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REVIEW ARTICLE

Environmental consequences of Caspian Sea desalination and water transfer to the central plateau of Iran

Hanif Reza Golzar[1] · Sina Mallah[1] · Mina Esteghamat[2] · Matthias Prange[3]

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Abstract

The Caspian Sea (CS), the largest lake in the world, has reportedly experienced a significant water level decline over the past decades. As an ancient endorheic lake with no surface outflow, it is particularly vulnerable to climate change. The proposed desalination and water transfer project from the CS to Iran's arid central plateau seeks to address water demands but could carry significant environmental risks. The project envisions transferring over 220 Million Cubic Meters (MCM) of desalinated water annually from an elevation of -27.5 m to 2312 m above sea level via eight pumping stations and two pipelines spanning 465 km. This process is estimated to require 448 megawatts (MW) of electricity and may discharge 2.6 million tons of salt into the CS annually. Brine discharge may increase local lake water salinity by up to 400% above standard limits within a 300-meter radius, posing risks to aquatic species. The annual release of 3.2 million tons of carbon dioxide (CO_2) and the loss of forests (70–100 ha), rangeland (738 ha), agricultural lands (161 ha), and high-quality soils (15 MCM) highlight possible ecological costs of the project. Additionally, outdated water transmission systems and water-intensive crop cultivation in receiving province (Semnan) could exacerbate inefficiencies in resource use. We suggest prohibiting the cultivation of non-strategic crops in the destination area to mitigate water resource depletion as a sustainable alternative. Without such measures, the environmental, economic, and social consequences of this project might be severe, with potentially far-reaching regional and global impacts.

Keywords Endorheic water · Water shortages · Water resource management · Seawater transfer · Desalination impacts · Greenhouse gas emissions

Introduction

Fresh water shortages pose significant threats to water and food security worldwide (FAO 2017), with evidence suggesting that human demand for fresh water, particularly in agriculture, is expected to grow (FAO 2012). Regional water management is becoming increasingly complex due to climate change. In this context, Inter-Provincial Water Transfer (IPWT) and Inter-Basin Water Transfer (IBWT) are commonly implemented strategies to address regional water shortages. These strategies are historically rooted in ancient Egypt, aimed to transport water from regions with abundant resources to those with higher demand (Karandish et al. 2021).

Countries such as the United States, Canada, Russia, India, Pakistan, and China are at the forefronts of IBWT projects in the modern era (Wang et al. 2008). However, examples like the desiccation of the Aral Sea in Uzbekistan, the shrinking of the Great Salt Lake in the USA, and Lake

✉ Hanif Reza Golzar
hr.golzar@gmail.com

Sina Mallah
s.mallah@areeo.ac.ir

Mina Esteghamat
minaesteqamat@gmail.com

Matthias Prange
mprange@marum.de

1 Soil and Water Research Institute, Education and Extension Organization (AREEO), Karaj 3177993545, Iran

2 Center for Conservation and Development of Sustainable Ecosystems (ZIPAK NGO), Tehran, Iran

3 MARUM – Center for Marine Environmental Sciences, Faculty of Geosciences, University of Bremen, Bremen, Germany

Urumia in Iran highlight the adverse ecological impacts of such projects. Since the early 21st century, the International Hydrological Program (IHP) of UNESCO has recommended that all water transfer projects undergo evaluation based on five key criteria to mitigate potential negative effects, such as inefficient water use in receiving regions, pollutant spread, soil salinization, fertility loss, declining water levels, and aquatic ecosystem damage in donor regions (Lin 1999; Liu et al. 2013; Sible et al. 2015; White 2013).

In Iran, the volume of IBWT is estimated at approximately five Billion Cubic Meters (BCM) per year, including 2070 MCM for operational projects, 2160 MCM for ongoing projects, and 823 MCM under study (IPRCI 2019). A review of 45 IBWT projects implemented since 1954 shows that in all projects, fresh water was transferred from the source of dam, river and lake to the new destination. Notably, there is almost no record of desalinated seawater transfer project reported in the country (Golzar 2015), but recently several IBWT projects have been initiated. Among these, the CS to the Central Plateau transfer project-annually transferring 220 MCM of water at an estimated cost of \$1.16 billion and requiring energy of 39,000 *GJ* of energy-is the most controversial (Golzar 2015; IPRCI 2014a). The proposed pipeline route passes through ecologically sensitive and resource-rich areas, raising concerns among researchers and local communities.

The Caspian Sea, the world's largest enclosed lake, is highly sensitive to changes in hydrography and climate due to its endorheic nature. While its low biodiversity is shaped by millennia of salinity fluctuations, the sea is home to unique species adapted to wide salinity ranges (Leroy et al. 2020). Large natural fluctuations in the Caspian Sea Level (CSL) exceed those of oceans (Krijgsman et al. 2019; Lahijani et al. 2023a, b), and recent human pressures, particularly along the Iranian shoreline, are intensifying due to economic development.

Desalinating and water transfer from the CS to the central plateau of Iran would contribute to greenhouse gas emissions. In 2019, global greenhouse gas emissions were estimated at 59 Gt of CO_2 equivalent (Ritchie et al. 2023), while Iran's emissions in 2022 were approximately 696 Mt (IEA 2022). Iran has pledged to reduce its greenhouse gas emissions by 4–12% by 2030 compared to 2010 levels, requiring a 40% reduction in fossil fuel consumption (Tavakoli 2019). Given that 95% of Iran's electricity production relies on fossil fuels (Sadeghi et al. 2014), the significant energy demands desalination and water transfer are expected to increase the country's emissions.

Despite agriculture being the largest freshwater user in both donor and receiving regions (IMAJ 2017), marginal areas such as the southeastern Caspian coast (e. g., Gorgan Bay) have suffered from water level fluctuations during the 20th and 21st centuries (Khoshravan et al. 2019). Meanwhile, unemployment rate in coastal provinces are 21% higher than those in industrialized receiving provinces (SCI 2020). Although the government initially claimed the project aims to expand agriculture in the destination region (Karandish et al. 2021), evidence suggests its primary goal is to provide drinking water for central Iran.

Historically, several water transfer projects involving the CS have been dismissed due to ecological concerns over the declining CSL and economical infeasibilities, with the Kara-Bogaz Gol barrier being a notable exception (Kosarev et al. 2009; Lahijani et al. 2023a, b; Voropaev and Ratkovich 1985). Nevertheless, the potential impacts of desalinated water transfer on atmospheric, aquatic, and terrestrial ecosystems remain understudied. Therefore, this paper synthesizes updated data to provide an overview of the Caspian Sea water transfer project. It also seeks to evaluate the environmental consequences of this initiative, focusing on its implications for the sustainability of the Caspian Sea and its surrounding ecosystems.

View of the Caspian Sea

The Caspian Sea (CS) is the largest inland body of water in the world, with a length of approximately 1,204-1,305 km, an average width of 443 km, an area ranging from 380,000 to 436,000 km^2, and a volume of 780,000 km^3. It is bordered by Russia to the north, the Central Asia plateau to the east, the Alborz mountains to the south, and the Caucasian mountains to the west (Fig. 1) (Amir Ahmadian 1996; Chen et al. 2017; Leroy et al. 2020). Its catchment area spans 3,733,000 km^2, of which 256,000 km^2 lies within Iran. The CS is fed by 130 rivers, with the Volga River accounting for 80–90% of the inflow. These rivers pass through countries surrounding the Caspian, including Iran, Russia, Azerbaijan, and Turkmenistan. Geomorphic features such as lagoons, bays and wetlands are prominent along its coastlines. The climate of the coastal region is predominantly arid and semiarid, except for the southern zone stretching from Lankaran in Azerbaijan to Gorgan in Iran, which experiences a humid subtropical climate (Molavi-Arabshahi et al. 2016). The shoreline extends for approximately 6,400 km, with 922 km falling within Iranian territory (Mamaev 2002). The slopes along the southern coast are home to Hyrcanian Forest, a dense and ancient forest shared by Iran and southern Azerbaijan.

Geological evidence suggests that the CS is a remnant of the vast Paratethys Sea, which existed over 14 million years ago during the Miocene epoch (Esin et al. 2018). During the Little Ice Age, raising the CSL led to the formation of sedimentary terraces at -27 m relative to sea level (Chen et al.

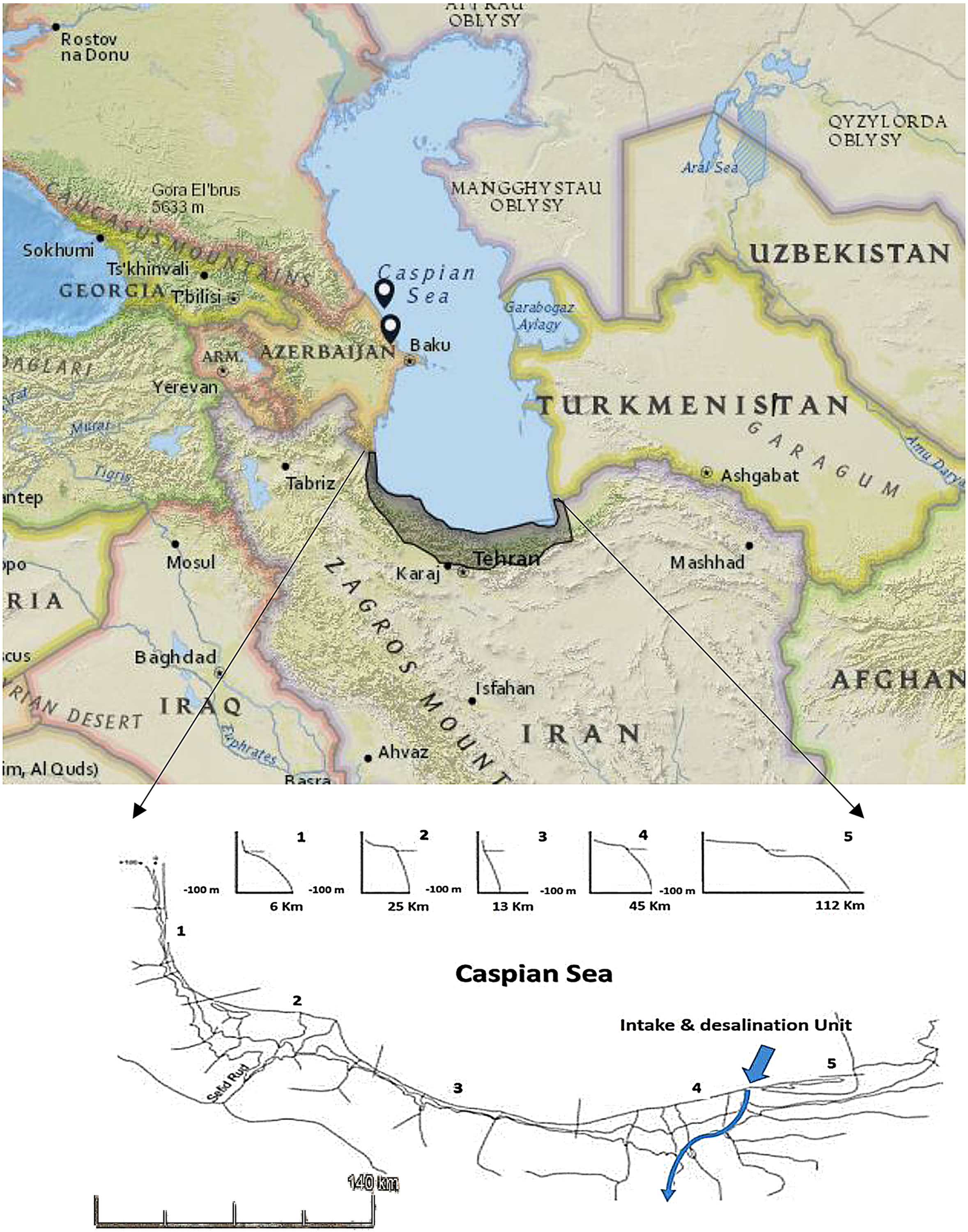

Fig. 1 Map and classification of the Iranian coast of the Caspian Sea with its continental shelf profilesSource: http://www.inio.ac.ir/Default.aspx?tabid=2015

2017). This elevation aligns with its status as a closed lake, having no outflow to the ocean. The Caspian Sea exhibits significant bathymetric variation. In the northern region, soft seabed sediments are typically 10–12 m deep, while the deepest areas, located in the central and southern parts, range from 700 to 1,052 m. These variations are influenced by clockwise water currents and the greater depth of the southern basin. Surface salinity in the CS varies geographically, increasing from 1 practical salinity unit (psu) in the northern section to 13 psu in the south (Leroy et al. 2020; Terziev et al. 1992). Compared to ocean water, the CS water is lower in sodium and chlorine ions but richer in calcium and sulphate (Leroy et al. 2020).

Challenges and implications

The rapid fluctuations in CS water levels could have profound impacts on its five littoral countries: Iran, Russia, Turkmenistan, Kazakhstan, and Azerbaijan. Limited economic resources, heavy reliance on natural resource extraction, and political or technological constraints—such as post-Soviet transitions and sanctions—may hinder coordinated responses to these challenges.

Water balance of the Caspian Sea

As an enclosed water body, the CS is highly sensitive to climatic variations and human activities. Its water budget is influenced by factors such as precipitation, river inflows, groundwater discharge, evaporation, and zonal wind regime alongside human interventions like changes in agricultural policies and extensive hydraulic constructions since the mid-20th century (Akhmadiyeva and Abdullaev 2019; Arpe et al. 2020; Lahijani et al. 2023a, b).

Approximately 130 rivers feed the Caspian Sea, primarily from the northwest, contributing an estimated 300 BCM of water annually. The Volga river is the largest contributor, supplying an average of 241 BCM of water per year. Other significant rivers include the Kura (13 BCM), Atrak (8.5 BCM), Ural (8.1 BCM), and Sulak (4 BCM). Precipitation adds 79 BCM/year, and drainage from adjacent lands contributes 4 BCM/year, bringing the total annual inflow to 383 BCM. However, evaporation which averages about one meter annually and peaks 80 mm/month in the central and southern CS (Terziev et al. 1992), removes approximately 397 BCM/year. This results in a net annual water loss of 14 BCM (IWPRDC 2014a). Climate models project a worsening water balance throughout the 21st century, with irreversible water consumption estimated at 43 BCM/year (Demin 2007; Samant and Prange 2023).

Water level fluctuations in the Caspian Sea

The CS water level is reported to experience short-term variations, ranging from a few centimeters within a half day to as much as 4 m during severe storms over 5–7 days. Long-term trends indicate significant fluctuations:

- A sharp decline of 3 m between 1930 and 1978.
- A subsequent rise of 2.5 m between 1978 and 1995, at an average rate of 15 cm/year.
- A steady decline since 1995, with an abrupt drop in 2010 and a further decrease of 30 cm between July 2021 and 2022 (Arpe et al. 2020; Khoshravan et al. 2019; Lahijani et al. 2023a, b).

Precipitation in the CS catchment decreases from 520 mm/year in 1945 to 460 mm/year in 2010, while its contribution to the sea's water input increased from 15 to 23% during the 20th century (Panin et al. 2014; Terziev et al. 1992). GRACE satellite data suggests a decline in CS water levels by 7–10 cm/year since 1996, with evaporation accounting for a loss of 32 BCM for every centimeter of water loss (Chen et al. 2017). Rising water temperatures (0.035 °C average increase between 1980 and 2020) may have exacerbated evaporation rates and could have impacted regional atmospheric circulation, such as the Jet Stream (Ginzburg et al. 2021).

Projections for the Caspian Sea in the 21st Century

Although some studies suggest stable or rising trends for CSL, most studies indicate significant declines by 2100. Projections under medium- to high-emission scenarios have estimated water level reductions of 9–18 m, driven primarily by increased evaporation that could potentially exceed river inflows and precipitation (Prange et al. 2020). A study by Samant and Prange (2023) forecasts declines of 8–14 m under Shared Socio-economic Pathways SSP245 and SSP585. These reductions are approximately double earlier estimates based on previous climate models. Projected consequences could include:

- Possible emergence of the vast northern Caspian and Turkmen shelves, as well as coastal areas in the central and southern parts.
- Potential complete desiccation of the Kara-Bogaz-Gol Bay.
- Possible shrinkage of the CS surface area by 23% for a 9-meter drop and 34% for an 18-meter drop (Prange et al. 2020).

Overview of the desalinated water transfer project from the Caspian Sea to Iran's central plateau

The project is expected to produce 220 MCM of freshwater annually for 30 years through desalination, which is equivalent to the storage capacity of Amirkabir Dam in Karaj, Iran (IPRCI 2019). The desalinated water is planned to be piped from the Gohar Baran coast and distributed to Sorkheh and Garmsar in the west, as well as Damghan and Shahroud in the eastern regions of Semnan province, subject to the allocated water quotas (IWPRDC 2015). To achieve this, the desalination plant is projected to process 400 MCM of Caspian Sea water annually, removing salts and producing freshwater with a maximum efficiency of 50% (Khabazi Khader 2019). The water is intended to be pumped from a depth of -27.5 m below sea level to a height of 2313 m and then transported by gravity to areas less than 1000 m above sea level (Fig. 2). The project involves two pipelines, each with a diameter of 1.4 m, which are planned to transfer water at a capacity of 7 m^3/s over a distance of 465 km. The pipelines are intended to pass through the Alborz Mountains, which would require eight pumping stations and consuming 448.8 megawatts (MW) of electricity annually (IWPRDC 2014b).

The project has reportedly faced substantial criticism from experts and non-governmental organizations (NGOs), who have raised alarms about its potential environmental and ecological impacts. Numerous letters, scientific papers, and technical reports have raised concerns about the risks, suggesting possible environmental catastrophes in the region (IPRCI 2014a, b, 2019). Despite these concerns, Iran's Ministry of Energy has responded by defending the project, stating that it poses no financial burden and is unlikely to negatively affect the surrounding environment (IWPRDC 2014a, b, 2015, 2019a, b).

Status of water resources in the destination region

Semnan province, the primary destination of the Caspian Sea water transfer project, covers an area of 97,491 km^2 and has a population of 702,360. It lies on the southern slopes of the Alborz mountain range and in the vicinity of Mazandaran province. Semnan is estimated to consume approximately 1.3 BCM of water annually. Of this, 950 MCM is reported to be allocated to the agricultural sector in this arid region (Fig. 3).

Despite its arid climate—characterized by an average annual rainfall of 110 mm and annual evaporation of 2230 mm—agriculture in Semnan province has expanded in recent years, supported by policies emphasizing IBWT projects (Golzar 2015). According to official statistics, the total area of orchards increased by 34,258 hectares in 2008 to 55,080 hectares in 2016. Additionally, 5,000 hectares of agricultural land is said to be used for non-strategic, water-intensive crops like melons and watermelons.

Water use efficiency and mismanagement in agriculture

Karandish et al. (2021) reported that the average water use efficiency (WUE) for producing 39 agricultural products is 0.35 in Mazandaran province, whereas it appears to drop to 0.14 in Semnan, highlighting the inefficiency of agriculture in the region. For instance, melon and watermelon cultivation in Semnan is estimated to consume approximately 125 MCM/year. With an irrigation efficiency of 35%, only 43 MCM might be effectively used, while 82 MCM could be wasted—a quantity that could be equivalent to 1.42 times the useful storage of the Shahid Shah Cheraghi Dam, the largest surface water reservoir in Semnan province (Golzar 2018). Greenhouse-based agriculture has been proposed as a potential alternative to traditional practices in this water-scarce region, where saline soils may further exacerbate the challenges of sustainable agriculture.

Urban and industrial water mismanagement

Water resource mismanagement extends beyond agriculture. Semnan's urban water distribution networks span over 2,500 km, of which 700 km are believed to require performance optimization (Golzar 2018). Improved wastewater collection and optimization could potentially increase domestic and municipal water efficiency by up to 10%, which may help alleviate some pressure on water resources in the region. Despite the national average per capita domestic water consumption of 150 L per day, residents of Semnan province and the city of Semnan reportedly consume 212 and 187 L per day, respectively (Golzar 2018). With a population of 700,000 in Semnan province, this is estimated to amount to an annual domestic water consumption of 54.16 MCM.

The mining and industrial sectors are thought to consume 52 MCM/year. However, over 50% of industrial units in Semnan are currently inactive, casting doubt on the potential for substantial industrial development. With total water consumption across all sectors at 1.3 BCM annually, the fate of approximately 244 MCM remains unclear, raising concerns about water management transparency.

Semnan is officially classified as a water-scarce region. Karandish et al. (2021) estimated that the water transfer project could possibly reduce the province's Blue Water Scarcity (BWS) index by 34%, lowering it to 2.48—still potentially classified as severely water-scarce. As with China's South-to-North Water Transfer (SNWT) mega-project, concerns have been raised about the effective utilization of transferred water. To address these challenges, it is crucial for neutral authorities to reassess Semnan's water balance, with a particular focus on agricultural and domestic sectors,

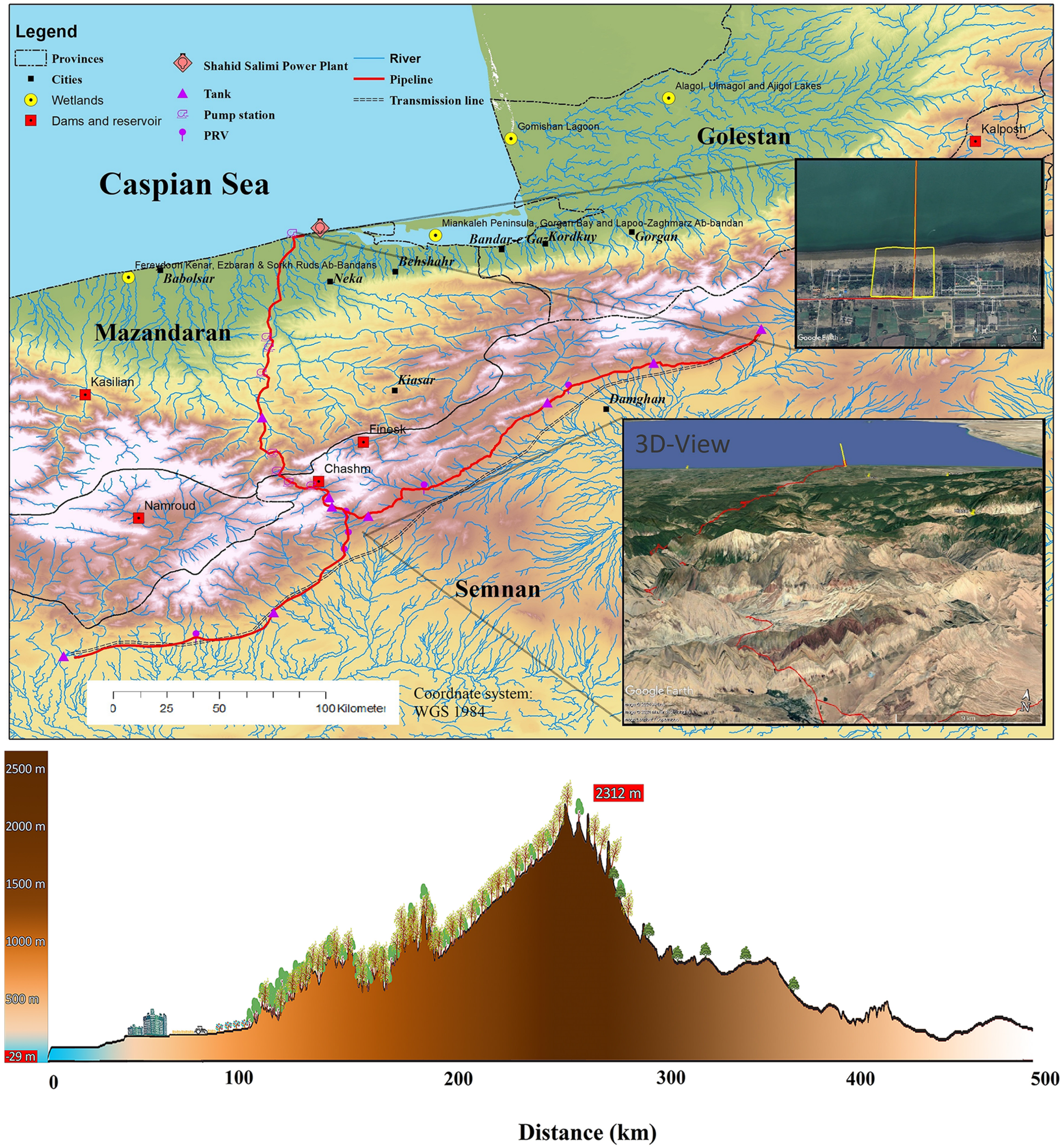

Fig. 2 A general view of the Caspian Sea water transfer plan to the central plateau of Iran, including an elevation profile. The map displays the geographical locations of dams, wetlands, rivers, cities, and other key features mentioned in the study. The upper zoomed-in image shows the coordinates for the construction of desalination facilities on the Gohar Baran coast covering an area of 40 ha. The lower zoomed-in 3D view illustrates the water transfer project, showing the elevation differences between the Caspian Sea and the central plateau of Iran

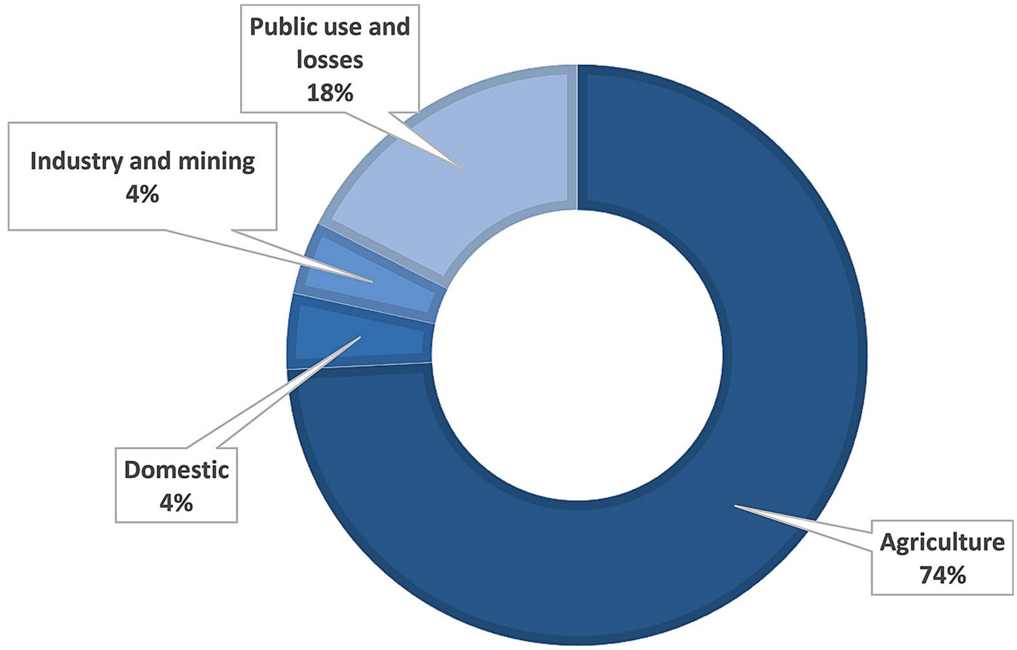

Fig. 3 Share of fresh water usage in Semnan province (IPRCI 2019)

in order to ensure sustainable and efficient water resource management.

Inter-basin water transfer projects to Semnan

Despite evidence suggesting water misuse across agricultural and domestic sectors, some local officials and Ministry of Energy representatives continue to claim that Semnan province faces critical water scarcity. Instead of prioritizing the implementation of water-saving policies, multiple IBWT projects have been proposed to extract water from neighboring provinces, including Tehran, Mazandaran, and Golestan. These projects could potentially jeopardize the water supply for the sensitive Hyrcanian forest ecosystem in northern Iran but have also led to significant water conflicts and social tensions between source and destination regions. The key IBWT initiatives include:

- Namrud Dam: Located on tributaries in Tehran province, this dam is designed to transfer 90 MCM of water annually to Garmsar city in western Semnan province.
- Kaslian Dam: Situated on the Talar River tributaries within the Hyrcanian forests of Mazandaran province, this project aims to transfer 30 MCM of water annually to Semnan city.
- Chasham (Rozieh) Dam: Built on the Kabirrood River, a tributary of the Talar River, this dam is intended to transfer 10 MCM of water annually to Semnan city.
- Finesk Dam: Constructed on the Espiro River, a tributary of the Tajan River, this dam is designed to transfer 10 MCM of water annually to Semnan city.
- Qatari Springs and ZarrinGol River Tributaries: Efforts are being made to transfer water from these sources to Shahroud city.
- Kalposh Dam: This project proposes to transfer water to Shahroud and Miami cities in eastern Semnan province.

While these initiatives are intended to augment the hydrological regime in the Semnan province, similar projects globally have shown adverse environmental and social impacts (Tien Bui et al. 2020). The disruption of hydrological cycles in the source regions has often led to long-term consequences, including ecosystem degradation and heightened social disputes. A map detailing the routes of these water transfer projects and the locations of their reservoirs is provided in Fig. 2.

Environmental consequences

While the reduction in the CSL is primarily attributed to climate change, the Caspian Sea and its surrounding regions are closely interconnected with global environmental systems. The threats facing the Caspian Sea are numerous, some of which manifest rapidly, leaving limited time for adaptation. As highlighted by Molavi-Arabshahi and Arpe (2022), changes in the CS could potentially influence global atmospheric circulation, suggesting that the desalination and water transfer project to Iran's central plateau might have far-reaching environmental impacts. Given the limited focus on the regional consequences of this water transfer project, this study aims to review its environmental effects across three domains: (a) threats to the aquatic environment, (b) threats to the terrestrial environment (including transmission and pipeline route), and (c) threats to the atmospheric environment.

Environmental damage to the Caspian Sea aquatic ecosystem

Sediment potential

A critical aspect of this project is the location selected for water intake from the Caspian Sea. As shown in Fig. 3, the designated area, situated near Gohar Baran is situated on the eastern Mazandaran coast, between the Neka and Tajan rivers (IWPRDC 2014a). While the average sedimentation rate in the coastal bay near the intake region is reported to be 2.5 mm per year (Amini et al. 2012), Kakroodi et al. (2014) argue that sedimentation processes along the Iranian shoreline are highly complex.

Gohar Baran, characterized by stable beaches, active sedimentation, and one of the gentlest seabed slopes on the Mazandaran coasts, is located east of Amirabad Port—the largest port on the southern shores of the Caspian Sea. This area also hosts the Amirabad port complex, Sadraship building company, oil piers, and the Neka thermal power plant, all of which might have significantly altered the surrounding ecosystem. These changes include extensive land-use transformations along the edges of the Miankaleh Wildlife Sanctuary and Wetland, a Ramsar Convention-designated type "A" Biosphere Reserve since 1975 (IPRCI 2014a).

The construction of marine structures and tranquil pools in this region may have disrupted the west-east sediment transport and natural seabed circulation, potentially amplifying sediment accumulation potential in the Gohar Baran area (IPRCI 2014a). Such sedimentary processes could create challenges for managing and treating sediment-laden water. However, these sediments are believed to play an essential role in forming coastal habitats by annually delivering significant amounts of nutrients and organic materials. For instance, Khoshravan et al. (2019) reported that the sedimentary deposits in Gorgan Bay's shallow wetlands contain over 54% sand and 30-50% silt particles. These deposits, upon desiccation, may potentially become sources of haze. Moreover, the infiltration of sandy sediments and the washing of surface salts in dry areas could contribute to the development of *Juncus* plant communities.

Water contamination and pollution

The activation of sediment loads along the Gohar Baran shoreline raises critical concerns when considering the contamination of these sediments with heavy metals. Research has shown that the concentration of pollutants such as lead and cadmium in the southern Caspian Sea sediments is known to increase from west to east, with sediment pollution on the eastern shores of the Caspian Sea in Iran exceeding international standards (Bagheri Tavani and Norouzi 2016).

Notably, fish caught in the southeastern Caspian Sea—near the proposed water intake site for the transfer project—might exhibit higher concentrations of lead and cadmium in their tissues compared to fish from the southern, central, and southwestern parts of the lake. This accumulation suggests the significant pollution of the lake water with these heavy metals. Further studies on the contamination of coastal Caspian Sea waters in Iran indicate that the levels of nickel, copper, zinc, mercury, cadmium, and lead surpass the standards established by ANZECC, MPL, and UKMPA (Bandani et al. 2016). Nevertheless, a consulting company has reported no significant concerns about heavy metal pollution in the water resources (IWPRDC 2014b).

Water contamination in the region is not limited to heavy metals; microbial pollution is another pressing issue. Research has found that the average concentrations of total coliforms and thermotolerant coliforms in some sampling stations exceed safety standards, making swimming inadvisable (Nabizadeh et al. 2012). A study conducted in Gorgan Bay revealed coliform levels of 1,555 per 100 cc and thermotolerant coliform levels of 817 per 100 cc, indicating significant microbial contamination in the water (Shahriari et al. 2008). Similarly, water samples from four coastal stations in Mazandaran province showed contamination with fecal streptococcus (Pond et al. 2005).

Threat to aquatic biotopes

The desalination and water transfer project could pose several significant threats to aquatic ecosystems in the Caspian Sea. During the project's executive phase, water intake operations from a depth of 5 to 7 m were considered the preferred option, despite earlier studies suggesting a saline discharge site at a depth of 25–35 m. This deeper option would have required at least 13 km of piping along the lakebed (IWRI 2019). However, due to technological constraints and investment costs, the Iran's Department of Environment (DOE) unexpectedly approved a reduction in the depth of effluent discharge to 5–7 m, limiting the discharge site to just 2.5 km from the shoreline (Fig. 4) (IWPRDC 2015).

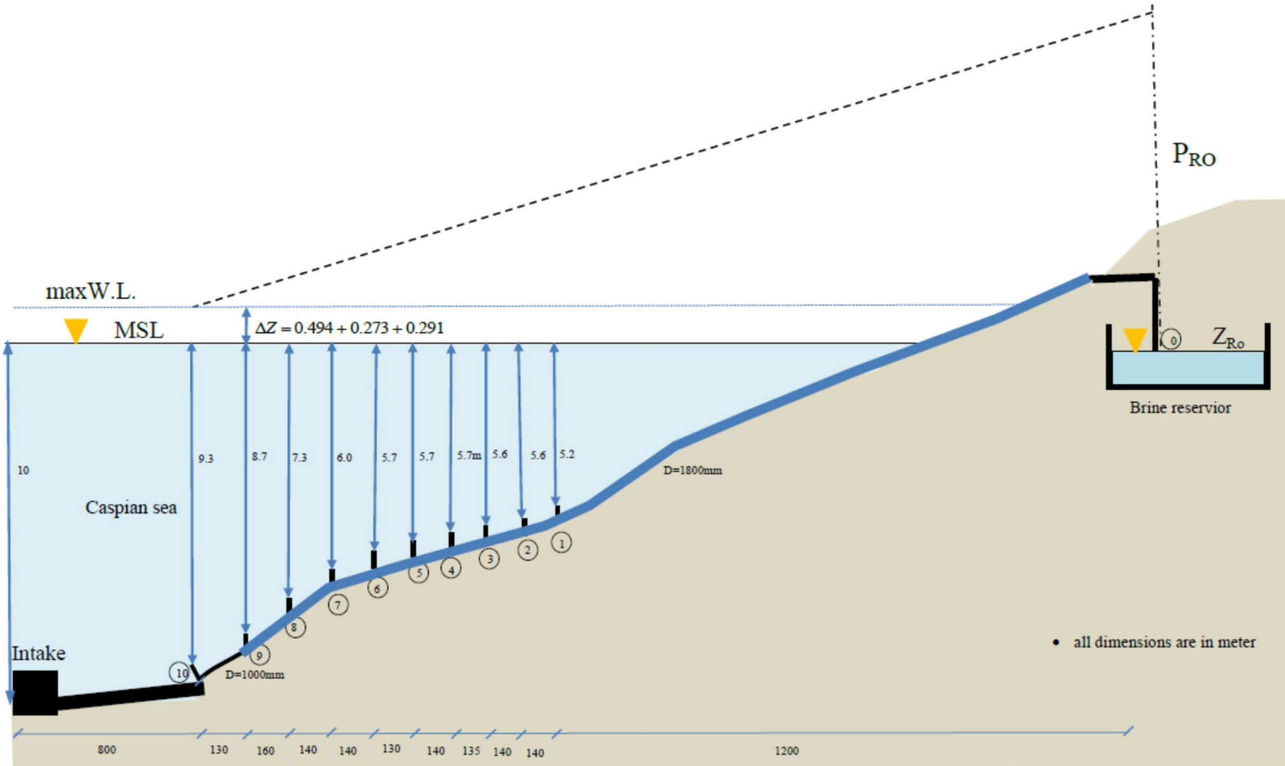

Fig. 4 Schematic of the longitudinal profile illustrating the effluent discharge route and the water intakepath to the desalination plant and pump basin (IWPRDC 2019b). The horizontal blue lines represent the estimated pipeline length, accounting for terrain slope and unevenness rather than direct horizontal distances. The vertical blue lines indicate water depths at different points along the route. The numbers (1–10) correspond to the division of the pipeline installation into 10 sequential work phases, dictated by steep slopes and terrain irregularities. The intake structure is positioned in the Caspian Sea, and the pipeline transitions from an initial diameter of 1000 mm to 1800 mm along its path to the brine reservoir

This distance may decrease in the future due to the ongoing CS water level decline.

Impact of Effluent Discharge The discharge of saline wastewater at shallow depths could affect near-surface zones with higher populations of aquatic organisms and biodiversity due to increased light penetration. Studies indicate that saline wastewater, with double the salinity of seawater, tends to settle on the seabed due to its density, forming a layer approximately 1 m thick at a depth of 9–10 m and extending up to 200 m from the discharge point (IWPRDC 2016). This dense saline layer could potentially destroy phytoplankton, zooplankton, and benthic communities.

According to DOE regulations in Iran, the increase in solute concentration at a distance of over 200 m from the discharge site is not supposed to exceed 10%. However, initial modeling shows that salinity levels within an area of approximately 300 m might increase by 10–400%, potentially severely impacting aquatic species. Particularly vulnerable could be rare and economically significant species such as wild sturgeon, whose populations may have already declined due to ecological disruptions since the 1970s (Ruban et al. 2019).

Additional ecological impacts The shallow discharge area and associated piping activities could disturb the seabed, temporarily increasing turbidity. This might affect feeding behavior and mobility of aquatic organisms. Mechanical activities during pipeline construction may disrupt habitats of sensitive species, including the Caspian seal (*Pusa caspica*), green algae (*Ruppia maritima*), xerophytes, and halophytes (IWRI 2019).

Desalination operations could further exacerbate environmental damage. Producing 220 MCM of fresh water annually would require desalinating 440 MCM of seawater, generating 220 MCM of hypersaline effluent. This process might trap fish eggs and aquatic larvae in intake pipelines, while the discharge of highly concentrated brine—2.6 million tons of salt annually—into the lake may significantly increases salinity in surrounding waters. Such conditions could risk creating ecological dead zones near effluent outlets, with prior studies suggesting rapid changes to coastal habitats caused by minor increases in electrical conductivity (Saeidi et al. 2014; Sharifnia et al. 2007). These activities could lead to habitat disruption and insecurity for these sensitive creatures in the region (IWRI 2019).

Climatic and vegetation stresses Projected decreases in precipitation in the southern Caspian region (Katsov and Govorkova 2013) could further stress aquatic organisms and vegetation, such as *Ruppia maritima*, *Salicornia*, *Tamarix*, *Juncus*, and *Punica*. Increased salinity in the water may exacerbate these pressures (Khoshravan et al. 2019).

Risks of saline water transport Transporting saline water via pipelines to consumption sites has been proposed. However, this option carries risks, including pipe corrosion, damage, and leakage, which potentially cause severe environmental consequences in sensitive ecosystems such as the Hyrcanian forests. These risks make saline water transport an unsustainable alternative.

Economic and industrial concerns Contrary to claims by proponents, the project might offer no practical benefits for agricultural or industrial sectors. Instead, the discharge of large volumes of effluent is likely to cause significant harm to the regional fishing industry, particularly in caviar production (Golzar 2015; Leroy et al. 2020). Project consultants have also identified a lack of suitable alternative fishing areas (IWPRDC 2014a).

Disappearance of ancient wetlands

The potential impact of the Caspian Sea (CS) water outflow on wetlands has been largely overlooked in past studies and warrants further investigation in future research. Wetlands, with an estimated global economic value of $5 trillion, provide a wide range of ecological goods and services that directly support biodiversity and fauna (Khoshravan et al. 2019; Lahijani et al. 2023a, b). These critical ecosystems, however could be increasingly threatened by desiccation resulting from the ongoing decline in the CS water level.

While the removal and transfer of water may have a relatively minor impact on the speed of wetland drying, the disruption of the hydrological balance in water withdrawal sites and adjacent wetlands-especially in low-slope and shallow-depth areas (Fig. 1)-requires further study (IPRCI 2014a). The drying and swamping of extensive portions of the Miankaleh International Wetland in southeastern CS, particularly in its western regions, serve as a potential example of the environmental consequences of water depletion and the subsequent retreat of the CS. Climate change could exacerbate these effects, amplifying the desiccation trend.

The Miankaleh Biosphere Reserve, one of 13 biosphere reserves in Iran, plays a vital role in hosting millions of migratory waterfowl and shorebirds annually. These birds rely on the reserve as a winter station and nesting site in its woodlands (Vilkov 2015). The CS is the sole water source for this critical wetland. However, water shortages in recent years have led to the desiccation of approximately 25% of the wetland's area, particularly in its western sections near the southern waters of Amirabad Port in Behshahr. These areas have transformed into swamps and salt marshes. Researchers predict that, under the current trend of CS water retreat, the Miankaleh Wetland could become entirely dry within 15 years (Sharbaty and Ghanghermeh 2016). This rapid loss poses significant ecological and economic threats, highlighting the urgent need for mitigation measures (Fig. 5).

Fig. 5 Drying and swamping of the western parts of Miankaleh wetland and biosphere reserve (Photos taken by H.R. Golzar in March 2020)

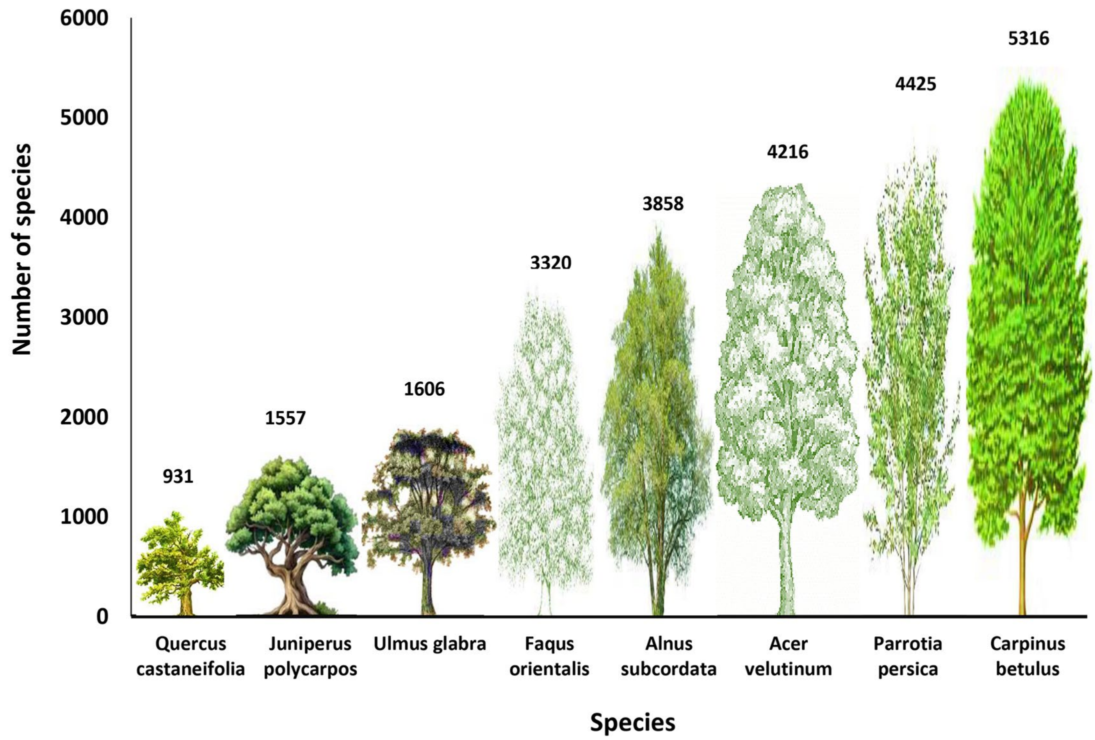

Fig. 6 Types and numbers of trees to be cut down for the water transfer project from CS to the central plateau of Iran

Environmental damage to the land ecosystem

Land use change

The construction of a 465 km pipeline to transfer desalinated water to Semnan province could involve significant environmental disruption across urban and rural areas, including 40 villages (IWPRDC 2014a). The pipeline installation may necessitate extensive land use changes, potentially resulting in severe environmental impacts, such as:

- Possible conversion or destruction of over 21 hectares of orchards, 18 hectares of rainfed fields, and 143 hectares of irrigated agricultural lands.
- Potential clear-cutting and degradation of 786 hectares of Hyrcanian-Caspian forests and Iran-Turanian habitats in the southern Alborz region.
- 738 hectares of rangelands could be affected.
- Potential loss of 8 hectares of urban and rural settlements.
- Potential removal of over 50,000 Hyrcanian deciduous trees for access road construction within the forest.
- Excavation and displacement of at least 15 million MCM of valuable soil (IWPRDC 2014a, 2019a, b).
- In addition to the pipeline route, 40 hectares of coastal land at the Gohar Baran beach construction site may be clear-cut and destroyed to accommodate desalination facilities (Mahab Ghodss consulting Engineering Co., 2019a).

Degradation of forest ecosystems

The Caspian desalination and water transfer project could have significant adverse impacts on the Hyrcanian-Caspian forests in the northern Alborz region. These forests are highly ecologically valuable and host numerous protected and endangered species. The key activities contributing to forest degradation could include:

Deforestation for Construction and infrastructure The installation of eight pump stations to transfer water from an elevation of -27.5 m at Gohar Baran Beach to 2313 m in the Alborz Mountains may require significant clearing of forested areas (Fig. 2). Of these, pump stations 5 through 8 are located in dense forested areas, necessitating the clearing of approximately 79 hectares of forest cover for the placement of high-voltage transmission towers (IWPRDC 2019a). For instance, in one of the areas where the piping operation is planned, over 42 km of the pipeline route would pass through pristine and intact deciduous forests-some of the most ecologically valuable areas in the region (IWPRDC 2014b). Estimates suggest that more than 55,237 trees and shrubs in the Hyrcanian and Iran-Turanian habitats may be felled. Many of these species are ecologically protected and prohibited from removal due to their critical environmental value (IWPRDC 2019a). Figure 6 provides a summary of the tree and shrub species that might be removed due to the project.

Extraction of resources from forested areas The construction of pumping and piping stations may require large quantities of stone, which could be sourced from mountainous-forest deposits. This means that the damage to significant area of the Hyrcanian-Caspian forests may not have been accounted for in the overall environmental impact assessments, adding to the cumulative damage to forest ecosystems.

Riverbed degradation and resource extraction

The project's environmental impact could extend to riverbeds, which are critically important ecosystems. Although the extraction of sand from riverbeds has been prohibited and considered a criminal act in Iran since December 14, 2003, the sand needed for installation and piping could be sourced from the bed of the Neka River. Excavation would occur at a depth of 5 m (IWPRDC 2014a), potentially causing substantial environmental degradation including disruption of aquatic habitats, alteration of river flow dynamics, leading to long-term ecological imbalances, and violation of environmental protection laws aimed at preserving river ecosystems.

Soil degradation

One of the biological consequences of the water transfer project could be the destruction of valuable soil resources along the pipeline route. Surprisingly, soil degradation has not been addressed in the environmental assessment of projects in Iran for unknown reasons. Surveys conducted by the consulting company indicate the displacement of at least 15.2 MCM of soil resources in the affected areas: 5 MCM between the desalination plant and pumping station No. 2, more than 4 MCM between pumping station No. 2 and pumping station No. 5, and over 6.2 MCM between pumping station No. 5 and the entrance of the Cheshmeh Rozieh tunnel upstream of Shahmirzad city (Mahab Ghodss consulting Engineering Co., 2019b). A review of the soil map of Iran (Banaei et al. 2005) shows that a major portion of the water transmission pipeline and the associated soil degradation concerns two valuable soil types in Iran: Alfisols and Mollisols. These soils are found only in the narrow northern strip of Iran (comprising just 3% of the country's soils) and are not likely to form elsewhere in the Middle East.

Environmental damage to the atmosphere

Implementing this mega project may not be feasible without the use of electrical energy. The total electricity required for this project could be estimated at 448.8 MW, with 180 MW allocated to seawater desalination facilities and 268.8 MW used for the eight water pumping stations (IPRCI 2014b). Considering the type of fuel and the efficiency of power plants in Iran, producing each kilowatt-hour (kWh) of electricity results in an average emission of 817 g of CO_2 (Sadeghi et al. 2014). It is estimated that consuming 448 MW of electricity for desalination and water transportation could generate nearly 3.2 million tons of excess carbon dioxide emissions, which may conflict with Iran's international commitments to reduce greenhouse gas emissions.

Conclusion and recommendation

Although water management in Iran is overseen by the Ministry of Energy, major water projects such as dam construction and inter-basin transfers are often influenced by external factors. Many of these projects are imposed on the government through the influence of local officials, who may view dams and water transfers as sustainable solutions for addressing the growing water crisis in their regions. These officials, along with companies motivated by financial gain from large-scale construction projects, often portray water scarcity as more severe than it might be, presenting structural water management as the primary solution. In the case of the Caspian Sea water transfer to Semnan, pressure from both private contractors and local officials could lead to prioritizing costly, environmentally harmful solutions over other potentially more sustainable, lower-cost alternatives.

Iranian law mandates Strategic Environmental Impact Assessment (SEIA) and Environmental Impact Assessment (EIA) reports for development projects. However, the Caspian Sea desalination and water transfer project initially proceeded without these assessments, largely due to strong political support. Following years of public and expert opposition, the project developers were eventually compelled to prepare the required reports. Nevertheless, a fundamental issue in Iran is that SEIA and EIA studies are often conducted by by entities with financial ties to the projects, which can lead to assessments that downplay environmental risks. Additionally, local officials and private contractors may frequently exert pressure on the Iran's Department of Environment (DOE) to approve incomplete or biased reports. In brief, financial incentives, administrative corruption, and inadequate enforcement of environmental laws could enable the approval of these costly and environmentally damaging projects.

Given large-scale water withdrawal, combined with the significant damage to aquatic and terrestrial ecosystems from desalination and water transfer from the Caspian Sea, the project presents serious concerns. Additionally, the financial burden of the project raises questions about its viability. The project risks violating several UNESCO criteria by increasing salinity over a wide area, discharging saline effluent from desalination plants, threatening the habitat of Caspian seals, and reducing fishing areas. It may also destroy farmlands, distrup local economies and affect farmers' livelihoods. The destruction of large areas of Hyrcanian and Iran-Turanian forests, along with an increase in electricity consumption, fossil fuel use, and bio-pollutant emissions, may further highlight the environmental costs of the project. From an international perspective, the project could harm Iran's legal standing and its relations with other Caspian Sea littoral states. Additionally, the projected annual emission of 3.2 million tons of CO_2, driven by the project's reliance on electricity consumption, would further undermine Iran's commitments to reducing greenhouse gas emissions by 2030.

Sustainable water resource management in Semnan province, for drinking, industry, mining, and agriculture, could be achieved at a much lower cost and with fewer environmental impacts. For instance, reallocating water from the agriculture sector could meet the demands of domestic and industrial needs. Additionally, non-water withdrawal solutions-such as optimizing cropping patterns, improving agricultural water productivity, restricting the development of water-intensive industries, controlling migration from the capital and northern provinces, modernizing water transmission networks, and promoting awareness to reduce water consumption, present more sustainable pathways to managing water shortages in the central plateau of Iran.

It is crucial to consider that about 80% of the Caspian Sea's water is supplied by the Volga River in Russia, and many of the Caspian Sea's environmental issues stem from reduced inflows caused by extensive dam construction along the Volga River. In addition, invasive species, chemical pollution and poaching are exerting considerable pressure on the overall Caspian ecosystem health (Lattuada et al. 2019). Therefore, addressing the challenges facing the Caspian Sea ecosystem solely through the lens of this project might detract from identifying and tackling these broader systemic issues. Moreover, although the economic justification for this project might seem to outweigh its environmental costs, the full extent of the environmental impacts, as discussed in this article, remains unclear. Given the lack of direct evidence regarding the environmental and economic consequences of this project, future research should focus on modeling its impacts. This would involve measuring key environmental and economic indicators to better understand the potential outcomes of its implementation, while also considering the broader, systemic factors, such as the role of the Volga River, in shaping the Caspian Sea's ecological challenges.

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Declarations

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