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Breaking the persisting supply–demand cycle: a critical review of water development and conflict in the Zayandeh-Rud basin

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ABSTRACT

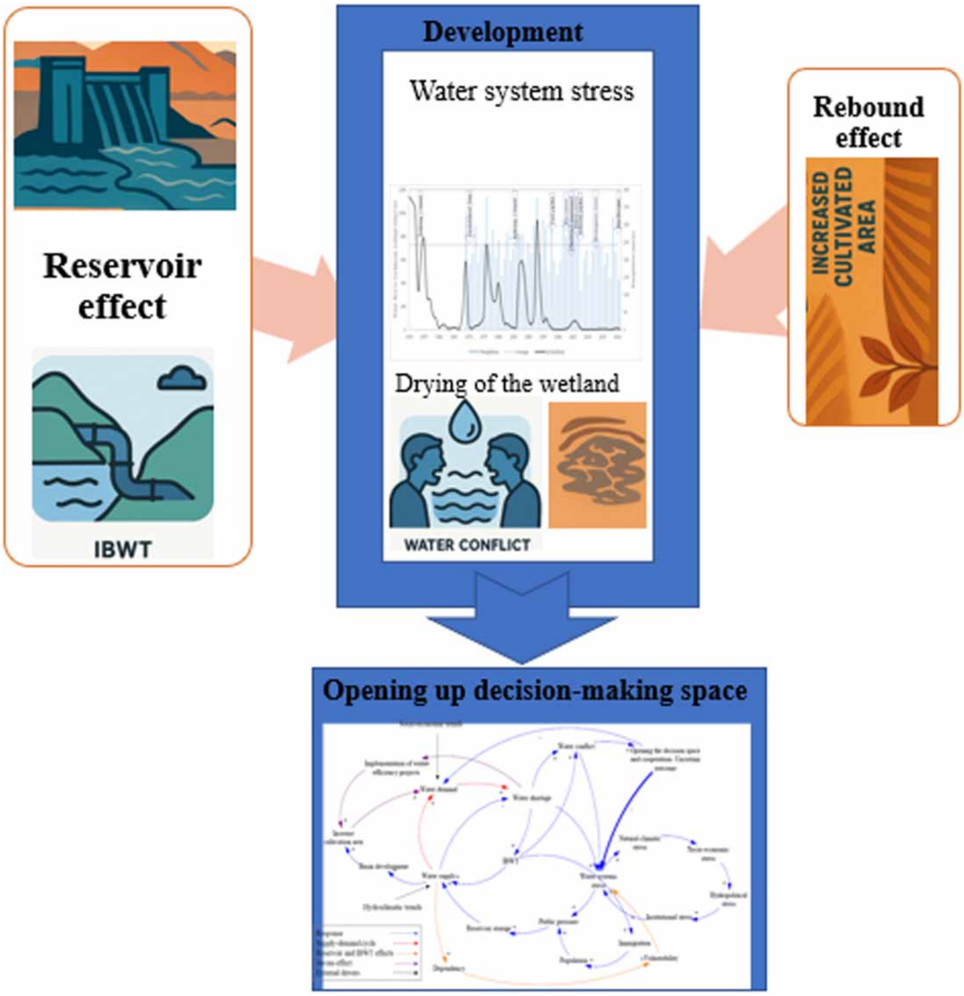
Endorheic basins are more sensitive to changes in the water balance than other basins. Therefore, human activities can create critical conditions. This study examines the complex interactions between water management practices and their various effects in the iconic Zayandeh-Rud basin, focusing on the unintended consequences of water infrastructure development, such as reservoirs and inter-basin transfers. The research highlights phenomena known as the 'reservoir effect' and 'rebound effect' where the construction of reservoirs or inter-basin water transfers that were intended to alleviate water shortages led to increased water demand, exacerbating the problem they were meant to solve. It shows how these phenomena have led to an increase in cultivated areas and the development of irrigation systems. The study explores broader impacts on agriculture, groundwater depletion, ecological degradation, and the economic, social, political, institutional, and organizational consequences, emphasizing the need for a more integrated and sustainable approach to water resource management. It can be argued that social conflicts have led to a greater focus on the conditions of the Gavkhoni wetland as a sensitive indicator of sustainable water and land use in the basin.

Key words: Endorheic basin, Inter-basin water transfers, Rebound effect, Reservoir effect, Zayandeh-Rud

HIGHLIGHTS

- Examining water management history in the framework reservoir and rebound effects.
- Vulnerabilities arising from the supply–demand cycle are evident in four water subsystems.
- Critical points and water conflicts can open windows of opportunity to change the approach.
- Zayandeh-Rud basin in the vicious supply–demand cycle.
- Water conflicts can have two responses: short-term (supply) or long-term (demand management) options.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Endorheic basins, also known as closed basins (Worku *et al.* 2014), are hydrological features where water is retained within the basin, leading to the formation of end or terminal lakes which are often saline. These basins are often significant for their ecological status. Endorheic basins are highly sensitive to changes in the water balance. Even minor changes can lead to significant fluctuations in water levels and salinity of the terminal lake, making them sensitive indicators of environmental stability and climate change (Wurtsbaugh *et al.* 2017). Human activities, such as water abstractions and land use changes, tend to have significant impacts in these basins (Hassani *et al.* 2020). In many endorheic basins these lakes are shrinking due to excessive use of water for agriculture, industry and urban needs (Wurtsbaugh *et al.* 2017). Lake Urmia, the Aral Sea, Great Salt Lake, Dead Sea, Walker Lake, Lake Poopó, and Owens Lake are some examples of end lakes shrinking as a result of anthropogenic interventions (Hassani *et al.* 2020). Graphic human interventions in this natural ecosystem are the construction of reservoirs and/or of water transfers in order to anticipate or respond to demand changes.

Reservoirs have historically been crucial in addressing water scarcity, supporting agriculture, urban growth, and industry. But reservoirs cause impacts. The 'reservoir effect' (Di Baldassarre *et al.* 2018) highlights a paradox where reservoirs, intended to boost water supply, can lead to unintended consequences: the resulting increased water availability can encourage higher water consumption, making regions more vulnerable during droughts. The reservoir effect is a manifestation of the supply–demand cycle, where the increased availability of water drives up demand, eventually neutralizing or even reversing the benefits of the additional supply. This phenomenon mirrors the 'safe development paradox'. Thus, while reservoirs aim to stabilize the water supply, they can sometimes exacerbate water shortages due to heightened demand (Di Baldassarre *et al.* 2018). In this situation, often efficiency-enhancing approaches are adopted, especially in the agriculture sector, as the largest water user. However, many examples have shown that improving irrigation efficiency may actually increase water use (Grafton *et al.* 2018), reflecting 'Jevons paradox' during technological advancements aimed at saving resources (Jevons 1866; Loch & Adamson 2015). These effects are often visible in endorheic basins.

Complementary and confirmatory research on the reservoir effect uses the concept of the legacy of water infrastructure. In this way, water infrastructure is not a purely physical phenomenon, but is perpetuated in a complex context of social, institutional, and political relations. The article by Di Baldassarre *et al.* (2021), entitled 'The Legacy of Large Dams in the United States,' examines the historical and institutional role of dams in shaping the relationship between society and water. They also use the concept of 'lock-in condition'; a situation in which communities, policymakers, and governing institutions become trapped in the logic of increasing supply, and it becomes difficult to reform consumption structures. In a study of the Mahaweli Development Project in Sri Lanka – one of the largest water transfer and storage projects in South Asia, begun in the 1960s and completed in the 1990s – Quealy & Paranage (2024) showed that water infrastructures continue to live on through institutions and governance policies even after construction, reproducing power relations and resource allocation. They conceptualize the long-term legacy of water development projects in the form of 'afterlives.'

The Zayandeh-Rud basin, a relatively small endorheic basin in Iran, faces a problem similar to the reservoir effect. Gohari *et al.* (2013) analyzed the water supply–demand cycle in the Zayandeh-Rud basin in detail. Conventional supply-oriented management approaches, such as inter-basin water transfer projects, were employed to address water shortages, more than doubling the natural flow of the river. A system dynamics model was developed to capture the interactions between various subsystems of the river basin, including hydrologic, socio-economic, and agricultural components. The findings indicated that merely increasing water supply without considering the interconnected dynamics led to higher water demand, demonstrating the 'fixes that backfire' archetype (Wolstenholme 2003; Gohari *et al.* 2013). In this regard, Madani & Mariño (2009) showed by modeling system dynamics that each wave of infrastructure development in Zayandeh-Rud has led to the expansion of consumption and increased institutional dependence on greater supply; a situation that Nazemi *et al.* (2020) have also considered as reproducing demand pressure in the form of future governance scenarios.

Other relevant research on the Zayandeh-Rud basin has been conducted in various areas, including the impacts of drought and climate change (Molle *et al.* 2008; Abou Zaki *et al.* 2020; Babadi *et al.* 2022), water resources problems (Nabavi 2017; Enteshari & Safavi 2021), the drying up of the Gavkhoni wetland at the end of the basin (Shiran *et al.* 2021), water governance (Reyhani & Grundmann 2021; Yousefi *et al.* 2024), the processes of water reallocation and conflicts (Talebi Eskandari 2021a; Mamasani 2024), and socio-economic issues including the importance of employment (Enteshari *et al.* 2020).

This research considers natural, socio-economic, hydropolitical, and institutional aspects together. This study adopts a holistic approach, examining the historical timeline and evolution of basin development to explore the rebound and reservoir effects – how these evolved and what other developments have played a role. It investigates how significant events, political decisions, and development programs have contributed to the formation of the same vicious supply cycle after each water shortage. This study reveals how this phenomenon has gradually fueled conflicts, which in some cases have led to the halt of inter-basin water transfers (IBWTs) and occasionally had positive outcomes. Although distinguishing the crisis caused by this cycle is a complex issue, as water shortages and droughts lead to environmental, socio-economic, and ultimately political-security crises through conflicts, this article aims to understand the status of the Zayandeh-Rud basin within the framework of the reservoir and rebound effect through a developed timeline of basin development. We follow Mianabadi (2016) in distinguishing four subsystems of the water system, namely the natural-climatic, socio-economic, hydropolitical, and institutional subsystems. This research examines the vulnerability in these four subsystems.

2. THEORETICAL BACKGROUND

IBWT and the reservoir effect

The 'reservoir effect' describes situations where an excessive dependence on water infrastructure, such as dams and reservoirs, leads to increased vulnerability. IBWTs involve moving water from areas of abundance to areas of scarcity, often requiring significant infrastructure like reservoirs and tunnels. While they can address immediate water needs for agriculture, industry, and urban areas, they also introduce several longer-term risks (Di Baldassarre *et al.* 2018).

The IBWT projects as a specific form of the reservoir effect in Athens, Las Vegas, and Melbourne have been reviewed by Di Baldassarre *et al.* (2018). Athens, Greece, faced severe water shortages historically. Infrastructure developments like the Marathon and Evinos Dams increased water supply but also led to higher consumption and dependence, and increased vulnerability from the 1990s. Las Vegas, USA, initially relied on groundwater, but population growth led to dependence on Lake Mead. The Southern Nevada Water System increased water availability. This led to unforeseen population increases and greater dependency on Lake Mead, demonstrating the reservoir effect during drought conditions. Melbourne, Australia, expanded its storage capacity with the Thomson Reservoir to combat droughts. This initially prevented shortages but led to higher consumption and dependency. During the Millennium Drought (2001–2009), increased demand exacerbated the drought's impact, highlighting the increased vulnerability due to reliance on reservoirs (Di Baldassarre *et al.* 2018). Godinez Madrigal *et al.* (2022) studied the supply–demand approach (Zapotillo project) in the Lerma-Chapala basin, Mexico, for the water supply of two cities and the challenges caused by the reservoir effect. Other cases have been reported widely in the literature (e.g. Urmia and Bakhtegan, Iran (Oftadeh *et al.* 2016; Abou Zaki *et al.* 2020); the Colorado and Tucson basins, USA (Larson & Kennedy 2015; Schneier-Madanes *et al.* 2017); the Lancang-Mekong Basin, Cambodia (Yuan *et al.* 2017).

The rebound effect

The rebound effect, originally introduced by Jevons in 1866 and now better known as 'Jevons' Paradox,' describes how improvements in efficiency (e.g., in steam engines) reduce resource costs, thereby increasing demand and consumption (Jevons 1866). The concept of the rebound effect was later used in agricultural water studies (Loch & Adamson 2015; Grafton *et al.* 2018). The rebound effect occurs when some or all water saved through efficiency improvements is used (Mazzucato *et al.* 2024; Singh *et al.* 2024). This can be explained by farmers who invest in expensive high-efficiency irrigation technologies are likely to use the saved water for extending the area irrigated.

3. MATERIALS AND METHODS

3.1. Study area

The Zayandeh-Rud River basin (Figure 1), central Iran, spans 27,000 km^2 and hosts a 400-km endorheic river that originates from the west and flows into the Gavkhoni Wetland in the east. The basin's primary surface water resources include the Pelasjan, Zayandeh-Rud, and Samandegan rivers, along with inter-basin water transfer tunnels, all feeding into the Zayandeh-Rud Reservoir, constructed in 1970. Agriculture and industry significantly contribute to the basin's socio-economic activities, with over 50 different crops cultivated and around 13,000 industrial units, particularly in steel, iron, power, refinery, and petrochemicals (Enteshari *et al.* 2020).

Most of the basin (93%) is in Isfahan province and 7% is in Chaharmahal-Bakhtiari province. This basin is facing many challenges including the reduction of groundwater and land subsidence, problems arising from water transfer projects, environmental issues, social-economic and security issues. One of the reasons for the challenges has been the very solutions provided to reduce water scarcity in the basin, specifically the inter-basin transfers conducted without comprehensive investigations. These water transfer projects are now becoming a platform for inter-provincial tensions. Figure 1 and Table 1 show the location of the basin, provinces, and water transfer projects.

3.2. Research approach and data resources

This research consists of three steps. In the first step, by using the resources available in books, scientific articles, theses, news and websites, data regarding the development of the basin has been studied, analyzed and collected in English and Persian. The collected materials were organized in the form of a timeline. In the second step, the

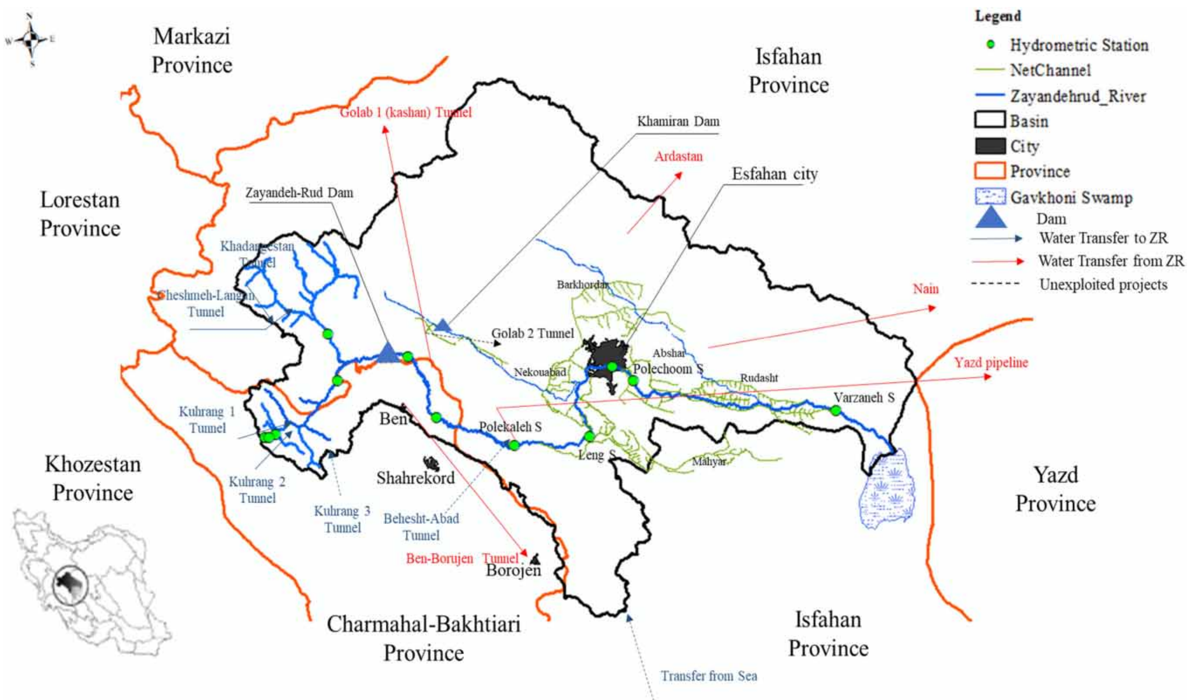


Fig. 1 | The Zayandeh-Rud River basin and inter-basin transfers.

Table 1 | All IBWTs to and from the Zayandeh-Rud basin (Gohari *et al.* 2013; Talebi Eskandari & Mirnezami 2020; Isfahan Regional Water Company 2023), operational and planned.

Operational since	Name IBWT	Donor basin	Recipient basin	Capacity Mm^3/year
IBWT into Zayandeh-Rud basin				
1953	Kuhrang 1 tunnel	Karun	Zayandeh-Rud	293
1985	Kuhrang 2 tunnel	Karun	Zayandeh-Rud	224
2004	Cheshme-Langan tunnel	Dez	Zayandeh-Rud	100[a]
2013	Khadangestan tunnel	Dez	Zayandeh-Rud	30[a]
Sub-total				**647**
Planned	Kuhrang 3 tunnel	Karun	Zayandeh-Rud	120
Planned	Beheshtabad Plan	Karun	Zayandeh-Rud	250
Planned	Line 3	Persian Gulf and Oman sea	Zayandeh-Rud	600
Sub-total				**970**
IBWT out of Zayandeh-Rud basin				
1999	Yazd Pipeline	Zayandeh-Rud	Kavir siahkoh	60
2003	Nain Pipeline	Zayandeh-Rud	Kavir siahkoh	37
2005	Kashan Pipeline (Golab 1 tunnel)	Zayandeh-Rud	Salt Lake basin	35
2007	Ardestan Pipeline	Zayandeh-Rud	Kavir siahkoh	15
2023	Ben-Borujen	Zayandeh-Rud	Karun	52
Sub-total				**199**

[a]The capacities of these two tunnels are not precisely known, but their combined capacity is 130 Mm^3/year.

supply–demand cycle, as well as recorded conflicts and cooperation, have been examined and analyzed. In the third step, vulnerabilities were examined and lessons learned from similar cases are presented. Table 2 shows the sources of information of the collected data.

4. RESULTS

This section presents the results in three parts: first is an account of basin developments since the 1950s, followed by the historical trend of the supply–demand cycles. The section ends with the identified vulnerabilities.

Table 2 | The information of the collected data.

Data	Source
The concept of reservoir effect, inter-basin water transfer and supply–demand cycles	Main papers: Di Baldassarre *et al.* (2018), Gohari *et al.* (2013)
Historical review	Papers, theses, books, websites (in Persian and English)
Hydrological data	Isfahan Regional Water Company, some papers
Economic data	Papers, Reports
Conflicts data	Theses (in Persian and English); news agency sites
Institutional-organizational data	Papers, webinars, administrative documents,

4.1. Basin developments since the 1950s

During the Safavid period (16th century), there were conflicts between upstream and downstream farmers. At that time, the lack of a regular and fair system for water allocation allowed influential people to take more water. This not only caused social tensions but led to a decrease in agricultural production and livelihood problems (Talebi Eskandari & Mirnezami 2020). In 1938, Lambton discovered the first rules for the allocation of water in the Zayandeh-Rud as described in the Sheikh Baha'i tumar (an edict or Scroll), which divided the water into 33 shares between upstream and downstream farmers (Lambton 1938; Molle *et al.* 2009a).

After reviewing the historical timeline of hydraulic development, Figure 2 illustrates the events that occurred in each period, including water transfer projects, legal changes, agricultural developments and conflicts. More detailed accounts of hydraulic development is provided in the Supplementary material. Figure 2 shows that with increased awareness and the formation of public institutions and organizations, the management system has been significantly influenced. Public movements in each province have led to delays or halts of new projects.

4.2. The hydraulic mission in Iran (1953–1980)

The groundwork for the hydraulic mission (Molle *et al.* 2009b) in Iran was laid with the initiation of the Point Four Program by Truman in 1949, which aimed to improve and support underdeveloped countries through scientific and industrial advances (Truman 1949; Bakhtiyari *et al.* 2020; Sheehan 2023). Isfahan was the first location in Iran selected for development, with the government taking control of water resource management through the

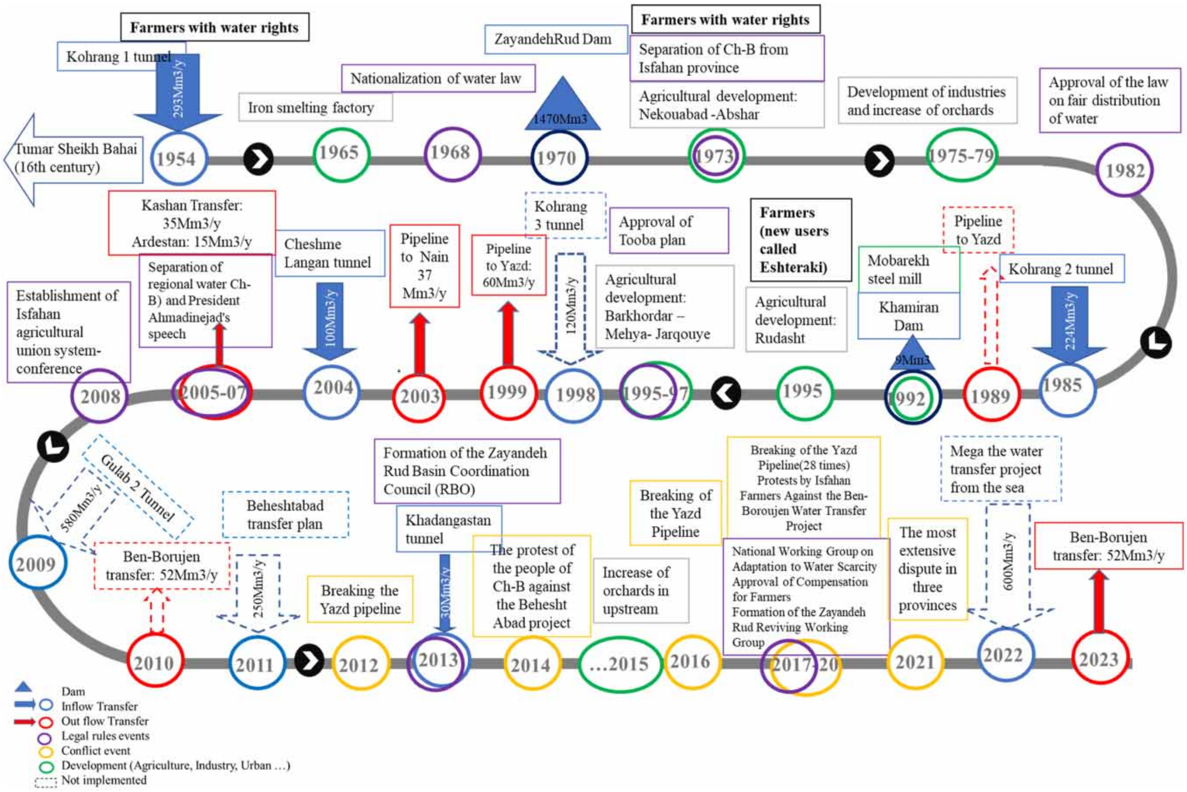


Fig. 2 | A timeline of events in the Zayandeh-Rud basin, 1954–2023.

construction of water structures and modern irrigation systems (Talebi Eskandari & Mirnezami 2020). This marked a step toward comprehensive development using technocratic approaches.

Due to water scarcity in the Zayandeh-Rud River basin, transferring water from the Kuhrang River was first proposed by Shah Tahmasab–Safavid king (1523–1576). Despite many failed attempts, the first Kuhrang tunnel was finally opened in 1953, with a capacity to transfer 293 Mm^3/year to address water shortages and expand agricultural land (Molle *et al.* 2009a). Farmers in Isfahan, who bore much of the construction cost, have held water rights (Haghabedar) based on a collective partnership for centuries, and today, these farmers play a key role in conflicts over water allocation.

After that, the Zayandeh-Rud dam, built in 1970 with a capacity of 1,470 Mm^3, aimed to increase water availability and support agricultural expansion, urban growth, and industrial development in the Isfahan region. Modern irrigation systems, including the Nekouabad irrigation system (12,000 hectares) and the Abshar irrigation system (15,000), were developed to support agriculture (Talebi Eskandari 2021a). The dam's objectives included irrigating the Isfahan plain, boosting farmers' incomes, supplying water for industries, providing flood protection, and generating electricity. After the dam's construction, summer cultivation of crops like rice and maize became possible (Ziaei 2020), and new landowners, called Sahmaba Bar, emerged during land reforms after the 1979 revolution (Mamasani 2024). Simultaneously, industries, particularly the iron smelting factory, expanded. Between 1975 and 1977, four major industries – defence, Mobarakeh steel mill, Isfahan oil refinery, and Sepahan cement factory – were established, requiring 60 Mm^3/year of water (Molle *et al.* 2009a).

4.3. The start of the supply–demand cycle (1981–2004)

By 1982, water consumption in Zayandeh-Rud had significantly increased. With this increase, the second water transfer plan from the Kuhrang River was considered. This plan was implemented in 1985 with a capacity of 224 Mm^3/year (Gohari *et al.* 2013). Supply-oriented management and the definition of new developments included the expansion of agricultural land under irrigation, the construction of canals, and the development of irrigation systems for transferring water to plains without water rights (such as Borkhar, Mahyar, Jarquyeh, and Karvan), exploiting the Rudasht irrigation system and increasing irrigable land from 17,000 hectares to about 42;000 hectares (Zayandab Consulting Engineering 2015), and transferring water to Yazd, Kashan, and Nain. Also, during this period, new users known as 'collective users (Eshteraki)' were added to the Zayandeh-Rud water users.

In the early 1990s, water withdrawals exceeded 500 Mm^3/year. The construction of Khamiran dam with a capacity of 9 Mm^3, was put into operation in 1992 to support agriculture in the Tiran region, covering an area of 5,000 hectares. The Tooba Project, approved in 1995, accelerated orchard development along the Zayandeh-Rud basin, shifting land use from pastures to peach and almond orchards. By the late 1990s, drought and overuse caused an imbalance between water resources. Following these conditions, in 1998, the construction of the third Kuhrang tunnel began with the goal of providing 120 Mm^3/year of water. Because the construction of the third tunnel faced challenges and could not be completed, the Cheshme-Langan Tunnel, another water supply source, was put into operation in 2004 (Talebi Eskandari 2021a). The supply–demand cycle had come into full swing (Madani & Mariño 2009; Nazemi *et al.* 2020).

4.4. Structural changes and the beginning of competition (2005–2011)

One of the significant events of this period was the approval in 2005 of the law converting regional water management into provincial water management offices. Although this law did not disrupt the political arrangements of many basins across the country, the situation was different in the Zayandeh-Rud basin. The province of Isfahan, responsible for basin management, now had to share its authority over the Zayandeh-Rud basin with the province of Chaharmahal-Bakhtiari (Talebi Eskandari 2021a). This law brought unprecedented legitimacy and authority to Chaharmahal-Bakhtiari. This was a unique opportunity for the development of the Chaharmahal-Bakhtiari province (Nabavi 2017). Another significant event during this period was a speech by then-President Ahmadinejad in 2005, which led to the regionalization of water companies, further reinforcing Chaharmahal-Bakhtiari's belief in their priority for utilizing water resources (Mamasani 2024). These measures gradually formed the basis for competition.

In addition, transferring water outside the Zayandeh-Rud placed additional pressure on the basin. One such project was the Ben-Borujen Water Transfer Project from the Zayandeh-Rud basin to the Karun basin. Initiated in 2006 to address water shortages in Chaharmahal and Bakhtiari province, the project planned to extract 52 Mm^3/year from the Zayandeh-Rud. However, it faced strong opposition from Isfahan farmers. Despite these objections, the project became operational in 2023. Critics argued that transferring water from a basin already suffering from water scarcity to another region was not only economically costly (due to pumping), but also unjustifiable in terms of land productivity.

4.5. Emergence of effects, empowerment of farmers, and conflicts (2012–2023)

Repeated droughts, competing development plans, and overuse of water resources led to serious issues. The environmental crisis followed the same supply-focused approach, triggering another water transfer project from Beheshtabad in Chaharmahal-Bakhtiari. However, strong opposition from donor regions halted all water transfer plans. Collective actions emerged from the people of Chaharmahal-Bakhtiari and Khuzestan against these projects, while Isfahan farmers defended their water rights. Isfahan farmers even broke the Yazd transfer pipeline. In addition, there was opposition from Isfahan farmers to the Ben-Brojen plan. The conflict gained national attention, leading to the formation of the Zayandeh-Rud Basin Coordination Council in 2013, involving farmer representatives from Isfahan and Chaharmahal-Bakhtiari in decision-making. During this period, farmers' power had increased significantly (Talebi Eskandari 2021b).

Despite efforts by the Working Group on Adaptation to Water Scarcity to compensate farmers, issues like delayed payments, unfair assessments, conflicts between water rights holders and sharecroppers, and cheaper water releases for orchards in western Isfahan led to continued protests. In the fall of 2021, farmers protested again due to water shortages, damaging the Yazd pipeline and staging a 16-day sit-in on the dry Zayandeh-Rud riverbed. The protests ended with a government crackdown, and the Minister of Energy promised new water transfer projects from the Karun basin (including the third tunnel and Beheshtabad).

Despite opposition from three provinces to water transfer projects and protests over water shortages, the Ben-Brojen transfer project (from Zayandeh-Rud basin to Karun basin) was implemented in 2023. Recently, construction work on the Kuhrang 3 dam has resumed, indicating a repetition of the same supply–demand cycle, with each party attempting to address the conflict through another technocratic approach. This is evident in the latest decision to transfer water, this time from the Persian Gulf and the Sea of Oman. The main shareholders of this project are industries and mines. This project is meant to transfer 400 Mm^3/year of desalinated seawater from the source of the Strait of Hormuz to the industrial and population centers of Isfahan province in two phases (Aghebat-Bekhair *et al.* 2022).

4.6. Supply–demand cycles in Zayandeh-Rud

The history of the Zayandeh-Rud Basin's water resources and consumption has undergone significant changes over the past 70 years (Figure 2). Figure 3 illustrates the supply-driven trend and water consumption in the basin. The consumption data in Figure 3 was extracted from three separate sources, meaning there is some uncertainty in the data; however, the general trends are clear. (The data from 1953–1990 by Gohari *et al.* (2013), 1991

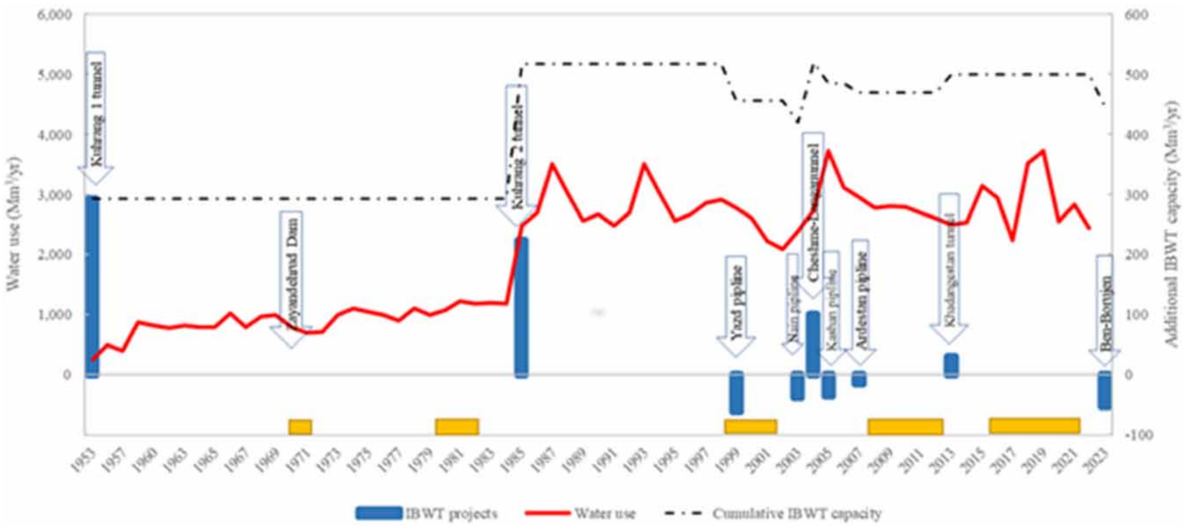


Fig. 3 | The historical trend of water use, the commissioning of IBWT, and the cumulative capacity of IBWT. The yellow boxes indicate drought periods.

to 2010 by Isfahan Regional Water Company (unpublished data), 2014–2021 by a collection of reports on surface and groundwater resources of Isfahan province (published).)

This chart shows the trend of IBWT, water use, and drought periods from 1953 to 2023. Three main variables observed in Figure 3 are:

- Additional IBWT Capacity (right axis, blue bars): Negative values indicate water transfer out of the basin.
- Cumulative IBWT Capacity (right axis, black dashed line): This represents the cumulative capacity of IBWT over time.
- Water use (left axis, red line): This line shows the amount of water usage over time. The yellow boxes indicate drought periods, derived from Figure 4.

As shown, during the hydraulic mission period (1950–1980), water consumption increased with slight fluctuations. However, after the construction of tunnels and the Zayandeh-Rud dam, and the onset of comprehensive developments, especially after the second Kuhrang tunnel, water consumption nearly tripled. In these years, it is evident that not only the effect of the Zayandeh-Rud dam but also the impact of water transfers contributed to the increase in water consumption. Even during drought periods in the 1990s, the use of groundwater resources mitigated the impact. However, in the late 1990s, coinciding with the drought between 1999 and 2001, there was a significant drop in water consumption which was due to the reduction of the available water. Although transfers out of the basin were relatively small compared to the incoming transfers, they had some impact during the dry period. This supply-driven cycle is again seen in 2004 with the renewed transfer of water through the Cheshme-Langanunnel tunnel, which temporarily increased water consumption. In 2011–2012, due to reduced rainfall and groundwater shortages, consumption decreased.

Overall, Figure 3 shows that the reservoir and water transfers created a highly critical situation. Continuously adding new water transfers is unlikely to have a positive effect on the basin's water resource management and security.

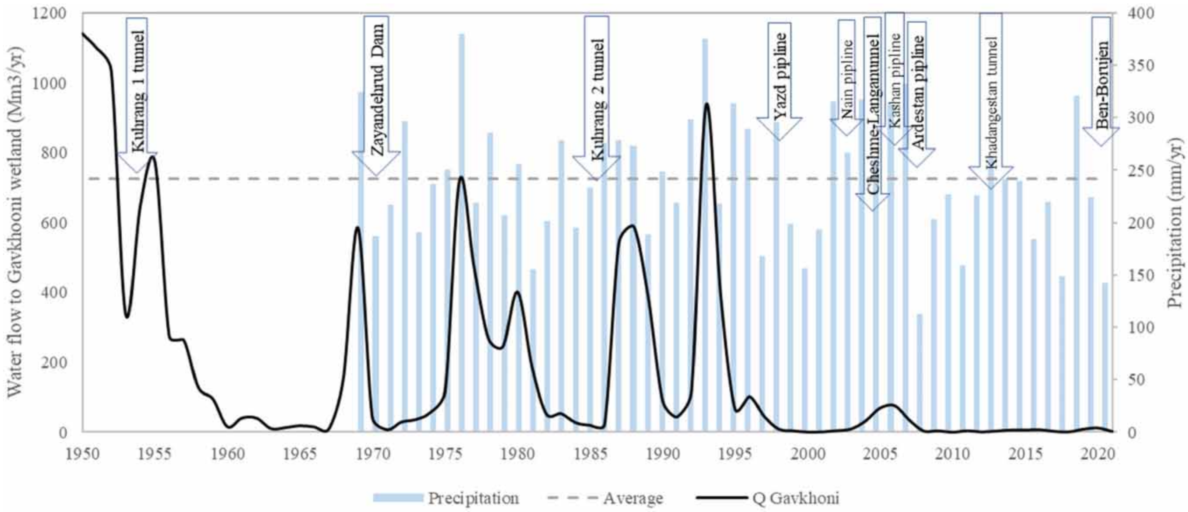


Fig. 4 | Water flow to the Gavkhoni wetland, annual and long-term average precipitation (Enteshari & Safavi 2021; Isfahan Regional Water Company 2023).

4.7. The rebound, reservoir, and IBWT effects, and basin vulnerabilities

This section examines how the Zayandeh-Rud closed basin has demonstrated significant sensitivity and vulnerability over the years. Impacts and vulnerabilities in the four water subsystems are reviewed.

4.7.1. Natural-climatic subsystem

In general, endorheic basins are very sensitive to human interventions. Changes in land use, expansion of irrigation systems, extraction of water from surface and groundwater sources, reservoirs, IBWTs and pollution have significant effects on this natural ecosystem in the long term (Wurtsbaugh *et al.* 2017).

Between 1985 and 2015, the Gavkhoni wetland area rapidly changed, with these changes being more closely related to changes in precipitation levels. Figure 4 shows the long-term precipitation in the basin compared to the average precipitation (242 mm/year) and water flow to the Gavkhoni wetland. In the 1950s the water flow to the Gavkhoni wetland was relatively high, but sharply declined afterward and remained at a low level. The Zayandeh-Rud River dried up shortly after the construction of the Zayandeh-Rud Dam. In 1970, rainfall decreased, and the construction of the dam resulted in less water being released to the wetland. Between 1975 and 1985, despite fluctuations in rainfall, the water right of the wetland was respected, and its condition remained stable. During this period, several peaks in water flow can be observed, particularly in the 1970s, 1980s, and 1990s, coinciding with higher precipitation. From the early 2000s onwards, the water flow has nearly dropped to zero, despite rainfall remaining close to the average in many years. This indicates that, despite significant rainfall, factors such as IBWTs, land-use changes, dam construction, and water resource exploitation of mainly irrigation have led to reduced water flow to the wetland.

Ignoring the wetland's conditions will turn it into a centre of toxic contamination, posing serious risks to the entire region, including many cities and villages (Shiran *et al.* 2021). Since 1996, the wetland has not been in a favorable condition. The wetland's decline coincided with the exploitation of new resources, the introduction of new pressures, the approval of the Tooba Project, and the further expansion of irrigated areas throughout the basin, including orchards in the upstream areas.

The condition of the wetland therefore reflects poor basin management. The wetland has been damaged, making the basin more vulnerable to even the slightest changes. This vulnerability due to the reservoir and IBWT effect manifests itself in dry periods. Evidence shows that drought primarily affects agriculture (Molle *et al*. 2008). The drought of 1999–2001 led to a reduction of 38% of the cultivated area (Figure 3). Following the reduction of surface water, farmers turned to groundwater sources. This led to a drop of the groundwater level and the drying of wells (Molle *et al*. 2008).

Between 1981 and 2015, groundwater levels declined in 12 major aquifers. On average, groundwater levels decreased by 0.6 m/year. Even in relatively wet years, such as 1986, 1993 and 2004, groundwater levels continued to decline, indicating unsustainable groundwater exploitation (Abou Zaki *et al*. 2020). To make things worse, modern irrigation systems led to an increase in cultivated area and a decrease in water returning to groundwater resources (Tasnim News Agency 2021). The resulting decline in groundwater levels led to land subsidence, cracks in some roads and canals, and the destruction of buildings in some villages, especially in mountainous areas (Enteshari & Safavi 2021).

4.7.2. Socio-economic subsystem

The Zayandeh-Rud basin has experienced significant changes in its population over the years, from 0.5 to 5 million from the 1950s to present, primarily driven by socio-economic and environmental factors. Since life depends on water, IBWTs have played a crucial role in attracting migrants from neighboring provinces, particularly Chaharmahal & Bakhtiari and Khuzestan, ironically provinces from where water resources were transferred into the Zayandeh-Rud. The growth of industry and agriculture in the Zayandeh-Rud basin has provided employment opportunities, further attracting migrants to the area. However, population growth and migration have led to several challenges. The increased demand for water due to population growth, industrial and agricultural activities has exacerbated water scarcity issues in the basin. This has resulted in reduced water allocation to downstream areas, leading to agricultural land becoming arid and to increasing unemployment. Consequently, water scarcity issues have sparked social unrest and protests over water allocation, and have increased social harm, such as crime and divorce rates (Enteshari *et al*. 2020).

Overall, it is evident that agricultural development has not been able to be sustained, despite of all supply-oriented increases. Currently, due to water shortages, the irrigated area in the Zayandeh-Rud Basin has decreased (Abou Zaki *et al*. 2020). This reduction has led to widespread unemployment among farmers and subsequent social and economic issues (Enteshari & Safavi 2021). The reduction of water flow in Rudasht, located downstream in the basin, has severely impacted local farmers. If this situation continues, it could lead to migration from Rudasht, with severe social and environmental consequences (Besalatpour *et al*. 2020). Both people and the government have suffered social and economic damage. The 2018 drought forced the government to compensate farmers for their inability to cultivate, manage protests, and address the damage from repeated breaks in water transmission lines (28 times to Yazd). During this period, the number of industrial units increased, growing from around 1,000 in 1991 to 8,000 by 2015, leading to a higher demand for water (Enteshari & Safavi 2021). This dependency on water for industries and continued development could result in significant economic losses if drought re-occurs and factories are forced to shut down. All these water shortages have turned the Zayandeh-Rud into a seasonal river, failing to maintain the minimum required flow in the central and downstream areas of the basin. This seasonality has had adverse effects on the region's tourism and economy (Enteshari & Safavi 2021).

4.7.3. Hydropolitical subsystem

As is evident, the drought over the past two decades has had the most significant, though not the only, impact on the basin (Babadi *et al*. 2022). While drought has played a crucial role, inefficient water resource management and human factors have had a substantial effect as well (Besalatpour *et al*. 2020). In the early stages of the drought, the vulnerability of farmers did not become clearly apparent due to varying approaches (e.g. utilizing groundwater, changing the crops cultivated, adaptive strategies adopted). Farmers with limited access to groundwater were more vulnerable, leading them to change cropping patterns, modify irrigation systems (or dig illegal wells), change occupations, or sell land. In contrast, those who could access groundwater continued their agricultural activities or rented out their land (Molle *et al*. 2008; Talebi Eskandari 2021a).

However, as this trend continued vulnerability increased. Economic problems and a sense of injustice led to the emergence of protests and water disputes. With the reduction of surface water flows and groundwater levels and the failure to meet farmers' water rights, the affected farmers unified and protests began to intensify, particularly from 2011 onwards. During this period according to the timeline (Figure 2), conflicts between farmers in eastern Isfahan and several other groups became evident. These included:

- Regional authorities over water management.
- The province of Chaharmahal-Bakhtiari over the Ben-Brojen project.
- Upstream farmers (in western Isfahan and Saman in Chaharmahal-Bakhtiari).
- Industrial sectors, due to their higher water use priority.
- The province of Yazd over water transfer.

Additionally, disputes between the residents of Khuzestan and Chaharmahal-Bakhtiari with Isfahan over the Third Tunnel and Beheshtabad water transfer projects further demonstrate the complexity of the issues and how vulnerabilities are becoming increasingly widespread (Mamasani 2024).

The government's policies increased dependency on water and caused beneficiaries to overlook the region's arid climate. Despite expectations that increased water supply would improve the Zayandeh-Rud basin's condition, water disputes among various stakeholders intensified (Nabavi 2017).

4.7.4. Institutional subsystem

According to Iranian law, all flowing water is considered national wealth and belongs to the public. The allocation of water usage permits for domestic, agricultural, and industrial purposes is the responsibility of the Ministry of Energy. The Ministry's affiliated companies, including the Iran Water Resources Management Company at the national level and the regional water companies at the provincial level, exclusively serve as representatives of the Ministry of Energy. The Supreme Water Council of Iran is the highest body for coordinating water policy (Yousefi *et al*. 2020). The central role of government in water supply and allocation has weakened the previously existing social cohesion and self-organizing systems. Under these conditions, the community, which once played an active role in water resource management, gradually distanced itself from participatory roles and became more reliant on the government to meet its needs (Talebi Eskandari 2021a).

In response to the drying up of the Zayandeh-Rud and the lack of coordination between the provinces of Isfahan and Chaharmahal-Bakhtiari following the shift from basin-based to provincial water management boundaries in 2005, the Supreme Water Council of Iran established the Zayandeh-Rud Basin Coordination Council in 2013 for integrated water resource management. Although this council was intended to be the key coordinating body, it failed to resolve conflicts over water rights. Decision-making was characterized by zero-sum negotiations, hard bargaining techniques with the concealment of information, and a focus on supply-side approaches (such as water transfers and reservoir releases). Meanwhile, no effective programs or measures were in place for monitoring and enforcing surface and groundwater withdrawals (Yousefi *et al*. 2024). Ultimately, due to the lack of coordination and significant tensions and conflicts over water, the Supreme Water Council dissolved the Zayandeh-Rud Basin Coordination Council in 2019 and replaced it with the 'Zayandeh-Rud Reviving Working Group.'

The Vice President of Iran heads this task force, and the representative of farmers was removed from the committee. Consequently, the solution focused on strengthening government authority in the basin, with an emphasis on increased centralization and reduced stakeholder participation (Yousefi *et al.* 2024).

Although during this period many efforts have been made to resolve conflicts and several working groups and councils have been formed to solve problems, a lack of integration and planning has led such efforts to fail (Yousefi *et al.* 2024). A crucial point is the significant influence of various stakeholders in water governance within the Zayandeh-Rud basin. The Zayandeh-Rud Basin Coordination Council failed to play a key role in promoting cooperation and coordination among stakeholders, as expected. The assumption that the Zayandeh-Rud Basin Coordination Council was a high-powered stakeholder with strong interests was flawed. For example, while parliament members were not directly involved in bureaucratic decision-making processes, they wielded considerable power and interest. They exerted their influence through informal networks, which could lead to varying outcomes in different decisions (Reyhani & Grundmann 2021). Ultimately, these political decisions weakened the authority of the public sector, eroded trust in institutions, and created challenges in coordinating efforts to address water issues. Figure 5 shows a timeline of the basin's organization and management institutions.

5. DISCUSSION

While reservoirs and water transfers both play critical roles in water management, they serve different functions. Reservoirs do not add additional water to a basin. Instead, they modify how water is distributed within the basin. This means that while they can help manage water availability during dry periods, they do not increase the overall water volume in the basin. Water transfers, on the other hand, act to increase the amount of water available in the receiving basin, as it introduces additional water resources that were not originally part of the basin's hydrological cycle.

Therefore, the effect of a reservoir will differ from that of a water transfer. It is worth noting that water transfers in the upper reaches of the basin increased the reservoir's water storage. The results of this research regarding the

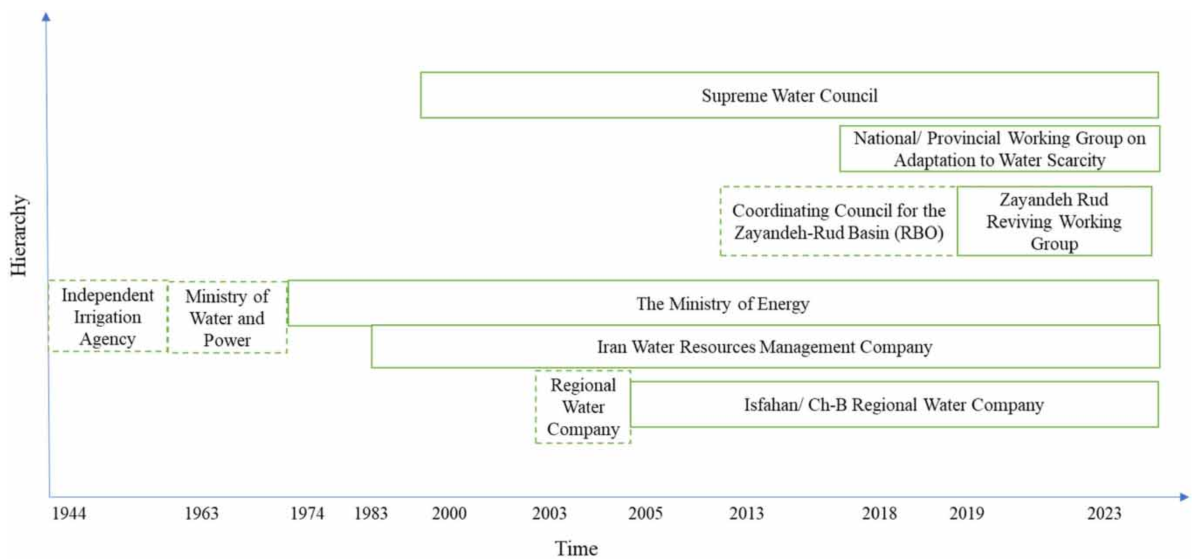


Fig. 5 | Timeline of the basin's organization and management institutions. (The dashed line boxes no longer exist now.)

effect of reservoirs align with studies by Di Baldassarre *et al.* (2018) and Gohari *et al.* (2013), but this study offers a more comprehensive view of the supply–demand cycle and the impacts of water transfers. In other words, the development of water infrastructure in the long term has not only not solved the problem of scarcity, but has also created a self-reinforcing cycle of supply and demand (Di Baldassarre *et al.* 2021).

Figure 6 expands on previous work by integrating the supply–demand cycle with the natural, socio-economic, institutional, and hydropolitical water subsystems. While previous research highlighted socio-economic vulnerabilities, this study, by examining changes over 70 years, has shown that, in addition to the natural and socio-economic subsystems, the institutional and hydropolitical subsystems were also significantly impacted. Gohari *et al.* (2013) pays attention to the supply and demand cycle and inter-basin transfers, but overlooked the vulnerabilities of the water systems. Di Baldassarre *et al.* (2018) show cycles of economic dependencies and vulnerabilities while ignoring water transfers and the vulnerabilities of other water subsystems, as well as water disputes, although in their other research they showed the institutional and social dependence on more water supply in the legacy of dams (Di Baldassarre *et al.* 2021). In line with this, research in the Zayandeh-Rud basin has also shown that policies to increase supply, in the absence of institutional reforms, have led to the reproduction of demand pressure and the continuation of instability (Madani & Mariño 2009; Nazemi *et al.* 2020).

Godinez Madrigal *et al.* (2022) focused on grassroots movements impacted by water transfers, which triggered water disputes that led to the formation of participatory workshops and eventually to agreements over water issues. However, the vulnerabilities to other water subsystems were not considered in this way. In this study, closer attention is paid to the vulnerabilities of four identified water subsystems (Figure 6). Additionally, civil protest movements and conflicts were seen to have led to the creation of working groups in this basin to develop decision-making spaces, though, as explained earlier, these efforts have, at least so far, not been successful.

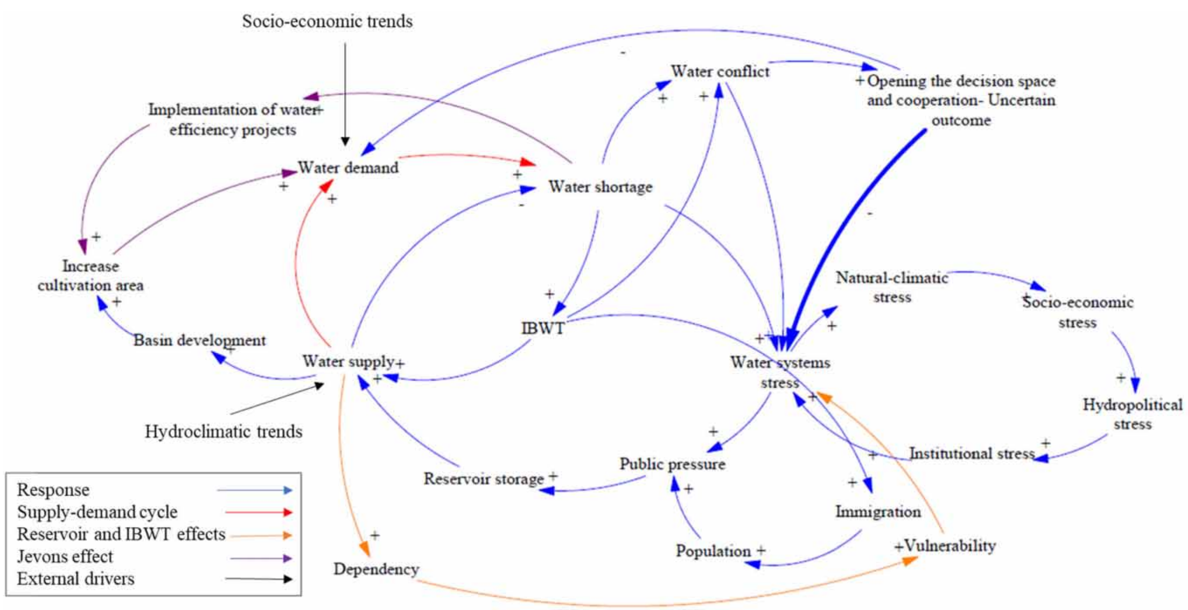


Fig. 6 | The interaction cycle of water supply and demand and the reservoir, IBWT, and Jevons effects in water resources management systems (adapted from Gohari *et al*. 2013; Di Baldassarre *et al*. 2018; Enteshari *et al*. 2020; Godinez Madrigal *et al*. 2022).

Furthermore, none of these studies have considered the Jevons effect in these interactions. This means that in response to water shortages, approaches to increasing efficiency in the agricultural sector have had the opposite effect, and water consumption has not decreased, instead it increased, as did the cultivated area.

Therefore, water infrastructures continue to reproduce institutional power relations and allocation patterns long after their physical construction is completed (Quealy & Paranage 2024) –a phenomenon that can also be observed in the Zayandeh-Rud basin through the persistence of supply-oriented policies and institutional responses. Just as Gohari *et al.* (2013) analyzed the supply–demand chart up to 2005 and predicted that short-sighted solutions that alleviate the symptoms of a problem without addressing its root causes would lead to the problem intensifying in the future, this study, updating the analysis up to 2023, shows that the onset of conflicts and the drying of wetlands could have been a turning point for a change in approach, but the same old approaches continued.

Lessons from various cases such as the Aral Sea, Lake Urmia, Athens, Las Vegas, Melbourne and others show that they all experienced a critical point when a change in their approach would have been possible, yet ignoring it has led to the current conditions. This scenario of environmental degradation has occurred globally. For example, the Toolibin Basin, located in the Blackwood River Basin in the Wheatbelt region of Western Australia, underwent extensive development throughout the 20th century. The most significant changes occurred between 1949 and 1969. By the early 1970s, over 90% of the basin's native vegetation had been cleared for rain-fed agriculture (mainly wheat and sheep farming), leading to severe environmental degradation. In the 1990s, the state government and local communities began implementing corrective measures to counter this trend and attempt to prevent or reverse the negative impacts of development (Elshafei *et al.* 2014). All similar examples have resulted in environmental degradation and the loss of lakes or wetlands after a peak period of development. The key point is that if a change in approach does not occur at the critical point, destruction will likely follow swiftly. The Gavkhoni Wetland has experienced such a critical point since 2005 and it is now serving as a 'canary in the coal mine' for the basin's inhabitants. Therefore, if the current local water management policies continue without necessary reforms and adaptations, the basin will inevitably face severely worsening water shortages in the future.

The conflicts that emerged since 2012 forewarned the basin's future condition. In such situations, grassroots movements may signal early warnings, and may in fact spearhead fundamental changes in water management approaches. A notable example is the 18-year-long conflict over the Zapotillo project in Mexico which demonstrated that grassroots movements in water conflicts drive socio-technical transitions in water management systems (Godinez Madrigal *et al.* 2024). The Zapotillo conflict, which began in 2005, became a political battleground. Grassroots movements to oppose the construction of the dam and the transfer of water to the city led to a halt and to a change of approach. In 2021, after negotiations with grassroots movements, the Mexican government agreed to irreversibly modify the project to reduce the maximum water level in the dam. This unexpected outcome shows that grassroots movements can drive transitions toward more sustainable and socially just water management, revealing a generative side to conflicts (Godinez Madrigal *et al.* 2024).

Water crises and conflicts allow grassroots movements to direct efforts toward specific, alternative, bottom-up policies, projects, and research programs (Godinez Madrigal *et al.* 2024). While it should be noted that water conflicts are no guarantee for finding sustainable solutions (Mohammadinezhad & Ahmadvand 2020), as they can also be an opportunity for technocrats to do more of the same rather than to fundamentally change decision-making approaches, they can offer opportunities for opening new spaces for decision-making.

6. CONCLUSION

The Zayandeh-Rud is experiencing developments that are similar experience to those in other endorheic basins in the world due to human interference. One of the human actions is irrigation system development and associated construction of reservoirs and water transfers, which create significant effects in the long term. The reservoir effect, when applied to IBWTs, highlights the potential for increased vulnerability and environmental degradation due to excessive reliance on transferred water and increasing the number of stakeholders involved and affected. Overall, the development based on increasing water supply in the Zayandeh-Rud river basin has not only failed to significantly improve the status of this basin but has also exacerbated conflicts and dissatisfaction. The growing demand for water from all stakeholders, coupled with their differing perspectives, has led to an illusion of development. Ultimately, increased demand for water without proper management has only intensified conflicts and inequalities. Despite the expectation that increased water access would improve the Zayandeh-Rud river basin, water disputes among various users have intensified over the years.

All these issues have led to the Gavkhoni Wetland being under severe water stress over the past 20 years. A review of the timeline and conditions of the Gavkhoni Wetland shows that water disputes emerged only after the wetland came under stress. Therefore, the wetland is potentially a useful sentinel. However, this was neglected or ignored, which severely complicated the situation. Although several efforts were tried to manage the problems of the basin, they did not yield any openings.

By analyzing the long-term supply–demand cycles, this research shows that decision-making on water allocation should be based on a comprehensive perspective that includes not only hydrological aspects and socioeconomic and environmental concerns, but also hydropolitics and institutional realities. Therefore, analyzing water policy in developing countries requires understanding the historical dynamics and continuity of power in the 'post-construction period', because large-scale water infrastructures continue to recreate relationships between the state, communities, and ecosystems (Quealy & Paranage 2024).

Water transfers have not been able to resolve the Zayandeh-Rud water crisis in the long term. And now new, more extensive long-distance water transfers from the sea are proposed that require substantial energy at huge costs. The Zayandeh-Rud basin has reached a point where it must be decided between continuing the current path (increasing water supply) or accepting the limits of the system and searching for alternative solutions. Although Gohari *et al.*'s (2013) argument could have been a turning point for a change in water resources management, continuing the same trend has exacerbated the crisis. Building on that trajectory, this article has depicted the emergence of institutional vulnerabilities and the beginning of social conflicts. Now, to break out of this 'dead-end street', it must be acknowledged that water is a limited resource; as Enteshari *et al.* (2020) have emphasized the need to prioritize livelihoods in water scarcity conditions, and Nazemi *et al.* (2020) also consider the transition to sustainability in the Zayandeh-Rud to depend on reforming the governance model and demand-driven policies, not supply-driven development. Therefore, solutions should include creating jobs that are less water-dependent, investing in more resilient agriculture such as vertical farming innovations, as well as promoting transparency and public participation. By understanding these dynamics and acknowledging the inefficiency of past solutions, a more sustainable and resilient path for the basin's future can be charted.

AUTHOR CONTRIBUTIONS

Atiyeh Fatehifar: Writing – review & editing, Writing – original draft, Methodology, Resources, Investigation, Data curation, Conceptualization. Mohammad Reza Goodarzi: Writing – review & editing, Supervision. Ali Talebi: Data curation, Conceptualization. Janez Sušnik: Writing – review & editing, Supervision. Pieter van der Zaag: Writing – review & editing, Supervision, Methodology.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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