gouli, and Heli) received 25 water use cycles over 39 days; Guchengying received 25 cycles over 50 days; and Xiaozhanying and Wufuying had 25 cycles over 41 days.

For the traditional spring-fed agricultural societies in the semi-arid northern regions of China, spring water management system was crucial for agricultural production and social stability. Starting from the Ming dynasty, a comprehensive river and canal management system was established, with appointed officials, such as canal chiefs and water wardens, from each village. In

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

the Qing dynasty (1729 CE), to prevent conflicts over water usage from the Jinci Spring source, the villages of Jinci, Chiqiao, and Zhifang were designated as part of the Jinci Main River. This designation allowed these villages relatively free access to water without a strict schedule.

Concurrently, land measurements were conducted for each river canal and village, resulting in the creation of the " Canal Management Manual", which was inscribed on stone tablets (Figure 3b) as the basis for managing spring-related affairs(Xing, 2005). This further refined the management system. The system included the appointment of one canal chief and several water wardens for the main river and each of the four subsidiary rivers. The chief managers of the main river oversaw the hydraulic affairs of the catchment, while the water wardens assisted the chiefs in managing the irrigation schedules and maintenance of the canals in their respective villages. These positions were rotated annually, with the canal chiefs and water wardens elected by all villagers. Farmers who owned more land and were known for their fairness were chosen to prevent the long-term monopolization of water resources and the abuse of power.

Residents of the irrigation areas, while benefited from the convenience of using the water channels, were responsible for channel maintenance. Led by the chief of the main canal, along with the canal chiefs of the four subsidiary canals and water warden farmers cleaned the canals twice a year, around the Qingming Festival and the Frost's Descent Festival. The maintenance costs were shared among the villages in the irrigation district. The system of collective labor and cost-sharing was essential for the normal operation of the hydraulic system. It also strengthened social bonds among residents and enhanced their sense of public responsibility, which was a crucial factor in maintaining the stability and sustainable development of traditional agricultural societies(Adusumilli et al., 2020).

Conflicts over priority and fairness in water resource allocation have been long-standing issues. The refinement of spring water distribution and irrigation marked significant progress in ancient hydraulic management. Water use conflicts and the imbalance between supply and demand drove the establishment and reforms of the spring water utilization system. The Jinci Springs water management system ensured effective management and relatively fair distribution of spring water resources through hierarchical management and collective participation. This system not only facilitated smooth agricultural production but also played a vital role in social stability and community cohesion.

3.2.2 Water Deity Worship

Local residents constructed the Jinci Temple around the three main outlets of Jinci Springs (Shanli Spring, Yuzhao Spring and Nanlao Spring) to express their worship for Jinci Springs, because their lives depended on the spring discharge (Figure 4 a, b, c, d). The local culture and beliefs of the Jinci region are closely linked to water, and the belief in water deities has continuously evolved throughout history(Hu et al., 2025; Xiao, 2015).

The local residents always chose a hero to represent water deity, with the hero changing over different dynasties. Before the Song dynasty, Shuyu Tang (Figure 4 e, f), who symbolized national orthodoxy and held the divine power of rain, was the primary deity of Jinci. After a destruction of ancient Taiyuan City during the Song dynasty, the central government introduced

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

the veneration of Shengmu (Holy Mother) (Figure 4 g, h) as an official water deity to aid people in surviving frequent droughts. Her palace was built next to Shuyu Tang′s. This transition aimed to consolidate state power in dealing with the local droughts by establishing a new belief system in the region. In the early Ming dynasty (1369 CE), the Shengmu Temple frequently held emperor-led rain praying ceremonies, reinforcing the connection between Shengmu and water. Although Shuyu Tang was still regarded as a symbol of Confucian traditional imperial authority, his role as a water deity diminished against the backdrop of Shengmu's growing prominence(Zhao S., 2019).

After Shengmu the local people chose another idol Chunying Liu as Water Mother Niangniang (Figure 4 i, j). During the Ming dynasty, the water rights of villagers were in a constant conflict with military water rights. This conflict persisted into the Qing dynasty. Jinsheng village, located at the end of the North River canal, frequently faced water shortages and conflicts with upstream villages occupied by the military. According to legend, Liu Chunying from Jinsheng village married into Jinci village and sacrificed herself to control floods. Thus, she was regarded as a deity worshipped by the local people. This legend empowered Jinsheng villagers in asserting their water rights. By continually reinforcing and mythologizing the story of Water Mother Niangniang, local villages established a basis for keeping their water rights. This continuous worship further strengthened the water rights of the spring region. Even to this day, the worship ceremonies for both Water Mother and Shengmu are major annual festivals in the Jinci region(Zhou X. et al., 2012).

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

Figure 4. Evolution of the primary deity worship at Jinci Springs. (a) Distribution of water deity temples within the Jinci complex; (b) Nannao Spring; (c) Shanli Spring; (d) Yuzhao Spring; (e) Shuyu Tang Temple; (f) Statue of Shuyu Tang; (g) Shengmu Hall; (h) Statue of Shengmu; (i) Water Mother Pavilion; (j) Statue of Water Mother Niangniang.

The beliefs in Water Mother and Shengmu represent two systems: one created by rural villagers as a local deity, and the other recognized at the national level. Both have become widely known and respected deities in the Jinci region. Different from the coercive power of authorities, deities acted as a vital supplementary means to deal with water conflicts and improve water managements. When official regulations failed to meet the daily needs or rights of local residents, they were more inclined to seek out or even create deities closely connected to their lives for worship, as a means to defend their water rights. Different

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

deity systems and legendary figures provided the local community with various symbols and support. These figures, as a part of cultural tradition reflecting the importance placed on water resources and the pursuit of power and fairness, also influenced local social norms and values.

4 The Process of Jinci Springs Dry-up

4.1 Analysis of the Causes of Flow Dry-up

Since 1950s, population growth and industrial development created a considerable need on the water resources of the Jinci Springs region. Extensive groundwater development largely depleted karst groundwater storage and reduced the spring discharge. The annual average Jinci Spring discharge remained relatively stable at around 1.9 m^3/s before 1960 (Figure 5a)(Z. Zhang et al., 2022). During a period of 20 years (1960-1980) of extensive groundwater development, the groundwater level of the spring catchment decreased 10 meters. During the same period, the spring flow rate decreased more than 60%, from 1.5 m^3/s in 1960 to about 0.5 m^3/s in 1980. The decreasing trend continued until the flow stopped on April 1994 (Figure 5a)(Hao et al., 2009; C. Li et al., 2024b).

It is believed that human activities and climate change are the two main causes of the dry-up of Jinci Springs. The annual average precipitation in the Jinci Springs region decreased from approximately 543.9 mm in the 1950s to 384.3 mm in the 1990s with a reduction of 29.3% (Figure 5b). Concurrently, the flow rate of Jinci Springs plummeted from 1.927 m^3/s to 0.148 m^3/s, a reduction rate of 92.3% (Figure 5b). This indicates that anthropogenic activities have caused at least 63% of the reduction in spring discharge.

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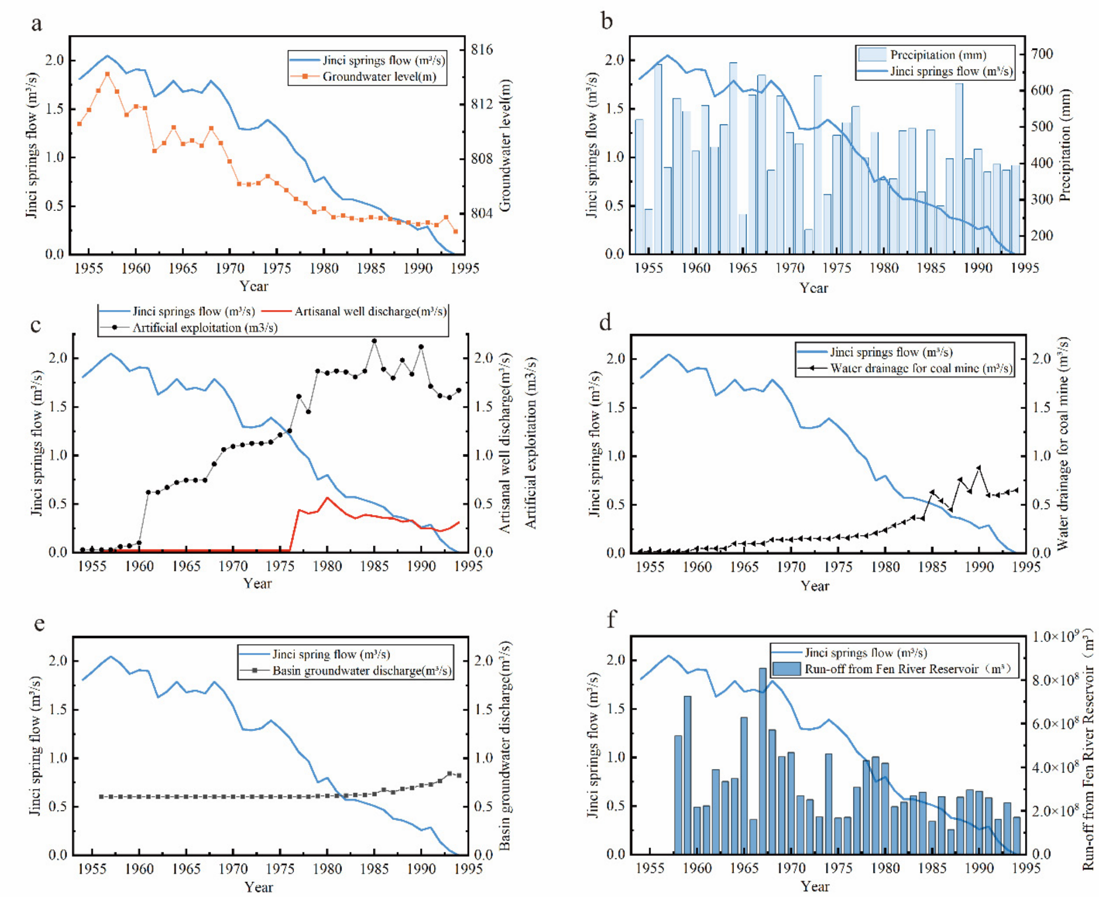


Figure 5. Factors contributing to the cessation of Jinci Springs. (a) Changes in water level and flow rate of Jinci Springs; (b) Precipitation at Jinci Springs; (c) Artificial extraction volume and flowing well discharge from karst springs; (d) Drainage from coal mining; (e) Subsurface discharge in the Taiyuan Basin; (f) Runoff volume of the Fen River.

The anthropogenic contribution to the spring dry-up can be summarized as four main human activities. The first one is the surge in industrial and agricultural water uses. In the 1950s, to attract investments to build factories, Taiyuan City offered incentives such as waiving industrial water fees (Editorial Committee of 'Records of Water' Conservancy in Jin River, 2002). Consequently, the Taiyuan Chemical Plant and Taiyuan Fertilizer Plant were established within the Jinci Springs catchment and both plants directly pumped groundwater from the karst aquifer (Yin, 2007). In the early 1960s, some pharmaceutical factories started operations with water supplied from groundwater in the Jinci Springs catchment. As industrial production expanded, the rate of water extraction for industrial uses reached 1.69 m³/s by the late 1970s. Simultaneously, the spring discharge had already dropped below 1.0 m³/s (Figure 5c). In the meantime, to meet the increasing demand for agricultural development, irrigation wells were also rapidly developed, inducing water conflict between industry and agriculture(Y. Li et al., 2019). Between 1976 and 1978, the government constructed 14 flowing wells at Pingquan village in the Jinci Springs

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

catchment for irrigation. Agricultural irrigation combined with industrial water supply caused the flow rate of Jinci Spring to drop from 1.21 m³/s to 0.75 m³/s within the three years (Figure 5c). In summary, from 1960s to 1990s, the decrease of Jinci Spring flow rate was 1.779 m³/s, while the increase in groundwater pumping for industrial and agricultural used exceeded 1.54 m³/s, which accounted for 86.6% of the total spring flow reduction (Yin, 2007). The decreasing of spring flow rate and the increasing of karst water extraction were inversely related with comparable magnitudes, indicating that extensive extraction of karst water was a main cause of the decrease and eventual cessation of Jinci Spring flow.

The second one was coal mining dewatering. In the Jinci Springs catchment, there were 298 coal mines, including nine large and medium-sized mines until 1994(Zhao J., 2013; Zhao W., 2013). Coal mining dewatering directly reduced the karst groundwater recharge from porous aquifers and shallow fracture aquifers, contributing the decline of Jinci Springs discharge (Qiao et al., 2010). From 1954 to 1978, coal mine dewatering gradually increased, then maintained a high rate. The mine dewatering rate increased from 0.02 m³/s in 1961 to an average of 0.638 m³/s in the 1990s, persistently impacting the spring flow (Figure 5d).

The third activity was the lateral recharge of karst groundwater into Taiyuan Basin. The Jinci Springs located the piedmont area and groundwater level is higher than that of Taiyuan Basin(C. Li et al., 2024b). A small amount of karst groundwater water discharges to the unconsolidated aquifers of the Taiyuan Basin in natural conditions (Wang Z. et al., 2020). Since the 1960s, groundwater extraction in the Taiyuan Basin has increased annually to meet the needs of economic development and residents, causing the water table in the basin to drop. This increased the hydraulic gradient in the eastern boundary mountains of the Jinci Spring region, ultimately leading to an increase in karst water discharge into the basin (Figure 5e). According to the Taiyuan Water Conservancy Bureau, the lateral recharge of karst water into the Taiyuan Basin increased from 0.6 m³/s to 0.8 m³/s during 1970s to the beginning 1990s (Liu et al., 2003). The increase in lateral recharge inevitably reduced the water flow towards Jinci Spring catchment.

The last activity was the construction of the Fenhe First Reservoir, which caused a reduction in recharge from the Fen River. Exposed carbonate rocks along Fenhe River created a nearly 44 km-long karst seepage zone(Q. Wang et al., 2024), the construction of the Fenhe First Reservoir (Figure 1) significantly reduced the runoff in the seepage zone (Du, 2010)(Figure 5f). It is estimated that the average seepage rate of the Fen River decreased from 0.74 m³/s in the 1950s to 0.65 m³/s in the 1990s, showing a reduction rate of 12.2%, accounting for 5% of the total decrease in spring water flow (Yin, 2007).

In summary, the long-term groundwater over-exploitation, coal mine dewatering, and the Fenhe reservoir construction were the leading human activities responsible for the drying up of Jinci Springs. These activities intercepted recharges to the spring in different ways, but all resulted in interruption of spring water flow, and eventually caused the flow to stop.

4.2 Wakening of Spring Water Protection Awareness and Lessons from the Cessation

One of the reasons causing groundwater overexploitation was that there existed an old belief that groundwater was inexhaustible. One other reason was the thirsty for economic development. To increase water supply and alleviate water

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

shortage in the Jinci Springs region, several measures were implemented since 1950s. These measures included drilling groundwater wells, constructing groundwater pump stations, building reservoirs and ponds, and recycling industrial wastewater and agricultural drainage. These efforts significantly increased water supplies in the Jinci Springs catchment. To enhance water use efficiency and reduce waste, the Jinci Springs irrigation system was restructured. The original four main channels were consolidated into two main channels (north and south), secondary channels were streamlined, and anti-seepage projects were undertaken to reduce channel leakage and improve irrigation water utilization (Editorial Committee of 'Records of Water' Conservancy in Jin River, 2002). Additionally, small field plots were introduced in agricultural areas, reducing the water used per acre from 80 m³ to 40 m³ through land modification and management (Editorial Committee of 'Records of Water' Conservancy in Jin River, 2002). Through these water conservation measures, from the 1950s onwards, the irrigation area of Jinci Spring steadily increased while water consumption per acre gradually decreased. By the 1970s, the irrigation area reached 297 hectares, with an annual water usage of 24 million m³ and a grain yield of 428 kg per acre.

In the 1980s, the significant reduction in Jinci Springs discharge (reaching as low as of 0.55 m³/s (Editorial Committee of 'Records of Water' Conservancy in Jin River, 2002)) led to the recognition of the limitation of groundwater by the local government. At that time, Taiyuan City established Shanxi Province's first spring water protection unit—the Taiyuan Jinci Water Source Protection Management Group. This group conducted surveys of the springs region, organized experts for protection and management efforts. They cut the irrigation area to 245 hectares to save irrigation groundwater. The water crisis in the irrigation area prompted a shift towards water-saving agricultural practices, with a recycling water system ensuring a stable water supply for agriculture. By the late 20th century, recycled irrigation water accounted for about 50% of the total irrigation water usage (Editorial Committee of 'Records of Water' Conservancy in Jin River, 2002). Meanwhile drilling of new deep wells pumping groundwater from karst aquifer was prohibited, and some existing karst water wells were closed.

In addition, in 1973, Taiyuan city government introduced water fees for restricting industrial use of groundwater, initially set at 0.03 CNY per cubic meter, and gradually raise to 0.1 CNY per cubic meter in 1983. Concurrently, several deep karst wells supplying groundwater for industrial use were forbidden gradually, and valve and water meter were installed on artesian wells in Pingquan Village and other locations to restrict groundwater pumping. To meet the water needs of chemical plants after forbidding deep karst groundwater pumping, shallow wells were drilled in the Fen River floodplain. However, due to the insufficient public awareness on limits of groundwater resources and predominant pursuits of economic gains, the local government's efforts were not enough to prevent the reduction in Jinci Spring's flow. Ultimately Jinci Springs ceased to discharge in April 1994. The flow cessation lasted 30 years.

The cessation of Jinci Springs led people to realize their misunderstanding of groundwater inexhaustibility and the consequence of overemphasizing economic developments while ignoring environmental conservation. The nearly 30-year cessation of Jinci Springs brought painful lessons to the region and prompted new efforts on environmental protection.

Jinci Springs are not only a branch of surface water, it also carries rich cultural and historical significance, which is considered sacred by local residents. The dry-up of the spring's flow also took away the associated natural and cultural landscapes,

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

prompting residents to re-examine their cultural identity, the impacts of the dry-up on social cohesion and stability. To bridge the generational gap caused by the spring's cessation, locals revived the river festival rituals to worship the Water Mother, which had been interrupted for over 50 years. The cessation further led to the decline of agricultural communities, transforming social groups and industries that had relied on spring water. Jinci rice, cultivated for over 3,500 years and renowned for its quality, had been a tribute rice in ancient times (Su, 2020). With the spring's cessation, farmers had to rely on groundwater and Fen River water for irrigation. This caused a significant decline in both quality and quantity of rice production. By 2006, the area and yield of Jinci rice cultivation had drastically decreased, pushing Jinci rice to the brink of extinction (Su, 2018). The cessation also altered people's perceptions and attitudes towards the natural environment, prompting the local society's desire for innovation and adaptation. People began to reassess their relationship with the environment, emphasizing ecological protection and sustainable development. A series of measures, including restructuring industries and improving water resource utilization efficiency, were implemented to revive the spring flow. These efforts united various social sectors in exploring new water resource management models to address the challenges posed by social and environmental changes.

5 Resurgence of Jinci Spring Flow

To make the springs flow again, the main strategies of local governments focused on two aspects: increasing recharge sources and reducing groundwater pumping. By 2008, the groundwater level of Jinci Springs had reached its lowest point at 774.83m amsl, 27.76 m below the spring outlet. After implementing the strategies, the groundwater level began to stabilize and rise (C. Li et al., 2024b) (Fig. 6a). In 2011, the Pingquan Spring, one of the outlets of Jinci Springs located southwest of the downstream area of Jinci Springs catchment, resumed flow. By the end of 2018, a decade of steady recovery, the groundwater levels around the main Jinci Springs outlets recovered to 1.61m below the surface (Zhao W., 2013). In 2023, multiple spring resurgence phenomena were observed in rice fields in the villages of Huata, Suo, and Wangguo surrounding the Jinci Springs outlet (Fig. 6b). Through persistent efforts, the Jinci Springs achieved resurgence on May 2023, after 30 years of dry-up. The main efforts that led to the flow resurgence are summarized below.

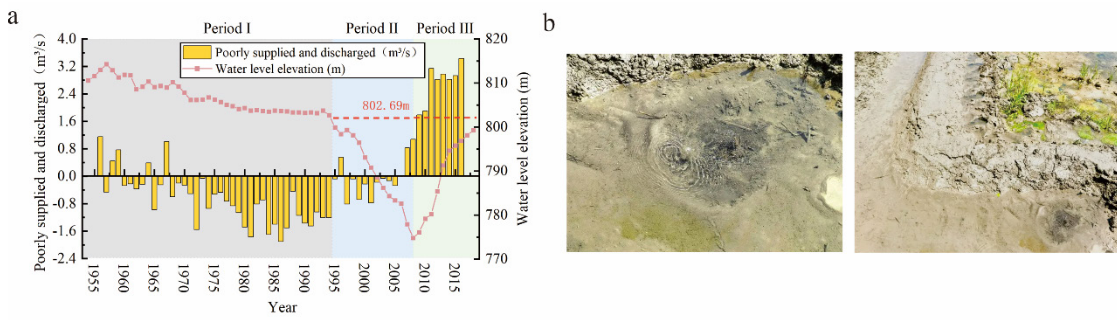
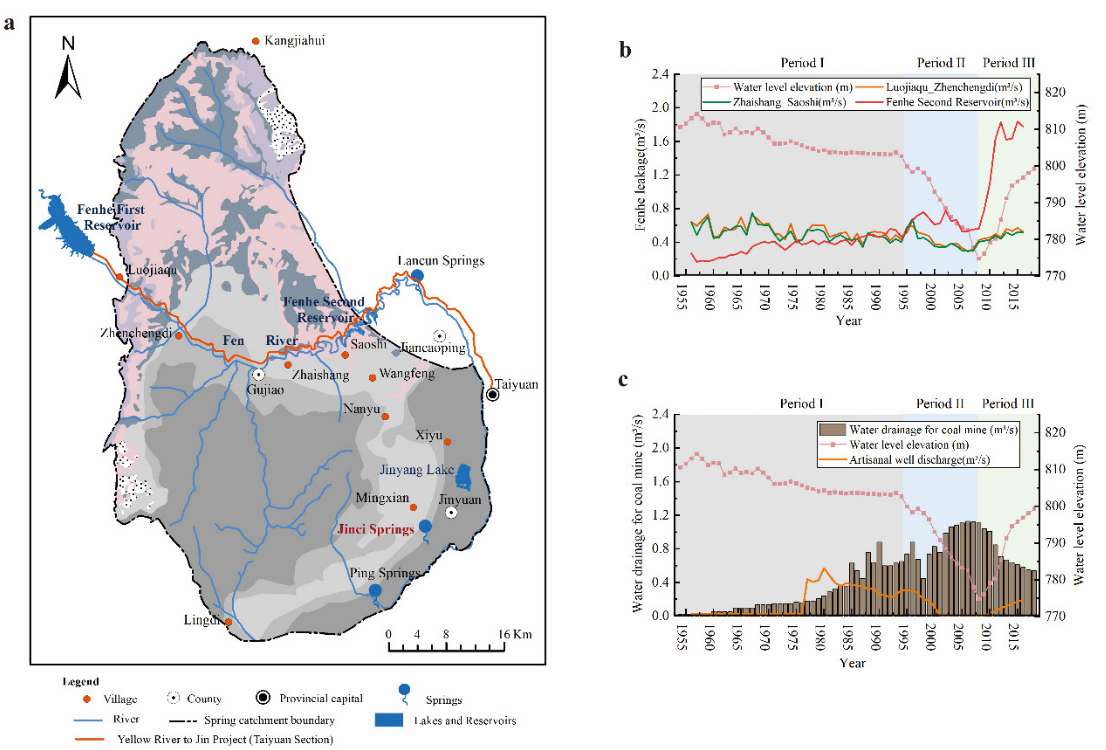


Figure 6. Recharge–discharge imbalance and recent resurgence of springs near Jinci. (a) Difference between recharge and discharge at Jinci Springs; (b) Springs that have resurged around the Jinci Springs area.

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

The first one was to increase water supply to the Taiyuan Basin. The Wanjiazhai Water Diversion Project was completed in 2003 to deliver water from Wanjiazhai Reservoir of the Yellow River in the northwestern Shanxi Province to Fenhe First Reservoir and supply water to Taiyuan City to replace the use of karst groundwater (Fig. 7a). The water convey path of the diversion project involves pipeline (57.4 km) and natural river (81.2 km), totaling approximately 138.6 km. The project delivers Yellow River water to Taiyuan with an annual capacity of 320 million m³ and a daily supply of about 315,000 m³ (as of 2006), accounting for 65% of Taiyuan's water consumption. This initiative has significantly alleviated the problem of groundwater overexploitation (Li Z. et al., 2007; Shanxi Provincial Department of Water Resources, 2009).

The second one was to increase groundwater recharge, a second Fen River Reservoir was constructed in the carbonate rock zone near the Jinci Springs catchment, creating large seepage recharge to Jinci Springs (Guo et al., 2018; Liang et al., 2019)(Figure 7b). The reservoir water infiltrates through carbonate fractures and fissures to reach the Ordovician karst aquifers to recharge Jinci Springs (Wang Y., 2022; Wang Z. et al., 2021). As the water level of the Fenhe Second Reservoir increased from 895 to 902 m by 2018, the seepage recharge to the Jinci Springs catchment reach 2.862 m³/s, raising the karst groundwater level (Guo et al., 2018; Wang Y., 2022). Concurrently, seepage canals were constructed from Luojiaqu to Zhenchengdi and from Gujiao to Fenhe Second Reservoir to deliver water for maintaining the runoff to the Fenhe River in the Jinci Springs catchment with 3-5 m³/s during the dry season (Liang et al., 2021; Wang Z. et al., 2020).



https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

Figure 7. Human interventions and discharge pathways affecting the Jinci Springs region. (a) The Yellow River Water Diversion Project; (b) Seepage volume in the Fen River section within the spring region; (c) Discharge volume of karst groundwater due to coal mining and well extraction.

The third one was to reduce groundwater pumping. A total of 593 groundwater pumping wells were shut across the Taiyuan City between 2003 and 2009, reducing groundwater pumping by 445,800 m^3/day (Fig. 7c). During this period, the average groundwater level in Taiyuan's urban area increased 3.05 m/year (Shanxi Provincial Department of Water Resources, 2009), which also reduced the subsurface water discharge from the Jinci Springs catchment to the Taiyuan City as the steady rise in pore water levels in Taiyuan has begun to reverse recharge the karst water (Liang et al., 2021; Q. Wang et al., 2024).

The fourth one was to reduce coal mining dewatering by reconstructing coal mines. From 2006 to 2009, Taiyuan reconstructured coal mines by shutting down 80% small coal mines (Fig. 7c), from 275 in 2003 to the current 57(C. Jiang et al., 2020). This effort reduced annual coal mining dewatering from 33.33 million m^3/year to 11.77 million m^3/year. The coal mining dewatering efficiency was also dropped from 1.14 m^3/ton to 0.65 m^3/ton, allowing more water remained in the coal-bearing strata (Zhao W., 2013). In 2020, additional closure of the coal mine located at confined aquifers also helped raise the groundwater level at the Jinci Springs outlet by 0.212 m (Wang Z. et al., 2020).

6 Discussion and Conclusion

Jinci Springs represent a quintessential example of balancing karst groundwater utilization and water resource conservation. The cycle of historical long-term stable discharge, and recent decline, dry-up, and resurgence of Jinci Springs offer valuable references and strategies for spring utilization, particularly in addressing global challenges of climate change and water scarcity. These insights provide a long-term perspective on sustainable water resource utilization and protection.

In ancient times, the Jinci Springs region functioned as a water-fed society where state elites, rural officials, and ordinary people participated in water development, protection, conservation and utilization. This enhanced the responsibilities of both national and local forces in maintaining the harmonious development of human-water relations. A hierarchical management system consisting of canal chiefs and water wardens was created during the Ming dynasty and improved in the Qing dynasty. This system alleviated conflicts and promoted fair distribution of water among villages. On the other hand, while the evolving beliefs in water deities was a main reflection of the humans' vulnerability to mother nature, the water deity worships also manifested the cultural power and authorities over local water right management. For example, the emergence of deities like the Water Mother, Liu Chunying, and the worship of various folk heroes assisted management system to maintain the stability of water rights in the Jinci Springs region. Therefore, the coexistence of multiple water deity beliefs and management systems sustained the relative harmony of human-water relations and the development of the spring-region society for millennia.

In modern times, the Jinci Spring region faced more complex challenges as the state of harmony between people and springs has been gradually broken due to population growth and industrialization. From 1960s to 1980s, excessive karst groundwater pumping disrupted the balance between groundwater recharge, runoff, and discharge, causing spring discharge to decline. In

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

response, local governments and water departments constructed modern hydraulic facilities, promoted water-saving technologies, implemented strict water resource management policies, and established specialized spring water protection institutions. These efforts were modern expansions of ancient water management system. Despite experts warned the threat of spring cessation in the 1980s and suggested implementation of protection actions, the measures of spring water management were weakness and insufficient, because most people are mistaken that groundwater is inexhaustible. Most decisions were made for economy development while ignoring spring water conservation. Those decisions led to the dry-up of Jinci Springs, negatively impacting the social, economic, and ecological sustainable development of the region.

The dual pressures of economic and environmental prompted the local government and populace to implement various measures to revive the Jinci Springs in an attempt to re-establish a sustainable human-water relation. The strategies included regulating water from the Fen River reservoir, increasing groundwater recharge and raising the groundwater level by constructing the Fen River Second Reservoir. Additionally, prohibiting the pumping of karst groundwater in the Jinci Springs catchment, implementing the Yellow River Diversion Project to use surface water in place of groundwater consumption, and restricting coal mining to reduce karst water discharge were also part of the plan. These efforts successfully achieved the resurgence of the Jinci Springs and reshaped the state of harmonious development between human and nature. Naturally karst aquifers develop a lot of caves, conduits, and fractures, forming efficient pathways for precipitation infiltration and providing large capacity for storing groundwater. When groundwater levels exceed the elevation of groundwater outlets, springs discharge to the surface. Groundwater storage and spring discharge are influenced by precipitation and groundwater pumping—the former being a natural process and the latter an artificial intervention. Overexploitation of groundwater always makes groundwater level to decline, causing spring discharge to decline and even dry up. Sustainable karst groundwater utilization should be based on groundwater storage and spring discharge.

The development and utilization of Jinci Springs exemplify the historical evolution of the human-water relationship. Water acts as the central thread, consistently emphasized and highlighted as humans have adapted to the water cycle throughout history. In prehistoric times, humans lived close to water sources and depended on them. With the advent of the Bronze and Iron Ages, people began to modify rivers and build dams, establishing a close relationship with Jinci Springs. During the feudal era, the modification of the Zhibo Canal demonstrated the springs could serve human needs. This marked a shift in the human-water relationship towards the active utilization of water resources for social and economic benefits, leading to the routine use of Jinci Springs. As the population increased, the interaction between humans and water intensified. A water resource management system gradually formed for resolving escalating water conflicts, supplemented by water deity beliefs to keep water right stability. During the Ming and Qing dynasties, water resources were tight but still sufficient for irrigation and domestic use. People were devoted to constructing and maintaining water channels to meet their needs. The human-water relationship has developed harmoniously for thousands of years within the carrying capacity of the environment. After the founding of the People's Republic of China, advancements in groundwater pumping technology accelerated groundwater overexploitation and environmental degradation. This made it difficult to curb the decreasing trend of spring flow and maintain the balance between recharge and discharge. Confronted with threats to their water supply, the residents of the spring region gradually implemented measures to protect the water environment. The history of Jinci Springs, characterized by excessive extraction, deterioration of the human-water relationship, and eventual resurgence, illustrates the awakening of environmental and water resource protection awareness amidst a water crisis. This process, spanning 60 years, represents the ongoing conflict between economic demands and water resource protection. Overall, the Jinci Springs region evolved from initial harmony to rupture and then gradual resurgence, with water remaining a consistent central theme. This historical development provides valuable lessons for modern sustainable water resource utilization.

Author contribution: QR: Data curation, formal analysis, conceptualization and writing (original draft). YH: funding acquisition, supervision and writing (review and editing). XZ: research conceptualization and supervision. YL: formal analysis and draft. YZ: field investigation and validation. YS: review and editing. TB: visualization and draft. All authors have participated in and reviewed the final manuscript to ensure the quality and credibility of the research.

Competing interests: The contact author has declared that none of the authorshas any competing interests.

References

Adusumilli, N., Dikitanan, R., & Wang, H. Effect of Cost-Sharing Federal Programs on Adoption of Water Conservation Practices: Results from Propensity Score Matching Approach. Water Econ. Policy, 06(01), 1950004. https://doi.org/10.1142/S2382624X19500048, 2020.

Ahmed, A. T., El Gohary, F., Tzanakakis, V. A., & Angelakis, A. N. Egyptian and Greek Water Cultures and Hydro-Technologies in Ancient Times. Sustainability, 12(22), Article 22. https://doi.org/10.3390/su12229760, 2020.

Alba, R., Betancur Alarcon, L., Pereira Prado, M., Jaramillo Villa, U., & Ortiz – Guerrero, C. E. Hydrosocial Territories Research: An Overview. Wiley Interdiscip. Rev.-Water, 12(3), e70023. https://doi.org/10.1002/wat2.70023, 2025.

Angelakis, A. N., Valipour, M., Ahmed, A. T., Tzanakakis, V., Paranychianakis, N. V., Krasilnikoff, J., Drusiani, R., Mays, L., El Gohary, F., Koutsoyiannis, D., Khan, S., & Giacco, L. J. D. Water Conflicts: From Ancient to Modern Times and in the Future. Sustainability, 13(8), Article 8. https://doi.org/10.3390/su13084237, 2021.

Barnes, J. States of maintenance: Power, politics, and Egypt's irrigation infrastructure. Environ. Plan. D-Soc. Space, 35(1), 146–164. https://doi.org/10.1177/0263775816655161, 2017.

Bozorg-Haddad, O. Economical, Political, and Social Issues in Water Resources, Elsevier, ISBN 978-0-323-90567-1, 2021.

Çallı, K. Ö., Chiogna, G., Bittner, D., Sivelle, V., Labat, D., Richieri, B., Çallı, S. S., & Hartmann, A. Karst Water Resources in a Changing World: Review of Solute Transport Modeling Approaches. Rev. Geophys., 63(1), e2023RG000811. https://doi.org/10.1029/2023RG000811, 2025.

de Sena, Í. S., Ruchkys, Ú. de A., & Travassos, L. E. P. Geotourism Potential in Karst Geosystems: An example from the Lund Warming Ramsar Site, Minas Gerais, Brazil. Catena, 208, 105717. https://doi.org/10.1016/j.catena.2021.105717, 2022.

Du B. Study on Fenhe River and Groundwater Interaction in Xishan Karst Region of Taiyuan City. Journal of Taiyuan University of Technology, 41(3), 272–277. https://doi.org/10.16355/j.cnki.issn1007-9432tyut.2010.03.008, 2010. (in Chinese)

Duan, Y., Gao, X., Li, C., Wang, H., Kang, C., Wang, W., Zhang, X., Sun, Z., Xiong, Y., & Wang, Y. Combining hydrodynamics, geochemical and multiple isotopic tracers to understand the hydrogeological functioning of karst groundwater system in Jinci, northern China. J. Hydrol., 648, 132375. https://doi.org/10.1016/j.jhydrol.2024.132375, 2025.

Editorial Committee of 'Records of Water' Conservancy in Jin River. Records of Water Conservancy in Jinci. Shanxi people's publishing house, ISBN 7-80598-487-5, 2002. (in Chinese)

Glowacki, M., & Malpass, M. Water, Huacas, and Ancestor Worship: Traces of a Sacred Wari Landscape. Lat. Am. Antiq., 14(4), 431–448. https://doi.org/10.2307/3557577, 2003.

Goldscheider, N., Chen, Z., Auler, A. S., Bakalowicz, M., Broda, S., Drew, D., Hartmann, J., Jiang, G., Moosdorf, N., Stevanovic, Z., & Veni, G. Global distribution of carbonate rocks and karst water resources. Hydrogeol. J., 28(5), 1661–1677. https://doi.org/10.1007/s10040-020-02139-5, 2020.

Guo F., Liang, Yongping, Wang Z., Shen, Haoyong, & Zhao, Chunhong. Attribution of spring fields and seepage calculation of Fenhe second reservoir in Xishan Taiyuan, Shanxi Province. Carsologica Sinica, 37(4), 493–500, 2018.

Hao, Y., Zhu, Y., Zhao, Y., Wang, W., Du, X., & Yeh, T. J. The Role of Climate and Human Influences in the Dry-Up of the Jinci Springs, China 1. J. Am. Water Resour. Assoc., 45(5), 1228–1237. https://doi.org/10.1111/j.1752-1688.2009.00356.x, 2009.

Harrower, M. J. Is the hydraulic hypothesis dead yet? Irrigation and social change in ancient Yemen. World Archaeol., 41(1), 58–72. https://doi.org/10.1080/00438240802668354, 2009.

Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., & Weiler, M. Karst water resources in a changing world: Review of hydrological modeling approaches. Rev. Geophys., 52(3), 218–242. https://doi.org/10.1002/2013RG000443, 2014.

Hu, C., Qi, Y., & Wang, C. An Analysis of the Spatial Characteristics of Jin Ancestral Temple Based on Space Syntax. Buildings, 15(1), Article 1. https://doi.org/10.3390/buildings15010085, 2025.

Vernon L. S. The Flow of Power: Ancient Water Systems and Landscapes. Lat. Am. Antiq., 15(1), 117–119. https://doi.org/10.2307/4141571, 2003.

Jana, S. K., & Tamang, P. Prospects of rehabilitation of ancient irrigation systems in India – A case study from coastal saline zone of West Bengal. Agric. Syst., 207, 103638. https://doi.org/10.1016/j.agsy.2023.103638, 2023.

Jiang, C., Gao, X., Hou, B., Zhang, S., Zhang, J., Li, C., & Wang, W. Occurrence and environmental impact of coal mine goaf water in karst areas in China. J. Clean Prod., 275, 123813. https://doi.org/10.1016/j.jclepro.2020.123813, 2020.

Jiang, G., Guo, F., Liu, F., Li, Z., & Milanović, S. Hydrogeological responses of karst compartments to meteorological drought in subtropical monsoon regions. J. Hydrol., 655, 132940. https://doi.org/10.1016/j.jhydrol.2025.132940, 2025.

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

Keqiang, H., Yuanyuan, G., Lu, G., Rengang, W., Dong, G., & Yongping, L. A systematic analysis of water flow reduction and water-quality deterioration of the Niangziguan Spring area in northern China. Environ. Earth Sci., 80(9), 347. https://doi.org/10.1007/s12665-021-09628-0, 2021.

Li, C., Cao, Y., Zhang, C., Qin, L., Deng, Z., Chen, Y., Zhu, S., Li, W., Yuan, J., Zhang, H., & Zhuang, Y. Earliest ceramic drainage system and the formation of hydro-sociality in monsoonal East Asia. Nat. Water, 1(8), 694–704. https://doi.org/10.1038/s44221-023-00114-4, 2023.

Li, C., Gao, X., Wang, W., Zhang, X., Zhang, X., Jiang, C., & Wang, Y. Hydro-biogeochemical processes of surface water leakage into groundwater in large scale karst water system: A case study at Jinci, northern China. J. Hydrol., 596, 125691. https://doi.org/10.1016/j.jhydrol.2020.125691, 2021.

Li, C., Gao, X., Xiang, X., Jiang, C., Duan, Y., Wang, W., Zhang, X., Tan, T., Wang, Q., & Wang, Y. Intense Human Activities Induce the Dynamic Changes of Interaction Pattern Between Karst Water-Quaternary Groundwater in the Basin-Mountain Coupling Belt Over the Past 60 Years. Water Resour. Res., 60(2), e2023WR035211. https://doi.org/10.1029/2023WR035211, 2024a.

Li, C., Gao, X., Xiang, X., Jiang, C., Duan, Y., Wang, W., Zhang, X., Tan, T., Wang, Q., & Wang, Y. Intense Human Activities Induce the Dynamic Changes of Interaction Pattern Between Karst Water-Quaternary Groundwater in the Basin-Mountain Coupling Belt Over the Past 60 Years. Water Resour. Res., 60(2), e2023WR035211. https://doi.org/10.1029/2023WR035211, 2024b.

Li, Q., Guo, H., Luo, L., Wang, X., & Yang, S. Impact Analysis of Land Use and Land Cover Change on Karez in Turpan Basin of China. Remote Sens., 15(8), Article 8. https://doi.org/10.3390/rs15082146, 2023.

Li, Y., Wang, Z., Gan, Q., Niu, X., & Xu, W. Paleoenvironmental conditions and organic matter accumulation in Upper Paleozoic organic-rich rocks in the east margin of the Ordos Basin, China. Fuel, 252, 172–187. https://doi.org/10.1016/j.fuel.2019.04.095, 2019.

Li Z., Liu Y., Yan X., Ren G., & Wang Y.. Summarization and application of high-tech in to Wanjiazhai Projects. Engineering Mechanics, S2, 21–32, 2007. (in Chinese)

Liang Y., Shen H., Zhao C., Wang Z., Tang C., Zhao Y., Xie H., & Shi W. Thinking and practice on the research direction of karst water in northern China. Carsologica Sinica, 40(3), 363–380, 2021. (in Chinese)

Liang, Y., Wang, Z., & Zhao, C. Study on the Karst Water System and Ecological Restoration of the Jinci Spring Region in Shanxi. China Science Publishing & Media Lid.(CSPM), ISBN 978-7-03-076907-7, 2024. (in Chinese)

Liang Y., Zhang F., Shen H., Tang C., Zhao C., Wang Z., Hou H., Ren J., & Guo F. Recognition of the critical hydrogeological conditions of the Jinci Spring and Lancun Spring in Shanxi. Hydrogeology and Engineering Geology, 46(1), 11-18+34. https://doi.org/10.16030/j.cnki.issn.1000-3665.2019.01.02, 2019. (in Chinese)

Liu J., Hao Y., & Wang Y. The Countermeasures of Sustainable Utilization of Groundwater Resources and Protection of Geological Environment in Taiyuan City. Journal of Shanxi University(Natural Science Edition), 4, 359–362, https://doi.org/10.13451/j.cnki.shanxi.univ(nat.sci.), 2003.

Lu, S., Chen, J., Zheng, X., Liang, Y., Jia, Z., & Li, X. Hydrogeochemical characteristics of karst groundwater in Jinci spring area, north China. Carbonates Evaporites, 35(3), 68. https://doi.org/10.1007/s13146-020-00602-8, 2020.

Luo, M., Chen, J., Jakada, H., Li, N., Guo, X., & Zhou, H. Identifying and predicting karst water inrush in a deep tunnel, South China. Eng. Geol., 305, 106716. https://doi.org/10.1016/j.enggeo.2022.106716, 2022.

Ma, R., Wang, Y., Sun, Z., Zheng, C., Ma, T., & Prommer, H. Geochemical evolution of groundwater in carbonate aquifers in Taiyuan, northern China. Appl. Geochem., 26(5), 884–897. https://doi.org/10.1016/j.apgeochem.2011.02.008, 2011.

Ma T., Wang Y., Ma R., Yan C., Shan H., & Chen L. Evolution of middle-low temperature carbonate geothermal system in Taiyuan, Northern China. Earth Science, 37(2), 229–237, doi:10.3799/dqkx.2012.023, 2012. (in Chinese)

Miller, T. G. Water Sprites and Ancestor Spirits: Reading the Architecture of Jinci. The Art Bulletin, 86(1), 6–30. https://doi.org/10.1080/00043079.2004.10786179, 2004.

Mithen, S. Thirst: For Water and Power in the Ancient World. Harvard University Press, ISBN 978-0-674-06693-9, 2012.

Nico Goldscheider, Chen, Z., Auler, A. S., Bakalowicz, M., Broda, S., Drew, D., Hartmann, J., Jiang, G., Moosdorf, N., Stevanovic, Z., & Veni, G. Global distribution of carbonate rocks and karst water resources. Hydrogeol. J., 28(5), 1661–1677. https://doi.org/10.1007/s10040-020-02139-5, 2020.

Oestigaard, T. Holy water: The works of water in defining and understanding holiness. Wiley Interdiscip. Rev.-Water, 4(3), e1205. https://doi.org/10.1002/wat2.1205, 2017.

Qiao X., Li G., Zhou J., Du J., Du C., Sun Z., & Wu R. Analysis of influence of coal exploitation on water resources and environment:A case study of coal exploitation in Xishan of Taiyuan City. Water Resources Protection, 26(1), 49–52, 2010. (in Chinese)

Salek, A. Rediscovering Community Participation in Persian Qanats: An Actor-Network Framework. European Journal of Creative Practices in Cities and Landscapes, 2(1), Article 1. https://doi.org/10.6092/issn.2612-0496/8674, 2019.

Sánchez López, E. H. Water and production reflections on the water supply to urban workshops in roman times. Water History, 15(1), 29–44. https://doi.org/10.1007/s12685-023-00323-4, 2023.

Schaik, H. P. J. van, & Willems, W. J. H. Water & heritage: Material, conceptual and spiritual connections. Sidestone Press, ISBN-13 978-9088902789, 2015.

Shanxi Provincial Department of Water Resources. Emergency Water Source Planning for Extreme Drought Years in Shanxi Province. ISBN 978-7-5084-6928-7, China Water&Power Press, 2009. (in Chinese)

Shen, H., & Yuan, B. Geophysical Characters for Archaeology in the Ancient City of JinYang, China. in: 2009 International Conference on Information Management, Innovation Management and Industrial Engineering, 2, 292–297. https://doi.org/10.1109/ICIII.2009.228, 2009.

Shi P., Song C., & Cheng C. Geographical synergetics: From understanding human-environment relationship to designing human-environment synergy. Acta Geographica Sinica, 74(1), 3–15, 2019.(in Chinese)

Shoemaker, D. Rivers of Power: How a Natural Force Raised Kingdoms, Destroyed Civilizations, and Shapes Our World: Laurence C. Smith. New York, NY: Little, Brown Spark, 356 pp., https://doi.org/10.1080/2325548X.2022.2036543, 2020.

Singh, P. K., Dey, P., Jain, S. K., & Mujumdar, P. P. Hydrology and water resources management in ancient India. Hydrol. Earth Syst. Sci., 24(10), 4691–4707. https://doi.org/10.5194/hess-24-4691-2020, 2020.

Storozum, M., Liu, H., Qin, Z., Ming, K., Fu, K., Wang, H., & Kidder, T. (2018). Early evidence of irrigation technology in the North China Plain: Geoarchaeological investigations at the Anshang Site, Neihuang County, Henan Province, China. Geoarchaeology, 33(2), 143–161. https://doi.org/10.1002/gea.21634

Su, Z. Jinci Rice: A Study on Agricultural Technology and Rural Social Change. The Commercial Press, ISBN 978-7-100-16083-4, 2018. (in Chinese)

Su Z. Research on the Agrarian Cultural Heritage Characteristics of Rice Cultivation in Jinci. Social Sciences Journal of Universities in Shanxi, 32(12), 62–65. https://doi.org/10.16396/j.cnki.sxgxskxb.2020.12.013, 2020. (in Chinese)

Sun, Z., Ma, R., Wang, Y., Ma, T., & Liu, Y. Using isotopic, hydrogeochemical-tracer and temperature data to characterize recharge and flow paths in a complex karst groundwater flow system in northern China. Hydrogeol. J., 24(6), 1393–1412. https://doi.org/10.1007/s10040-016-1390-2, 2016.

Vilhar, U., Kermavnar, J., Kozamernik, E., Petrič, M., & Ravbar, N. The effects of large-scale forest disturbances on hydrology – An overview with special emphasis on karst aquifer systems. Earth-Sci. Rev., 235, 104243. https://doi.org/10.1016/j.earscirev.2022.104243, 2022.

Wang, Q., Gao, X., Jiang, C., Li, C., Zhang, X., Wang, W., Duan, Y., Luo, W., Mao, Z., & Wang, Y. Multiple contamination sources, pathways and conceptual model of complex buried karst water system:constrained by hydrogeochemistry and δ2H, Zδ18O, δ34S, δ13C and 87Sr/86Sr isotopes. J. Hydrol., 131614. https://doi.org/10.1016/j.jhydrol.2024.131614, 2024.

Wang Y. Study on ecological restoration strategy of karst spring region in north China:Taking Jinci spring as an example. Carsologica Sinica, 41(3), 331–344, 2022. (in Chinese)

Wang Z., Liang Y., Tang C., Shen H., Shen C., Guo F., Xie H., & Zhao Y. Ecological restoration pattern and quantitative evaluation of recirculation measures for northern discontinuous karst spring: A case study of Jinci Spring in Taiyuan City, Shanxi Province. GEOLOGY IN CHINA, 47(6), 1726–1738, 2020. (in Chinese)

Wang Z., Liang, Yongping, Shen, Haoyong, Zhao, Chunhong, Xie H., & Zhao. Dynamic Characteristics of Karst Groundwater in Jinci Spring Under Superimposed Influence of Natural and Human Activities. Journal of Jilin University(Earth Science Edition), 51(6), 1823–1837. https://doi.org/10.13278/j.cnki.jjuese.20200204, 2021. (in Chinese)

Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., Porkka, M., Staal, A., Jaramillo, F., Dahlmann, H., Singh, C., Greve, P., Gerten, D., Keys, P. W., Gleeson, T., Cornell, S. E., Steffen, W., Bai, X., & Rockström, J. A planetary boundary for green water. Nat. Rev. Earth Environ., 3(6), 380–392. https://doi.org/10.1038/s43017-022-00287-8, 2022.

Xiao, R. Analysis of the Layout Axis of Jinci in Taiyuan, Shanxi Province. Advanced Materials Research, 1065–1069, 2601–2604. https://doi.org/10.4028/www.scientific.net/AMR.1065-1069.2601, 2015.

Xing L. The Case Study on the System of lrrigation and Sacrificial Rites in the 36 Villages of jinshu Drainage Area. Historical Review, 4, 1-10+123, 2005. (in Chinese)

Yang, D., Yang, Y., & Xia, J. Hydrological cycle and water resources in a changing world: A review. Geogr. Sustain., 2(2), 115–122. https://doi.org/10.1016/j.geosus.2021.05.003, 2021.

Yates, J. S., Harris, L. M., & Wilson, N. J. Multiple ontologies of water: Politics, conflict and implications for governance. Environ. Plan. D-Soc. Space, 35(5), 797–815. https://doi.org/10.1177/0263775817700395, 2017.

Yin D, Research on Reflowing Condition of Jinci Spring In Shanxi Province, Master's thesis, Jilin University, 2007. (in Chinese)

Zhang, X., Yang, S., Lu, P., Li, Y., Chen, P., & Xia, Z. Holocene landscape evolution and its interaction with human activities in the southern piedmont of Taihang Mountain, Central China. Front. Plant Sci., 13, 980840. https://doi.org/10.3389/fpls.2022.980840, 2020.

Zhang, Z., Xu, Y., Wang, Z., Zhang, Y., Zhu, X., Guo, L., Zheng, Q., & Tang, L. Ecological restoration and protection of Jinci Spring in Shanxi, China. Arab. J. Geosci., 13(15), 744. https://doi.org/10.1007/s12517-020-05729-5, 2020.

Zhang, Z., Xu, Y., Zhang, Y., Guo, L., Wang, Z., & Zheng, Q. Impact of groundwater overexploitation on karst aquifer and delineation of the critical zones: Case study of Jinci spring in Shanxi, China. Carbonates Evaporites, 37(4), 68. https://doi.org/10.1007/s13146-022-00812-2, 2022.

Zhao J. Analysis of the Impact of Human Activities on the Spring Flow of Jinci Springs, Master's thesis, Tianjin Normal University, 2013.

Zhao S. Multiple Signs and Multilayered Structures: A Case Study of the Jinci Temple in Taiyuan and lts Surrounding Areas. Journal of Capital Normal University(Social Sciences Edition), 1, 1–23, 2019. (in Chinese)

Zhao W. The Relationship between Pingquan Spring and Jinci Spring and the Possibility Analysis on jinci Spring's Reflow. Shanxi Hydrotechnics, 4, 83-84+89, 2013. (in Chinese)

Zheng, J., & Wang, J. P. Brief Analysis of Settlement Patterns in Taiyuan County in Ming Dynasty. Applied Mechanics and Materials, 477–478, 1152–1155. https://doi.org/10.4028/www.scientific.net/AMM.477-478.1152, 2014.

Zheng, X., Kazemi, E., Gabreil, E., Liu, X., & Chen, R. Sustainability of the Dujiangyan Irrigation System for over 2000 Years–A Numerical Investigation of the Water and Sediment Dynamic Diversions. Sustainability, 12(6), Article 6. https://doi.org/10.3390/su12062431, 2020.

Zhou, Q., Yuan, E., Feng, S., & Gong, L. Impact of socioeconomic factors on vegetation restoration in humid karst areas of China: Evidence from a survey of 45 villages. J. Rural Stud., 114, 103546. https://doi.org/10.1016/j.jrurstud.2024.103546, 2025.

https://doi.org/10.5194/egusphere-2025-5309
Preprint. Discussion started: 5 January 2026

Zhou X., Shen Y., & Xiao F. The Spring Gone with the World——Study on Water Deities Belief Cultural Landscape in Jin-river Basin. Chinese Landscape Architecture, 28(5), 25–28, 2012. (in Chinese)

Zhuang, Y. State and irrigation: Archeological and textual evidence of water management in late Bronze Age China. Wiley Interdiscip. Rev.-Water, 4(4), e1217. https://doi.org/10.1002/wat2.1217, 2017.

Zhuang, Y., Altaweel, M., Water Societies and Technologies from the Past and Present. UCL Press, Gower Street, London, 332pp., https://doi.org/10.2307/j.ctv550c6p., 2018.