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Economic valuation of virtual groundwater in hyper-arid regions of Iran☆

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ABSTRACT

Access to high-quality water in Iran's hyper-arid regions faces growing challenges due to increasing demand, climate variability, and scarce freshwater resources. The Bajestan watershed consists of two parts: the plain and the playa. The groundwater consumption in this area is such that the plain, which contains relatively better water and is mainly owned by the people, is used for the agricultural sector. Meanwhile, the government is compelled to utilize the saline groundwater resources from the playa through a desalination process to provide good-quality groundwater for drinking and sanitation purposes and to introduce it into the drinking and sanitation network. To evaluate groundwater allocation efficiency, this study integrates virtual groundwater accounting with economic indicators—Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR). The analysis shows that producing bottled water via desalination reached a cost of 45.07 million RI per cubic meter in 2023, resulting in a negative NPV, undefined IRR, and BCR = 0.46—rendering it economically unviable. In contrast, saffron cultivation yielded a significantly higher return (BCR = 2.21) than pistachio (0.89) and pomegranate (0.76), despite requiring far less water. Yet, over 94 % of groundwater is still allocated to agriculture, while only 4 % serves essential domestic needs—revealing a critical misallocation. The findings advocate for cost-reflective water pricing, revised allocation priorities, and expansion of virtual water accounting frameworks to support equitable and climate-resilient water governance. To ensure long-term sustainability, the study recommends implementing cost-reflective water pricing, revising allocation priorities, and enhancing virtual water accounting frameworks. These measures can support more equitable and climate-resilient water governance in Iran's hyper-arid regions.

1. Introduction

Water scarcity stands as one of the most pressing socio-environmental challenges in hyper-arid regions, particularly in Iran. This crisis arises from a convergence of drivers—including rapid infrastructural expansion, unsustainable agricultural practices, and the intensifying effects of climate change on the hydrological cycle. In resource-limited settings, such pressures heighten competition over water access and escalate risks of conflict (Kinzelbach et al., 2003). Subtropical and arid zones, characterized by high atmospheric pressure and low precipitation, face increasingly multifaceted demands for water across agriculture, industry, recreation, and urban use—especially for drinking water (Romano et al., 2018).

In the broader Middle East, water management is further complicated by hydrological uncertainty and climate variability (Lionello et al., 2006; Bacro and Chaouche, 2006). In Iran, groundwater—the primary source of water in most rural and arid areas—has become highly vulnerable. Changes in recharge rates and over-extraction, aggravated by prolonged droughts, threaten aquifer sustainability (Vaccaro, 1992). At the policy level, agricultural self-sufficiency programs such as crop

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subsidies and guaranteed procurement have encouraged water-intensive cropping patterns, misaligned with local hydrological conditions (Madani, 2014).

As dry regions face mounting challenges in water availability, these pressures are often exacerbated by outdated infrastructure, poor groundwater governance, and sectoral mismanagement—particularly in agriculture. In parallel, the absence of transparent water pricing mechanisms and inadequate regulatory oversight hinder rational water allocation and cost recovery (World Water Council, 2009). Despite water scarcity, heavily subsidized tariffs have contributed to inefficient and sometimes excessive water use in urban areas, undermining long-term sustainability. In Bajestan, weak pricing mechanisms and lack of public awareness have resulted in poor water use practices, particularly in non-agricultural sectors. Beyond quantity, water quality deterioration—particularly salinity—has also emerged as a critical constraint in hyper-arid zones.

In providing water resources for human communities in arid regions, drinking water and sanitary water are of particular importance. This has become a major and concerning challenge in these regions, especially with the occurrence of droughts, since groundwater resources are the only source of drinking, sanitary water, and subsequently, water for agriculture. Groundwater pollution increasingly limits the usability of water for domestic purposes. In arid regions, the main issues related to groundwater pollution and aquifers are high salinity—exacerbated by increasing drought stress and greater exploitation of aquifers. On the other hand, in cases where groundwater treatment infrastructure is limited, it poses health risks (Brinda and Elango, 2015). In these situations, bottled or packaged water is used according to emergency conditions (Delpla et al., 2009). Beyond these acute conditions, growing dissatisfaction with the quality of tap water has also led to a steady increase in bottled water consumption in Iran (De Giglio et al., 2015), despite significant environmental and energy costs (Garfí et al., 2016).

In such contexts, desalination of brackish groundwater has gained traction as an emergency solution. However, desalination technologies—particularly reverse osmosis (RO)—remain energy-intensive and economically burdensome, especially when implemented in inland areas with deep wells and high salinity levels (Abraham and Luthra, 2011; Gleeson et al., 2012; Karagiannis and Soldatos, 2008; Ziolkowska, 2015). While technological advances have contributed to cost reductions (Ghaffour et al., 2013), the continued expansion of desalination infrastructure without complementary economic assessment raises concerns over sustainability. In response to these challenges, the concept of virtual water—the volume of water embedded in goods and services—has emerged as a promising framework for evaluating resource allocation efficiency (Allan, 1997; Hoekstra and Chapagain, 2007). Virtual groundwater accounting allows policymakers to quantify the hidden water costs of economic activities, especially in agriculture, and to compare water uses not only by volume but also by value added. However, despite its analytical power, virtual water remains underutilized in most water policy and economic valuation frameworks.

This study seeks to bridge that gap by developing an integrated virtual groundwater accounting model tailored to the hyper-arid conditions of the Bajestan Plain in eastern Iran. In this region, water usability is severely constrained by high electrical conductivity (EC) levels. Agriculture dominates groundwater consumption, often favoring pomegranate and pistachio orchards, which are water-intensive and economically less efficient. In contrast, saffron—an economically valuable, low-water-demand crop—remains underutilized. At the same time, the drinking water sector relies increasingly on costly desalination or bottled sources drawn from highly saline playas, highlighting a mismatch between supply, affordability, and social equity. Moreover, due to the elevation difference between playa wells and demand centers, delivering this water requires high pumping energy, adding further economic strain on service provision.

This study not only estimates virtual water volumes but also integrates them into an evaluative framework for decision-making regarding water allocation across competing sectors (drinking, sanitation, and agriculture). To evaluate whether current water allocations in Bajestan are economically and socially sustainable, this study employs a multi-sectoral virtual groundwater valuation framework. This model combines financial indicators—Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR)—with volumetric virtual water assessments across three competing sectors: drinking, sanitation, and agriculture.

This study introduces one of the first empirical frameworks in Iran to integrate real-cost valuation of desalinated groundwater with virtual water accounting. By quantifying both the physical and virtual economic value of water across key sectors—drinking, sanitation, and agriculture—it provides a robust analytical tool for identifying inefficiencies in current allocation practices. The framework supports data-driven prioritization of water uses, highlighting opportunities for reallocation that balance economic return, equity, and sustainability. As a result, the research offers both conceptual insights and practical guidance for designing adaptive water pricing strategies in hyper-arid regions like Bajestan, where escalating water stress and salinity require innovative and integrated management approaches.

This framework is also applicable to other hyper-arid and groundwater-stressed regions, where water salinity and energy costs undermine the effectiveness of conventional economic assessments. This is one of the first empirical studies in Iran to simultaneously apply virtual groundwater accounting and economic viability indicators to assess multi-sectoral water use in a hyper-arid context.

2. Study area, groundwater issues, and methodological framework

2.1. Study area: Bajestan Watershed

The Bajestan Watershed is located in the southern part of Razavi Khorasan province, Iran, and is classified as an arid region (Yousefi et al., 2020; IWMI , 2019). This watershed consists of two distinct ecological zones: the plain and the playa. The plain region features relatively flat terrain and higher-quality groundwater, whereas the playa consists of dry lake beds with saline soils and clay-rich geological formations (Khazaei et al., 2018). These saline deposits significantly affect water quality, making resource management more complex. Over the last two decades, the Bajestan region has experienced notable climate shifts. According to data from the Iran Meteorological Organization (2023), the region's average annual precipitation has decreased from 160 mm in the early 2000s to approximately 110 mm in recent years, leading to severe water scarcity, especially for agricultural, domestic, and health-related uses. Simultaneously, average temperatures have risen by 1.4 °C since 2000, accompanied by increased frequency of extreme heat events. Regional climate projections (Department of Environment Iran, 2022; IPCC, 2021) suggest further warming of 1.8–2.5 °C and a 15–25 % reduction in precipitation by 2050 under moderate emission scenarios. These trends have critical implications for groundwater recharge, quality, and sustainability in hyper-arid zones such as Bajestan (Molle and Mollinga, 2003). Bajestan City, centrally located within the watershed, has a population of approximately 14,032 residents (Statistical Center of Iran, 2016). As a hyper-arid region, Bajestan depends primarily on groundwater resources, which are extracted through deep wells, traditional Qanats, and, to a lesser extent, natural springs. Qanats, an ancient irrigation system widely used in Iran, play a crucial role in sustaining water supply despite declining water tables (Behnia, 2014). The socio-economic structure of Bajestan is strongly tied to water availability, particularly in agriculture, which remains the backbone of the local economy. Farmers cultivate high-value crops, including saffron, which is known for its economic viability and relatively low water consumption (Ghazaryan and Qureshi, 2017). Given the absence of surface water resources in the region, all water demands—including agricultural irrigation, drinking, sanitation, urban green spaces and industry—are entirely met through groundwater extraction. This sole dependence on aquifers has significantly increased pressure on underground reserves, threatening their long-term sustainability and raising serious concerns about future water security (Madani et al., 2016). The geological and hydrological diversity of the Bajestan Watershed results in disparities in water availability and quality. While plains offer relatively fresh groundwater, playa areas are affected by high salinity levels, making desalination and advanced water treatment essential for ensuring safe drinking water (UNESCO, 2020). These geographical challenges highlight the critical need for an integrated water resource management strategy to balance economic development with environmental sustainability (Fig. 1: Location of Case Study in Iran).

2.2. Hydro-geological constraints on water availability in Bajestan

The Bajestan region, situated in an ultra-arid zone of eastern Iran, faces severe hydro-geological constraints that significantly affect water resource availability and quality. The watershed encompasses two dominant landscape units: the alluvial plain and the playa. The plain consists mainly of coarse-grained sediments, allowing moderate infiltration and better-quality groundwater with EC values ranging from 1000 to 3000 μm/cm. This water is primarily used for agricultural irrigation, often extracted via Qanats and deep wells.

In contrast, the playa is dominated by fine-grained alluvial deposits, with over 70 % clay content and extensive evaporitic layers—especially gypsum and salt. These geological characteristics restrict groundwater flow and result in highly saline water, with EC levels reaching up to 20,000 μm/cm. Such poor-quality water must be desalinated before it can be used for drinking or domestic purposes.

Due to the absence of surface water sources, the region relies heavily on groundwater extracted from the playa, which presents substantial logistical and economic challenges. Water must be pumped across a vertical elevation difference of over 460 m and a horizontal distance of approximately 30 km to reach the central plain. The contour lines in the following figure illustrate this elevation gradient between the saline wells in the playa and the desalination facility on the plain. This topographic configuration requires water to be lifted from the lower-lying playa to the higher-elevation plain, moving against the natural hydraulic gradient. As a result, the transfer process imposes considerable energy and operational costs (Fig. 2).

This system, managed by the Bajestan Water and Sewerage Organization and supplemented by bottled mineral water companies, underscores the urgent need for more integrated and cost-efficient water management strategies.

Furthermore, groundwater access remains unequal. While over 70 % of water in the plain is extracted through community-owned Qanats, most high-yield sources—especially deep wells—are under the control of agricultural stakeholders. Consequently, urban and public sectors often rely on high-EC wells, limiting access to safe water and intensifying social disparities. These overlapping hydro-geological, economic, and governance issues highlight the importance of strategic resource reallocation and virtual water accounting in regions like Bajestan.

2.3. Data sources, validation, and local measurement systems

The data used in this study were collected between 2019 and 2023 and are grouped into three main categories.

a) Hydrological and Hydrogeological Data

This category includes measurements from groundwater monitoring wells, discharge volumes from traditional Qanats, and salinity indicators such as electrical conductivity (EC). Data were provided by the Khorasan Razavi Regional Water Authority and supplemented with fieldwork conducted during the research period.

b) Economic and Financial Data

These datasets covered fixed and variable costs related to water transfer infrastructure (e.g., pumping stations, pipelines) and bottled water production. Records were obtained from the Bajestan Mineral

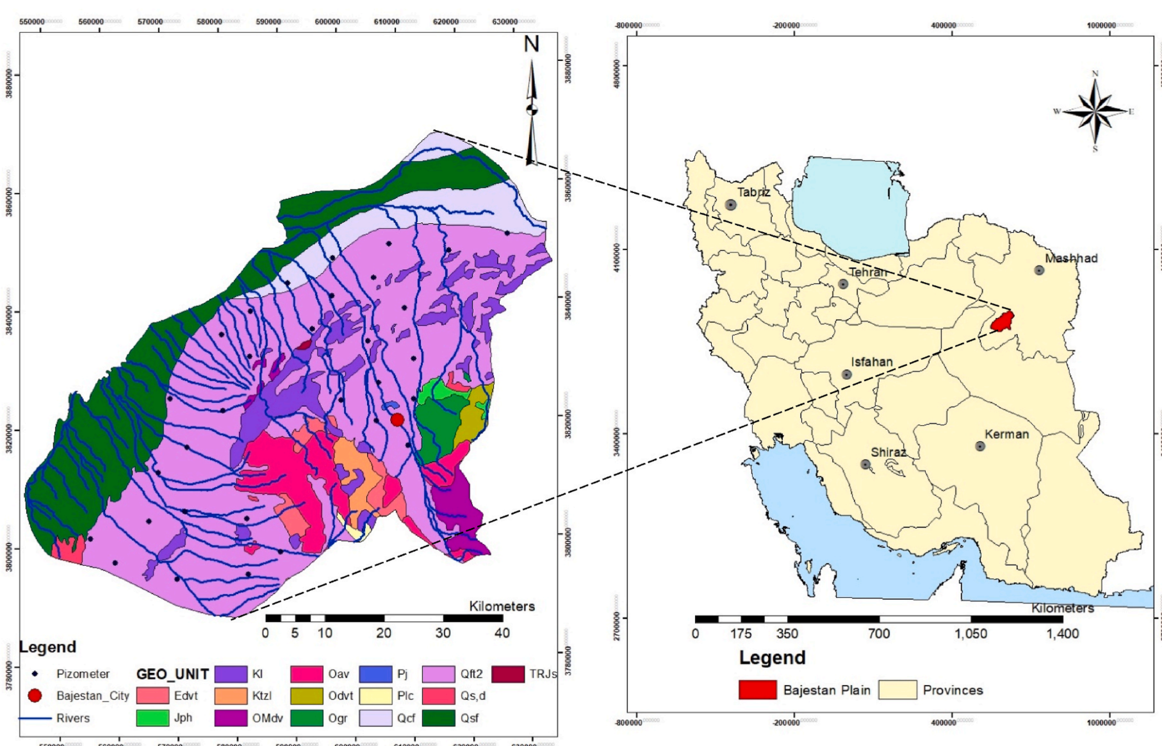

Fig. 1. Location of case study in Iran.

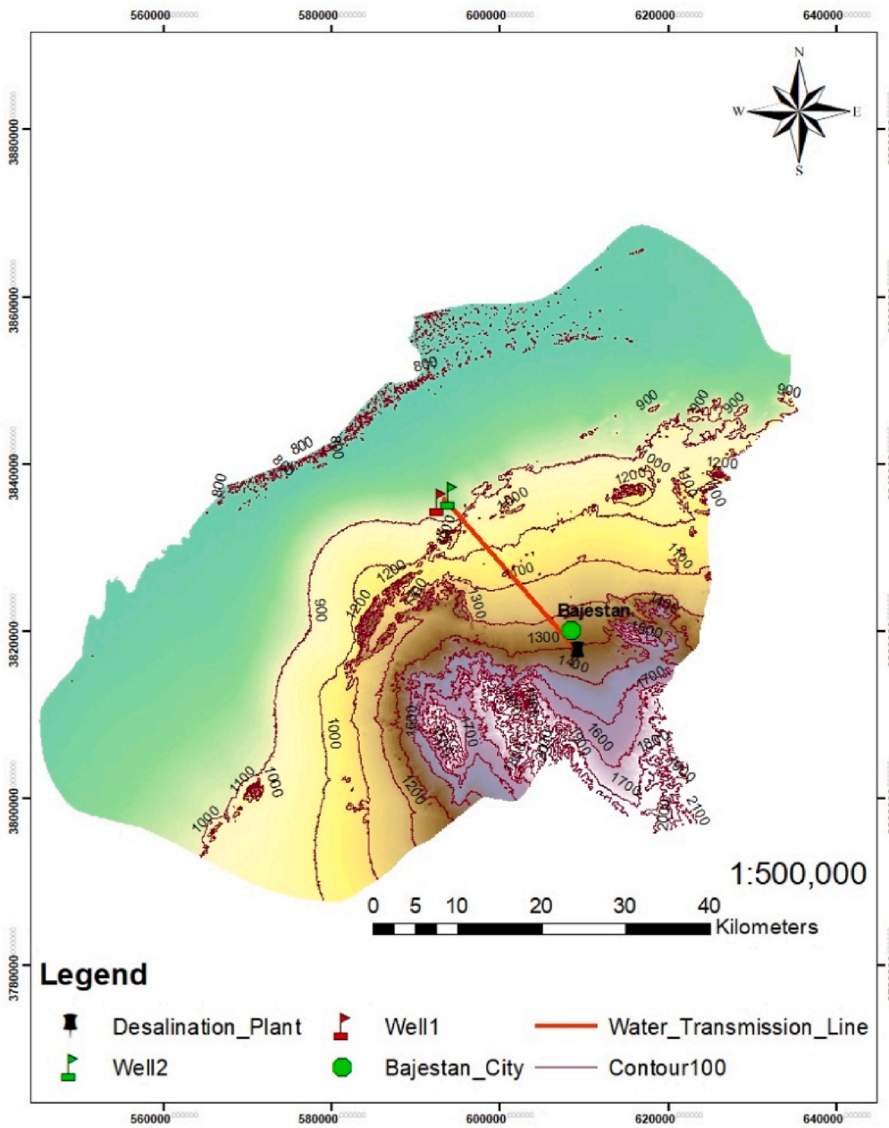

Fig. 2. Water transfer diagram from playa to plain.

Water Factory and the Urban Water and Wastewater Archive. To ensure comparability and account for inflation, all monetary values were adjusted to 2023 values using the Consumer Price Index (CPI) published by the Statistical Center of Iran.

c) Agricultural and Land-Use Data

Agricultural water usage, input costs (e.g., labor, pruning, fertilizers), production outputs, and sale prices for key crops were collected from local agricultural agencies. Particular attention was given to traditional irrigation allocation units.

- Qafiz: A traditional unit of land area in Iran, commonly used in eastern regions to denote the size of cultivated plots (e.g., one Qafiz ≈ 1000–1200 m^2 depending on local interpretation).
- Pengān: A customary water-sharing unit historically used in Qanat-based irrigation systems to allocate water rights across multiple farmers over fixed intervals.

The datasets were then incorporated into a set of economic valuation models (described in Section 2.4), including calculations for Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR), enabling comprehensive evaluation of sectoral water use.

These datasets were documented and categorized with detailed source references, ensuring the replicability of the methodology for future case studies in similarly constrained regions.

2.4. *Virtual water accounting framework*

The financial and operational data applied in the virtual water model cover the period 2019–2023, encompassing seasonal variations in water demand, cost inflation, and productivity patterns across the three target sectors.

2.4.1. *Determine the Period of Analysis (PA)*

Before conducting the economic analysis of virtual water across different sectors, it is essential to define the Period of Analysis (PA). A five-year span from 2019 to 2023 was selected based on two key criteria: operational stability in water-related infrastructure and the availability of consistent data across sectors. This timeframe minimizes the effects of inflation and exchange rate volatility in Iran, enabling more accurate estimation of economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR).

It reflects the operational and climatic conditions under which data on water supply, usage patterns, cost structures, and financial outcomes were collected and analyzed. As such, the period provides a robust basis for evaluating project performance and policy implications related to virtual water management in the Bajestan region.

2.4.2. Virtual groundwater accounting in water uses (drinking, sanitary, agriculture)

This research evaluates the economic structure of groundwater use across three key sectors in Bajestan: drinking water (supplied primarily through desalination), sanitation services, and agriculture. Emphasizing the concept of virtual water, the study integrates physical water use with economic performance indicators to assess the efficiency and sustainability of current allocation patterns in this ultra-arid region.

A set of standard financial indicators—including Net Present Value (NPV), Internal Rate of Return (IRR), Benefit-Cost Ratio (BCR), Present Value (PV), and Depreciation Costs (DCs)—was used to analyze each sector in terms of operational and capital costs, service outputs, and financial returns. These metrics help identify cost-effective strategies and support informed decision-making for water management and reallocation. These indicators collectively offer insights into the financial viability of water projects and investments in Bajestan, as detailed below.

o Depreciation Costs (DCs)

In engineering economics, capital depreciation expenses help quantify the loss of asset value over time. In this study, capital depreciation represents the decline in the RI value of the initial fixed capital over the project's lifetime. The useful life of the project is assumed to be 20 years, with a bank interest rate of 15 %. Although the economic analysis spans the five-year period from 2019 to 2023, the results presented here focus on the year 2023 as the reference year, providing the most updated and relevant data for final valuation and policy interpretation, So Investment costs have been adjusted for 2023, incorporating the latest inflation data in Iran to provide a realistic economic estimation. While future costs may fluctuate due to economic uncertainty, this study presents an approximate valuation based on current market conditions in the drinking, health, and agricultural sectors. The annual depreciation of capital is calculated as follows:

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \times A \quad \text{(Eq. 1)}$$

where.

- a = Depreciation of capital per year (RI)
- n = Useful life of the plan (years)
- A = Initial investment of the plan (RI)
- i = Bank interest rate that is (15 %)

The depreciation cost of the initial fixed capital is then aggregated with the project's total annual operating costs, providing a comprehensive estimate of annual water transfer costs.

o Present Value (PV)

The Present Value (PV) function serves as the primary economic evaluation index in this research. PV represents the current value of future financial flows, adjusted for a specific discount rate. In essence, PV reflects the capital required today to achieve a particular financial outcome in the future. The formula is as follows:

$$PV = \frac{C1}{(1+r)^n} \quad \text{(Eq. 2)}$$

where.

- C_1 = Initial investment (RI)
- r = Interest rate in this study is 15 %
- n = Analysis period (year)

PV is crucial for comparing investment options. Among multiple water supply methods, the most cost-effective approach is the one with the lowest PV value. In this research, PV serves as a benchmark for evaluating alternative water provision strategies.

o Net Present Value (NPV)

The Net Present Value (NPV) assesses the profitability of an investment project. Here, I represents the initial investment, while B_1 to B_n denote project Incomes, and C_1 to C_n represent operating costs during the analysis period:

$$NPV = PV - I = \sum_{i=1}^{n} \frac{(Bn - Cn)}{(1+r)^n} \quad \text{(Eq. 3)}$$

A project is deemed economically feasible if NPV $\geq$ 0. Conversely, a negative NPV suggests that the project lacks financial justification (Damodaran, 2012).

o Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) is defined as the discount rate at which NPV equals zero. IRR is calculated by solving the equation:

$$IRR = \sum_{i=1}^{n} \frac{(Bn - Cn)}{(1+r)^n} - I = 0 \quad \text{(Eq. 4)}$$

If IRR $\geq$ discount rate, the project is economically viable; otherwise, it is not financially sustainable (Boardman et al., 2018).

o Benefit-Cost Ratio (BCR)

The Benefit-Cost Ratio (B/C) is an economic metric that compares the present value of expected benefits with the present value of costs:

$$BCR = \frac{\sum_{t=1}^{n} \frac{Bt}{(1+r)t}}{\sum_{t=1}^{n} \frac{Ct}{(1+r)t}} \quad \text{(Eq. 5)}$$

where.

- B_t represents the expected benefits in year t
- C_t represents the costs in year t
- r is the discount rate.
- n is the total number of years in the analysis period.

A project is economically justified if BCR $\geq$1; otherwise, it is not financially viable (Devarakonda, 2019).

This detailed economic evaluation framework enables policymakers to assess investment risks and optimize resource allocation in Bajestan's water management sector. In the following sections, we examine in detail the economic structure of water uses across three key sectors—drinking water, sanitation services, and agriculture—by outlining the cost components, valuation methods, and financial indicators applied in each case. The next section focuses on the economic implications of desalination as the primary source of drinking water in Bajestan.

2.4.2.1. Drinking water. To assess the economic aspects of virtual water in Bajestan, it is essential to determine the cost of producing each cubic meter of drinking water. These costs include extraction and transportation expenses from the playa to the plain, as well as investment costs for desalination and mineral water production facilities. The overall production cost can be categorized into two main groups (Abraham and Luthra, 2011): expenses related to water extraction from wells in the playa and its transportation to the desalination plant in the plain—divided into fixed costs (FCs) and variable costs (VCs), collectively referred to as "FCs and VCs of Extracting and Transferring Water from Playa to the Plain"—and (Allan, 1997) the costs associated with the production and packaging of mineral water, also including fixed and variable components, known as "FCs and VCs in the Mineral Water Factory." Evaluating the economic feasibility of drinking water production thus requires a detailed analysis of these cost structures along with the incomes generated from water sales, particularly in the context of desalinating underground water to meet potable water demands.

Two key organizations manage the drinking water supply in Bajestan. The Bajestan Water and Sewerage Organization is responsible for transferring water from the playa to the plain and preparing it for public use. In parallel, the Mineral Water Factory handles filtration, refinement, and packaging into 0.5 and 1.5-L bottles. Clarifying the associated cost structures is essential for calculating the unit cost of bottled drinking water and understanding the embedded virtual water and energy intensity of producing potable water from brackish groundwater.

The total fixed costs (FCs) for establishing the mineral water factory are calculated using the following equation:

$$FCs = FL + MDs + POEs \tag{Eq. 6}$$

where.

- FCs = Total fixed costs (RI)
- FL = Costs associated with providing the required location and facilities (RI)
- MDs = Costs of purchasing machinery and equipment (RI)
- POEs = Pre-operation expenses, including administrative and service costs before commissioning (RI)

This equation ensures that all essential capital expenditures are accounted for in the cost analysis of the mineral water production facility.

o FCs and VCs of Extracting and Transferring Water from Playa to the Plain

As previously outlined, the extraction and transfer of water from the Bajestan Playa to the plain involve both fixed and variable costs. Fixed costs mainly include capital investments such as well construction, pipeline infrastructure, and pumping stations.

To ensure an accurate economic evaluation of fixed investments, all fixed costs have been adjusted using the Consumer Price Index (CPI) to reflect 2023 values, accounting for inflation and changes in purchasing power over time. The inflation-adjusted fixed costs (FC2023) are calculated as follows:

$$FC_{2023} = FC_{2004} \times \frac{CPI_{2023}}{CPI_{2004}} \tag{Eq. 7}$$

where.

- FC_{2023} = Inflation-adjusted fixed costs in 2023 (RI)
- FC_{2004} = Original fixed costs incurred in 2004 (RI)
- CPI_{2023} = Consumer Price Index for 2023
- CPI_{2004} = Consumer Price Index for 2004

This adjustment helps to minimize the effects of economic distortions caused by inflation and currency devaluation over time and allows for a more realistic assessment of the cost-efficiency of the water transfer system.

These are essential for enabling reliable water transfer and represent a significant share of the project's financial burden.

The annual fixed cost (AFC) is calculated by dividing the total fixed costs (FCs) by the length of the transmission path (PL) (FAO, 2009):

$$AFC = FCs/_{PL} \tag{Eq. 8}$$

In contrast, variable costs (VCs), also referred to as operating costs, encompass the ongoing expenses associated with the daily operation and maintenance of the water extraction and transportation system. These include electricity for pumping stations, personnel salaries, fuel, routine maintenance, and occasional repairs. Additionally, unexpected operational issues—such as pipeline leaks or equipment failures—can significantly increase the overall cost of water transfer.

In this study, Total Variable Costs (TVCs) were calculated as the sum of all annual variable expenditures directly associated with the operation of the water transfer system. The cost data were obtained from the official operational and financial records of the Bajestan Water and Sewerage Organization and the associated desalination plant, averaged across the study period.

Given the increasing demand for water in Bajestan, understanding these fixed and variable costs is crucial for assessing the economic sustainability of the water supply system. The total annual transfer cost (TATC) is calculated using Equation (9):

$$TATC = TVCs + AFC \tag{Eq. 9}$$

By accurately analyzing these costs, this study provides a financial framework for evaluating the long-term feasibility of the water transfer project in Bajestan.

o FCs and VCs in the Mineral Water Factory

The establishment of a mineral water production facility involves not only water supply and transfer costs but also construction, equipment, and operational expenses. Similar to other investment projects, the costs of setting up a mineral water factory are categorized into Fixed Costs (FCs) and Variable Costs (VCs).

Fixed costs (FCs) include land acquisition and facility construction, purchasing machinery and equipment, and pre-operational services and formalities. These costs represent the initial capital investment necessary for the establishment of the production line.

This mineral water factory is designed to produce 1500 bottles per day in 0.5 and 1.5-L sizes, operating 312 working days per year. The ongoing operational expenses include raw materials, salaries, maintenance, water procurement, electricity, and logistics, collectively categorized as variable costs (VCs). The total variable costs are calculated using the following equation:

$$VCs = RM + ES + MCs + WCs + ECT \tag{Eq. 10}$$

where.

- VCs = Sum of variable costs (RI)
- RM = Raw Materials (RI)
- ES = Employee's Salary (RI)
- MCs = Maintenance Costs (RI)
- WCs = Water Costs (RI)
- ECT = Electricity & Communications Transportation (RI)

o Income Calculation for the Mineral Water Factory

To evaluate the economic feasibility of the mineral water factory, it is necessary to determine its potential income streams. With a daily production capacity of 4 m^3, and assuming 312 working days per year, the annual production volume reaches approximately 1000 m^3. This volume is bottled and sold in 0.5- and 1.5-L packages by specialized mineral water companies. The income of the factory is thus derived from the total annual production of bottled water and its unit price in the consumer market.

To analyze the profitability of this process in the context of virtual water accounting, we calculate the price per cubic meter of bottled water (PW), expressed in Million RI/m^3/yr, based on production and distribution data.

- TAPs refer to the Total Annual Productions of bottled water, expressed in liters (i.e., 1000 $m^3 \times 1000 = 1,000,000$ L).
- DCs represents the *Distribution Costs*, including expenses related to packaging, labeling, warehousing, and transporting the bottled water to distribution points.

Accordingly, the price per cubic meter of bottled water is calculated using the following equation:

$$PW = \frac{VCs + DCs}{TAPs} + \frac{FCs}{PA \times TAPs} \quad \text{(Eq.11)}$$

2.4.2.2. Sanitary water. The sanitary water supply for Bajestan originates from the edge of the Bajestan Playa. In this study, the term "Sanitary Water" refers to non-potable water used for domestic hygiene purposes such as washing, cleaning, and toilet flushing. It is distinct from both drinking water and wastewater (i.e., water discharged after use).

By addressing the significant energy demand associated with water transfer across rugged topography, upon arrival, the water undergoes basic purification, including chlorination and microbial treatment, before being distributed through the sanitary water network. However, no desalination is performed, meaning that its high salinity remains a concern for various applications.

The electrical conductivity (EC) of the water entering the treatment plant is approximately 7500 μm/cm, which is the same level present in the sanitary water network. Given the limited treatment process, this water is primarily used for non-drinking purposes, such as sanitation and irrigation. The cost per cubic meter of sanitary water is largely determined by the combined fixed and variable costs associated with water supply and extraction.

Fixed Costs (FCs) represent the initial capital expenditures related to the water transfer and extraction infrastructure, while Variable Costs (VCs) include ongoing operational expenses such as manpower, energy, consumables, taxes, and sanitary water network maintenance. The estimated price per cubic meter (m^3) of sanitary water (BSW) is calculated using the following equation, where PA is the affected population and DPSW is the daily per capita sanitary water consumption (m^3/person/day):

$$BSW = \frac{VC_S + FC_S}{PA \times (365 \times DPSW)} \quad \text{(Eq.12)}$$

where.

- BSW = Price of Brackish Sanitary Water (RI/m^3/year)
- ΣVCs = Total Variable Costs (RI)
- FCs = Fixed Costs (RI)
- PA = Period of Analysis (years)
- DPSW = Daily Per Capita Sanitary Water Consumption (m^3/day)

o Income Calculation for Sanitary Water

To analyze the economic indicators of virtual water in sanitary water use, it is necessary to determine the total Income generated. The Bajestan Water and Wastewater Company is responsible for selling each cubic meter of sanitary saline water. The total annual income is calculated as follows:

$$DI = DPSW \times \text{P} \quad \text{(Eq. 13)}$$

$$AI = DI \times 365 \quad \text{(Eq. 14)}$$

where.

- DI = Daily income from selling sanitary water (RI)
- DPSW = Daily per capita sanitary water (m^3)
- P = Population of Bajestan city
- AI = Annual income from selling sanitary water (RI)

By incorporating these economic calculations, this study provides a detailed assessment of the financial feasibility of Bajestan's sanitary water system and its implications for virtual water management.

2.4.2.3. Agricultural water use. Agriculture plays a vital role in the economy of Bajestan, where the majority of the population is engaged in farming activities. The primary source of agricultural water in the Bajestan Plain comes from three Qanats that supply high-quality groundwater. However, a significant portion of these groundwater resources is privately owned, creating challenges in ensuring equitable access to water. More than 94 % of the available water in this region is used for agricultural purposes, exerting considerable pressure on water resources. Notably, higher-quality water from the Qanats is predominantly allocated to agriculture, as these systems are owned and managed by local farming communities. The traditional irrigation system in Bajestan relies on ancient water measurement units, which define both the time-based allocation of water and land area calculations. The Pengān is a historical unit used to measure water flow, where one Pengān corresponds to approximately 4.5 min of continuous water discharge from a Qanat, Pengān, a traditional irrigation allocation tool still used in parts of Bajestan, exemplifies historical groundwater-sharing customs (see Supplementary Figure S_1). Additionally, land area is measured using the Qafiz, with each Qafiz covering 366 m^2 (Yazdi and Khaneiki, 2019). These customary units are still used in official records by local agricultural cooperatives, enabling realistic quantification of water usage and land productivity in economic models.

The number of Pengāns required per Qafiz varies based on the type of crop and its irrigation needs. For instance, pomegranate and saffron each require two Pengāns per Qafiz, whereas pistachios require only one Pengān per Qafiz. The interval between each irrigation cycle, known as the "Irrigation Cycle," typically ranges from 10 to 21 days, depending on the crop type and seasonal conditions. Understanding the specific irrigation needs of each crop allows for precise calculation of water consumption and costs.

The total flow rate of the three Qanats supplying water to the Bajestan Plain is 65 L per second. In this study, we calculated the volume of water required per Qafiz and the annual water cost per agricultural product using the following formulas.

The total irrigation time required per year (TU) is determined as:

$$TU = NI \times \text{Y} \times \text{t} \quad \text{(Eq. 15)}$$

where.

- TU = Total time using Pengān (minutes)
- NI = Number of irrigation cycles
- Y = Yield (RI)
- t = time (minutes)

Using this, the annual volume of water consumed (Va) is calculated as:

$$Va = TU \times \text{Q} \quad \text{(Eq. 16)}$$

where.

- V_a = Volume of water used (m^3)
- TU = Total time using Pengān (minutes)
- Q = flow rate (m^3/s)

The total cost of agricultural water for each crop per Qafiz per year (Ct) is calculated as:

$$Ct = C \times \mathrm{TU} \tag{Eq. 17}$$

where.

- C_t = total cost of agricultural water for each yield in the unit of Qafiz per year Pengān in RI/yr for each yield (RI)
- C = Cost of each Pengan per year (RI)
- TU = Total time using Pengān (minutes)

Finally, the annual income (I) for each crop is determined based on average production per Qafiz (APQ) in kg and the unit selling price (Up) in RI for 2023:

$$I = Up \times \mathrm{APQ} \tag{Eq. 18}$$

These calculations allow for an economic evaluation of water allocation in agriculture, providing insights into cost efficiency, profitability, and water resource sustainability. Understanding the economic value of agricultural water across different regions will aid in improving water allocation policies and enhancing long-term water management practices.

All economic indicators and calculations presented in this study were directly informed by empirical datasets obtained from local institutions, including groundwater discharge records, cost sheets from municipal and private water providers, and agricultural input-output data. This integration ensures both contextual relevance and reproducibility of the results.

2.5. Methodological framework: economic implications of desalination

The outcome of this method is further evaluated in the results section to determine financial feasibility and sectoral trade-offs.

This study evaluates the economic impact of desalination by calculating the cost per cubic meter of drinking water, incorporating expenses related to water extraction, transfer, treatment (desalination), and bottling. These calculations are embedded within a broader virtual groundwater accounting framework that aims to assess the real economic burden of water provision across multiple sectors in Bajestan.

To conduct this assessment, we compared the actual cost of producing drinking water with its applications across municipal, domestic, and agricultural uses. This analysis helps distinguish between the nominal price paid by users and the true economic cost of water, which includes sourcing, treatment, energy input, infrastructure maintenance, and distribution. Identifying discrepancies between market prices and actual costs reveals inefficiencies in water pricing, particularly in hyper-arid settings where resource constraints demand strategic allocation.

By incorporating virtual water accounting, this study provides a comprehensive view of the hidden economic costs embedded in groundwater use. Virtual groundwater accounting not only quantifies volumetric use but also contextualizes water value based on financial viability and sectoral priorities. For example, desalinated water—due to its high energy and capital costs—may be economically justified for essential uses such as drinking and sanitation, but not for agriculture or landscaping.

All financial calculations in this study are presented in Iranian Rials (RI) to reflect the local economic context. In 2023, the exchange rate fluctuated around 500,000 RI per 1 USD. Due to substantial currency devaluation and the impact of international sanctions, expressing costs in USD would significantly distort the perceived economic burden for Iranian stakeholders. It could also create the false impression of low water prices in global terms, thereby undermining the urgency of local water valuation challenges. Maintaining all monetary values in RI ensures contextual accuracy and preserves the integrity of the economic analysis.

Understanding groundwater cost structures is particularly important in hyper-arid regions such as Abu Dhabi, where extraction and treatment costs often exceed global norms (Dawoud, 2020). Applying similar logic in Bajestan, virtual groundwater accounting can serve as a decision-support framework by aligning virtual water volumes with economic indicators such as Benefit-Cost Ratio (BCR), Net Present Value (NPV), and Internal Rate of Return (IRR). This approach enables managers to assess trade-offs and make informed choices regarding sectoral water allocation.

Ultimately, virtual groundwater accounting functions not only as a measurement tool but also as a strategic planning instrument. By revealing inefficiencies and highlighting opportunities for reallocation, it can guide more sustainable and equitable water management policies in resource-scarce environments like Bajestan.

3. Results and discussion

3.1. Analysis of virtual water accounting

3.1.1. Drinking water

- o FCs and VCs of Extracting and Transferring Water from Playa to the Plain

Although the economic analysis spans the five-year period from 2019 to 2023, the results presented here focus on the year 2023 as the reference year, providing the most updated and relevant data for final valuation and policy interpretation.

Based on the methodology described earlier (Equation (7)), the inflation-adjusted fixed costs for the water transfer infrastructure were estimated. The total fixed costs for transferring water to the plain amount to 196,777,557,020 RI in 2023 values. This figure includes capital investments such as well construction, installation of pumping equipment, and infrastructure required for water transportation from the playa to the plain.

The fixed costs cover a broad range of expenses, including.

- Well construction
- Installation of pumping equipment
- Development of infrastructure required for water transportation

Additionally, the total variable costs (TVCs) for extracting and transferring water to the plain have been calculated at 4,530,628,482 RI.

To ensure a systematic economic evaluation over the project's lifespan, which is projected to be five years, it is necessary to calculate costs on an annual basis.

Based on Equation (2) (AFC = FCs/PL), the Annual Fixed Cost (AFC) for water transfer in Bajestan is calculated to be 6,925,335,274.7 RI, reflecting the amortized annual burden of fixed infrastructure investments over the 30-km transmission route.

The Total Annual Transfer Cost (TATC) as we mentioned in equation (3) is amounts to 11,455,963,756.7 RI. This value provides a clear understanding of the financial requirements for sustaining water transfer operations in the Bajestan region.

- o FCs and VCs in the Mineral Water Factory

The selection of an optimal location for the mineral water plant is a key factor in ensuring operational efficiency. The site must be strategically positioned near distribution centers, transportation routes, and water sources to minimize logistical and operational costs.

The fixed costs (FCs) associated with constructing the factory are categorized into three main components.

1. Infrastructure and Facilities: This includes construction of production halls, warehouses, and administrative offices.
2. Machinery and Equipment: This category covers packaging machines (triblock machines, labelers, UV sterilizers), reverse osmosis (RO)

water purification systems, loading lifts, and conveyor belts. Additionally, the factory operates with two storage tanks: a 400 m^3 capacity tank and a 10,000-L polyethylene tank.

3. Pre-Operational and Administrative Costs: These involve legal and administrative fees, permits, and registration costs for establishing the factory.The total fixed costs (FCs) for establishing the mineral water factory were estimated at 12,018,800,000 RI. Incorporating depreciation, the annual capital depreciation cost (DCs) was calculated as 3,559,969,743 RI. The total variable costs (TVCs) for the factory's annual operation reached 8756.04 million RI. A detailed breakdown of these figures is available in Supplementary Tables S1 and S2.

With a daily production capacity of 4 m^3, the annual production volume is 1000 m^3 (based on 312 working days). The price per cubic meter of bottled water (PW) is determined using equation (5) is 45.95 RI/m^3/yr.

o Income Calculation for the Mineral Water Factory

To estimate monthly and annual Income, we consider production volumes for 0.5L and 1.5L bottles, while factoring in a 4 % loss due to manufacturing waste (Table 1).

The results of the economic evaluation indicate that desalination-based bottled water production is not financially viable. Table 2 presents the Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR).

The negative NPV indicates that the project does not generate sufficient financial returns to cover its investment and operational costs. Furthermore, the IRR is not meaningful because the net cash flow remains negative throughout the analysis period, making it impossible to identify a positive discount rate that satisfies the IRR equation.

Additionally, the BCR value is less than one, confirming that the project is economically unfeasible.

However, the financial outlook could improve if desalination is avoided by sourcing water from lower-salinity aquifers in the plain region. Furthermore, securing direct ownership or long-term leases of these wells could reduce both operational dependency and treatment costs.

The calculated costs of desalinated water reflect not only economic inefficiency but also an inflated virtual water footprint for drinking purposes, emphasizing the need to reassess its allocation in the context of essential versus non-essential uses.

For comparative purposes, international benchmarks offer additional perspective. According to Dawoud et al. (2024), the capital cost of reverse osmosis desalination systems typically ranges from 800 to 1000 USD per cubic meter of installed capacity. Operational costs generally fall between 0.45 and 0.65 USD per cubic meter of water produced, and average energy consumption ranges from 3.0 to 4.0 kWh per cubic meter. While direct currency conversion is not appropriate in the Iranian context due to high inflation and exchange rate instability, these figures provide a useful frame of reference.

From a virtual water perspective, these international benchmarks further highlight the embedded energy and capital intensity of desalinated water, reinforcing the argument for allocating scarce groundwater resources toward more socially essential and hydrologically efficient uses.

Table 1
Estimation of income based on bottle type (2023).

Annual Loss Rate (Million RI)	Annual Production Income (Million RI)	Type of Bottles
561,600	14,040,000	0.5 Lit
312,000	7,800,000	1.5 Lit

Source: Bajestan Mineral Water Factory

While bottled water remains the dominant and measurable source for drinking in Bajestan, exploring decentralized, small-scale water treatment solutions could reduce both economic and virtual water costs and merits further investigation. Previous field-based investigations of drinking water access in Bajestan confirm the widespread reliance on bottled water despite the introduction of other decentralized options (Mohammadzadeh et al., 2024).

3.1.2. Sanitary water

o FCs and VCs of Extracting and Transferring Water from Playa to the Plain

In the drinking and health sector, the virtual water cost of supplying sanitary water per cubic meter is directly related to the provision of transitional saline water, which does not require desalination. This water cost captures not only the physical volumes used but also the embedded energy and infrastructure resources required to make water accessible. These costs were estimated using financial reports from project implementation and include two main categories: fixed costs (FCs)—representing initial capital investments—and variable costs (VCs)—covering ongoing operational expenses.

The water transfer and extraction project began in 2014, with initial fixed costs amounting to 15,098,337,477 RI. However, due to inflation and currency fluctuations, the Consumer Price Index (CPI) adjustment was applied to ensure that these costs are evaluated based on 2023 economic conditions. The inflation-adjusted total fixed cost was calculated using Equation (7), based on the CPI escalation between 2014 and 2023. Using this adjustment, the final fixed cost for 2023 was estimated at 322,899,520,610 RI. This significant increase reflects the financial commitment required for establishing a sustainable water extraction infrastructure, including pipelines, pumping stations, and operational equipment.

The variable costs, on the other hand, were directly recorded in 2023 and therefore did not require CPI adjustment. These include expenses for electricity, labor, maintenance, and operational services, as detailed in Table S3, titled "Variable Costs for Supplying and Transferring Water to the Plain in 2023."

The total variable cost of transferring sanitary water in 2023 was 8.62 billion RI. The cost breakdown—including electricity, labor, and maintenance—is provided in Supplementary in Table S3.

Given a daily extraction capacity of 40 m^3, the total annual cost of water supply consists of both fixed (FCs) and variable costs (VCs) associated with extraction and transfer.

From a virtual water perspective, these capital and operational investments represent the hidden cost of making sanitary water physically and economically available in hyper-arid regions.

To determine the price per cubic meter of sanitary water (BSW) in 2023, The calculated price per cubic meter of sanitary water in 2023 was 607,627.95 RI, whereas the price charged to consumers remains at 11,000 RI per cubic meter.

The price per cubic meter of water for this section is set at 11,000 RI for consumers. According to available statistics, Bajestan has a population of 14,032, with a daily per capita consumption of 110 L. Consequently, the company's daily Income from potable water amounts to 16,978,720 RI, leading to an annual Income of 6,197,232,800 RI. Based on these cost and Income calculations, the profit-to-cost ratio for the potable water sector in 2023 was determined to be 0.182, as shown in Table 3.

The findings from Table 3 reveal a major disparity between the reported available cost of water (11,000 RI/m^3) and the actual cost (607,627.95 RI/m^3). This results in a profit-to-cost ratio of 49.5, indicating a severely unsustainable water supply model.

Key Implications.

Table 2
Final evaluation of the Bajestan brackish water desalination project based on economic indicators (2023).

BCR	IRR	NPV (Million RI)	PV (Annual Selling Price of Water per m^3 in Million RI)	Initial Investment Cost (RI)	Distribution Costs (m^3/RI)
0.46	Not Defined	−422,184,979,434	27,474,307,883	20,966,400	449,659,287,317

Table 3
Calculating the Profit-to-Cost Ratio in the current method of drinking water supply and distribution.

Water Usage Type	Cost per Cubic Meter (Available) (RI)	Actual Cost per Cubic Meter (RI)	Daily Water Consumption Volume (m^3)	Daily Water Cost per Urban Population (Available) (RI)	Daily Water Cost per Urban Population (Actual) (RI)	Ratio of Actual Cost to Available Cost
Sanitary	11,000	607,627.95	1543.52	16,978,720	93,283,042	49.5

1. Financial Unsustainability: The current pricing model does not reflect actual costs, creating financial instability for water supply authorities.
2. Policy Reevaluation: Policymakers must reassess water pricing to align it with real costs, ensuring sustainable management. Historically, water pricing in Iran has been based on heavily subsidized, fixed tariffs that do not account for the real costs of extraction, transfer, treatment, and infrastructure maintenance. While adjusting prices to reflect actual costs is essential for financial sustainability, it must be accompanied by a tiered pricing model that considers the financial capacity of various users to avoid adverse social impacts and ensure equitable access.
3. Resource Allocation: Accurate cost assessments can help authorities make informed decisions about investment in infrastructure.
4. Consumer Awareness: Educating consumers on the real cost of water can lead to more responsible usage and conservation efforts.
5. Long-Term Sustainability: Addressing cost disparities is crucial to ensuring an economically and environmentally sustainable water supply system. In addition to aligning prices with real costs, it is also necessary to conduct cost-benefit assessments from the perspective of end-users—particularly local farmers—to ensure that pricing strategies are perceived as fair, feasible, and socially acceptable.

This analysis underscores the urgent need to align water prices with real economic conditions to promote financial sustainability, improve consumption behavior, and ensure efficient resource management in urban areas. Despite water scarcity, heavily subsidized tariffs have contributed to inefficient and sometimes excessive water use, particularly in non-agricultural sectors of Bajestan.

While the provision of sanitary water relies on untreated brackish sources, the virtual water footprint of this practice remains high due to substantial energy inputs and infrastructure costs. This highlights the inefficiency of using low-quality groundwater for basic health-related services, and underscores the need to explore alternative low-footprint solutions.

3.1.3. *Agricultural water*

o Calculate the costs for yields

The total water flow from three Qanats is utilized for irrigation in the Bajestan Plain, where water distribution is determined by traditional measurement units such as Qafiz (land area) and Pengān (water allocation unit). The cost of purchasing or renting each Pengān (C) is approximately 8,000,000 RI per year, which forms the basis for calculating total agricultural water costs per Qafiz annually (Ct). Table 4 provides an overview of water costs associated with different crops.

To determine the real cost of agricultural production, additional inputs such as fertilizers, labor, pesticide spraying, and irrigation costs must be considered. For example, annual input costs per Qafiz for pomegranate and pistachio were estimated at 3.5 million RI, while saffron required only 1 million RI. Full cost breakdowns are presented in Supplementary Table S4.

Table 4
Water cost needed for agricultural yields in Bajestan plain (in RI) per Qafiz for the year 2023

Yield	TU	NP	TU (min)	Volume (m^3/yr)	Cost (Million RI/yr)	Total Cost (RI/yr)
Pomegranate	2	21	189	737.1	16	16,000,000
Saffron	2	2	18	70.2	16	16,000,000
Pistachio	1.5	12	81	315.9	12	12,000,000

o Income from Agricultural Products and Calculation of Profit-to-Cost Ratio

Table 5 presents the annual income per Qafiz from key agricultural products cultivated in Bajestan Plain. The results reveal significant variation in economic returns. Saffron, with an annual income of 60,000,000 RI per Qafiz, demonstrates the highest profitability despite its low water requirement, highlighting its suitability for hyper-arid regions. In contrast, pomegranate generates only 35,000,000 RI per Qafiz, while pistachio matches saffron in income (60,000,000 RI) but typically demands more water and longer cultivation cycles. These findings support a shift toward cultivating high-return, low-water-demand crops—like saffron—as a strategy to optimize agricultural water use and enhance economic sustainability in water-scarce regions.

3.1.4. *Economic feasibility of agricultural water use*

To evaluate the profitability of different agricultural yields, the profit-to-cost ratio (BCR) was calculated based on income per Qafiz (Table 6).

These results indicate that saffron is the only economically viable crop in Bajestan, with a BCR of 2.21, while pomegranate (0.76) and pistachio (0.89) are not cost-effective. Given these findings, a shift towards low-water-demand crops is recommended. Considering saffron's compatibility with local agroecological conditions, its low water requirements, and sustained high market value, its large-scale adoption can maintain profitability and enhance water-use efficiency in the region.

The analysis reveals that a significant portion of high-quality

Table 5
Income from agricultural products in Bajestan plain (in RI) per Qafiz for the year 2023

Product	Production Amount (Kg)	Unit Price (RI)	Annual Income (RI/yr)
Pomegranate	500	70,000	35,000,000
Saffron	20	3,000,000	60,000,000
Pistachio	150	400,000	60,000,000

Table 6
Agricultural product incomes per Qafiz (2023).

Yield Name	Total Profit (RI/yr)	Total Cost (RI/yr)	BCR
Pomegranate	35,000,000	45,700,000	0.76
Saffron	60,000,000	27,100,000	2.21
Pistachio	60,000,000	67,400,000	0.89

Based on cost and Income calculations, the BCR values for each crop are outlined in Table 6.

groundwater is allocated to crops with low economic returns. From a virtual groundwater accounting perspective, this reflects a misalignment between water value and usage, suggesting that optimizing crop selection based on both economic output and water efficiency is critical for sustainable resource management.

3.2. Economic implications of desalination

Desalination has become a necessary response to water scarcity in Bajestan, particularly through the use of reverse osmosis (RO) technology. However, the infrastructure and operational costs associated with this approach are substantial. In 2023, the cost of producing 1 L of desalinated water reached 45,067 Iranian Rials, underscoring the significant financial burden placed on both municipalities and consumers. This elevated cost exerts considerable pressure on municipal budgets and may require increases in water tariffs, potentially diverting public funds from other essential services such as education and healthcare.

Furthermore, desalination is highly energy-intensive and is often powered by fossil fuels, particularly heavy fuel oil (mazut). This dependency not only raises economic costs but also contributes to environmental degradation. In a country like Iran, where the energy sector is largely reliant on such fuels, widespread adoption of desalination runs counter to sustainability goals unless more energy-efficient and cleaner technologies are implemented.

From an economic standpoint, current desalination projects lack financial viability when assessed using standard financial indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR). The negative NPV reflects that high capital and operational expenditures outweigh potential revenues, while consistently negative cash flows over the analysis period render the IRR undefined, indicating no feasible discount rate at which the project would break even. These findings highlight the financial risk associated with continuing investments in large-scale desalination initiatives.

From the perspective of virtual water, the inefficiency of allocating substantial financial and environmental resources to desalinated water becomes even more evident—especially when such water is used for low-priority sectors or bottled consumption. This reinforces the need to reconsider how water resources are valued and distributed.

In the agricultural sector, which remains the primary consumer of groundwater in Bajestan, many of the dominant crops—such as pistachios and pomegranates—are not only water-intensive but also economically inefficient. Saffron presents a more sustainable alternative due to its low water requirements and high market value. Nonetheless, expanding saffron cultivation must be approached cautiously, given the region's increasing reliance on saline groundwater and the declining recharge of traditional qanat systems. These constraints limit the scalability of any single-crop strategy.

A gradual transition toward more sustainable cropping patterns is essential. This transition should prioritize crops like saffron while taking into account the region's hydrogeological limitations. Virtual water accounting can serve as a valuable tool in guiding this process by helping maximize the economic return per unit of water used and promoting long-term resilience of water resources.

To move forward, several policy recommendations emerge. First, water pricing reform is essential to ensure that tariffs reflect the actual cost of production, thereby improving financial sustainability. Second, a shift toward low-water-demand agriculture must be encouraged, with careful consideration of groundwater availability and long-term viability. Third, virtual water indicators should be integrated into resource planning to better capture hidden economic and environmental costs and to enhance cross-sectoral water allocation. Finally, it is critical to invest in alternative water strategies, such as decentralized wastewater reuse and managed aquifer recharge, which offer significantly lower virtual water and energy footprints compared to centralized desalination systems.

4. Conclusion

Effective water management in hyper-arid regions like Bajestan demands a shift from volume-based to value-based groundwater allocation. This study applied a virtual groundwater accounting framework integrated with economic indicators (NPV, IRR, BCR) to evaluate sectoral water use. The results reveal a stark misallocation: agriculture consumes over 94 % of high-quality groundwater, while saline water is reserved for drinking and sanitation—despite its high treatment costs and energy footprint.

Our analysis shows that desalinated bottled water is economically unfeasible, with a negative NPV of −422 billion RI, undefined IRR, and a BCR of 0.46. The price per cubic meter of sanitary water reached 607,628 RI in 2023, while consumers pay only 11,000 RI—a price-to-cost ratio of 49.5. These findings underscore the urgent need to reform water pricing systems to better reflect real production costs. However, such reforms must remain socially inclusive by considering affordability and the economic capacities of end-users—particularly farmers and rural households.

In agriculture, saffron demonstrated a BCR of 2.21, significantly outperforming pomegranate (0.76) and pistachio (0.89), while also requiring far less water. This evidences the economic and hydrological efficiency of shifting toward low-water-demand crops. Yet, the continued dominance of water-intensive crops points to a lack of awareness and weak incentives for change.

To address these issues, the study recommends integrated strategies.

(i) realigning cropping patterns through gradual policy incentives favoring crops like saffron,
(ii) applying tiered pricing models that balance cost recovery with social equity,
(iii) mainstreaming virtual water indicators in decision-making frameworks to capture hidden economic and environmental costs, and
(iv) investing in decentralized, low-energy water treatment systems (e.g., wastewater reuse, managed aquifer recharge), adapted to Bajestan's climate and infrastructure limits.

This dual valuation—capturing both physical scarcity and embedded economic value—offers a replicable framework for water allocation in other hyper-arid regions facing similar groundwater salinity, subsidy dependence, and governance challenges. Ultimately, aligning economic signals with hydrological realities through virtual water accounting can help achieve more equitable, efficient, and climate-resilient water governance.

CRediT authorship contribution statement

Fatemeh Mohammadzadeh: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammad Reza Ekhtesasi:** Writing – original draft, Visualization, Supervision, Formal analysis, Conceptualization. **Jessen George:** Visualization, Software, Conceptualization. **Fei Zhang:** Writing – original draft, Visualization, Data curation, Conceptualization. **Kevin Harding:** Writing – review & editing, Writing – original draft, Supervision, Data curation,

Conceptualization.

Conflict of interest statement

We, the undersigned authors of the manuscript titled *"Economic Valuation of Virtual Groundwater in Hyper-Arid Regions of Iran,"* declare that we have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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We confirm that no external funding was received for this research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100835.

Data availability

Data will be made available on request.

References

Abraham, M.A., Luthra, K., 2011. Desalination technologies and economic viability: a study for brackish water desalination. Int. Rev. Bus. Res. Pap. 7 (1), 172–182.
Allan, J.A., 1997. Virtual water: a strategic resource in water-scarce countries. Groundwater 35 (1), 11–16.
Bacro, J.N., Chaouche, A., 2006. Climate variability and uncertainty: impacts on water management in the Mediterranean region. Clim. Res. 32 (2), 189–199.
Behnia, P., 2014. Qanat: a sustainable groundwater system in Iran. J. Hydrol.
Boardman, A.E., Greenberg, D.H., Vining, A.R., Weimer, D.L., 2018. Cost-Benefit Analysis: Concepts and Practice, fifth ed. Cambridge University Press.
Damodaran, A., 2012. Investment Valuation: Tools and Techniques for Determining the Value of Any Asset. John Wiley & Sons.
Dawoud, M.A., 2020. Groundwater economics in arid regions: Abu Dhabi case study. Desalination Water Treat. 192, 243–250. https://doi.org/10.5004/dwt.2020.25456.
Dawoud, M.A., Elsheikh, A., Soliman, H., Fathy, M., 2024. The performance and feasibility of solar-powered desalination for brackish groundwater in Egypt. Water 16 (3), 411. https://doi.org/10.3390/w16030411.
De Giglio, O., Posa, M., De Santis, M., 2015. Bottled water consumption in Italy: a market analysis driven by health concerns. J. Consum. Aff. 49 (3), 523–543. https://doi.org/10.1111/joca.12087.
Delpla, I., Jung, A.V., Baures, E., Clement, M., Thomas, O., 2009. Impacts of climate change on surface water quality in relation to drinking water production. Environ. Int. 35 (8), 1225–1233.
Department of Environment Iran, 2022. Regional climate risk assessment for arid and semi-arid zones of Iran. Tehran: DoE Reports.
Devarakonda, S., 2019. Calculating the economic viability of corporate trainings (traditional & eLearning) using benefit-cost ratio (BCR) and return on investment (ROI). International Journal of Advanced Corporate Learning 12 (1), 41–57.
FAO, 2009. Economic analysis of water supply projects. FAO Investment Centre. Food and Agriculture Organization of the United Nations, Rome.
Garfí, M., Cadena, E., Sanchez-Ramos, D., Ferrer, I., 2016. Life cycle assessment of drinking water: comparing conventional water treatment, reverse osmosis, and mineral water in glass and plastic bottles. J. Clean. Prod. 137, 997–1003.
Ghaffour, N., Missimer, T.M., Amy, G.L., 2013. Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. Desalination 309, 197–207.
Ghazaryan, D., Qureshi, A.S., 2017. Water productivity of saffron in eastern Iran. Agric. Water Manag.
Gleeson, T., Wada, Y., Bierkens, M.F.P., van Beek, L.P.H., 2012. Water balance of global aquifers revealed by groundwater footprint. Nature 488 (7410), 197–200. https://doi.org/10.1038/nature11295.
Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by source and production and consumption patterns. Water Resour. Manag. 21 (1), 35–48. https://doi.org/10.1007/s11269-006-9039-x.
Intergovernmental Panel on Climate Change, 2021. Sixth Assessment Report: Climate Change 2021 – the Physical Science Basis. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/.
Iran Meteorological Organization, 2023. Annual Climate Bulletin: Precipitation and Temperature Trends in Arid Regions. IMO Publications, Tehran.
IWMI (International Water Management Institute), 2019. Groundwater Assessment in Iran.
Karagiannis, I.C., Soldatos, P.G., 2008. Water desalination cost literature: review and assessment. Desalination 223 (1–3), 448–456.
Khazaei, M., et al., 2018. Soil salinity and land use in arid playas of Iran. Geoderma.
Kinzelbach, W., et al., 2003. Groundwater resources and water management: research needs in hyper-arid regions. Hydrogeol. J. 11 (1), 287–300. https://doi.org/10.1007/s10040-003-0250-4.
Lionello, P., Malanotte-Rizzoli, P., Boscolo, R., 2006. The Mediterranean climate: an overview of the present and future climate change impacts. Reg. Environ. Change 6 (3–4), 193–205. https://doi.org/10.1007/s10113-006-0020-5.
Madani, K., et al., 2016. Water management in Iran: what is causing the crisis? J. Environ. Stud.
Mohammadzadeh, F., Ekhtesasi, M.R., Hosseini, S.Z., 2024. Feasibility of sustainability separation of drinking water network by groundwater desalination Bajestan urban catchment, Iran. Groundw. Sustain. Dev. 26, 101227. https://doi.org/10.1016/j.gsd.2024.101227.
Molle, F., Mollinga, P.P., 2003. Water poverty and policy in arid regions. Water Int.
Romano, S., Nasta, P., Luongo, F., 2018. Water scarcity and agricultural stress: impacts of climate change in the Middle East. Environ. Sci. Pol. 84, 77–86. https://doi.org/10.1016/j.envsci.2018.02.014.
Statistical Center of Iran, 2016. National Census of Population and Housing.
UNESCO, 2020. Desalination and Water Reuse in Arid Areas.
Vaccaro, J.J., 1992. Groundwater management: Over-exploitation, recharge, and quality monitoring. Water Resour. Bull. 28 (3), 467–482.
World Water Council, 2009. 5th World Water Forum: Final Report. Istanbul, Turkey. Retrieved from. https://www.worldwatercouncil.org.
Yousefi, H., et al., 2020. Climatic classification and drought analysis of eastern Iran. Iran. J. Nat. Resour.
Ziolkowska, J., 2015. Cost of groundwater desalination: a review. J. Water Supply Res. Technol. - Aqua 64 (8), 1132–1140. https://doi.org/10.2166/aqua.2015.036.