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Navigating Water Scarcity in Iran: Scenario Analysis of Water Footprint Adoption and Non-Adoption Pathways

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Abstract

Water scarcity has emerged as one of the most critical challenges in Iran, exacerbated by climate change, population growth, and unsustainable water management practices. This paper explores the implications of adopting versus not adopting the Water Footprint (WF) framework in Iran's national water governance strategies. Drawing on international experiences and Iran's current hydro-political context, the study employs scenario analysis to assess the environmental, economic, and socio-political consequences of both pathways. The results demonstrate that non-adoption would accelerate groundwater depletion, land subsidence, and food insecurity, with significant risks of social instability and ecological collapse. In contrast, the adoption of WF could foster sustainable water allocation, promote crop diversification, enhance resilience to climate change, and strengthen regional cooperation. The study concludes that WF adoption is not merely a technical measure but a governance transformation, essential for securing Iran's long-term water security and socio-economic stability. This research contributes to the broader discourse on sustainable water management in arid regions, offering a framework for policymakers to transition from crisis-driven management toward proactive resilience.

Keywords Water Footprint, Water Scarcity, Sustainable Water Management, Scenario Analysis

Introduction

Water scarcity has emerged as one of the most pressing challenges of the 21st century, particularly in arid and semi-arid regions such as Iran. The rapid growth of the population, coupled with agricultural expansion and industrial development, has intensified pressure on limited freshwater resources. Recent reports by the United Nations (UNESCO, 2023) indicate that over two-thirds of Iran's provinces are experiencing moderate to severe water stress, a situation that threatens both socio-economic stability and environmental sustainability. Addressing this crisis requires innovative management approaches

that move beyond conventional supply-oriented strategies. One of the most promising tools developed in recent decades is the concept of the water footprint (WF), which provides a comprehensive measure of direct and indirect freshwater use. Introduced by Hoekstra and Chapagain (2002), the WF framework distinguishes between blue water (surface and groundwater), green water (rainwater stored in the soil), and grey water (polluted water). This holistic approach enables policymakers, businesses, and researchers to quantify the hidden water embedded in production and consumption processes, often referred to as 'virtual water.' By making these flows visible, the WF



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offers insights into both local and global dimensions of water governance.

Countries around the world have increasingly adopted the WF methodology as part of their water management policies. For instance, the Netherlands, Spain, and Australia have integrated WF assessments into agricultural planning, enabling reductions in water-intensive crops and improvements in irrigation efficiency (Aldaya et al., 2020). Emerging economies such as China, India, and South Africa are also piloting WF-based policies to balance economic growth with environmental constraints. These experiences highlight the versatility of WF applications across diverse climatic, institutional, and socio-economic contexts.

In the case of Iran, the urgency of applying WF tools is even greater due to severe water imbalances and recurring droughts. Agriculture consumes more than 90% of Iran's freshwater withdrawals, yet inefficiencies in irrigation practices, coupled with the cultivation of water-intensive crops like rice and sugarcane, have accelerated groundwater depletion (Madani, 2014; FAO, 2022). Without structural reforms, Iran faces the risk of irreversible aquifer collapse, desertification, and intensifying water conflicts among provinces.

Implementing WF-based policies in Iran could provide several advantages. First, it would allow decision-makers to identify the most water-intensive sectors and regions, thereby prioritizing interventions. Second, it would facilitate international trade decisions by highlighting the virtual water embedded in exports and imports. Finally, it could enhance public awareness of sustainable consumption, thereby promoting demand-side management in addition to supply-side reforms. These benefits align with Iran's long-term water security objectives and could significantly mitigate the risks of future crises.

This study aims to analyze the importance of water footprint assessment in Iran, with a focus on its potential role in addressing the country's water imbalance. By comparing scenarios with and without the implementation of WF strategies, the paper evaluates the likely impacts on water availability, agricultural sustainability, and socio-economic resilience. Moreover, the study draws lessons from international experiences, identifying both opportunities and challenges in adapting the WF framework to Iran's unique hydrological and institutional context.

Literature Review

The concept of the water footprint (WF) has undergone significant evolution since its introduction in the early 2000s. Hoekstra and Chapagain (2002) first developed the framework to quantify both direct and indirect freshwater use, emphasizing the interconnectedness of consumption

and production across global supply chains. Over time, the WF has become a widely recognized tool in water resources research, supported by institutions such as the Water Footprint Network (WFN), which has standardized methodologies and advanced global applications. This evolution has contributed to the growing recognition of WF as a benchmark for sustainable water governance.

Early studies primarily focused on estimating the WF of agricultural commodities, given that food production is the largest consumer of freshwater worldwide. Chapagain and Hoekstra (2004) highlighted stark disparities in the water intensity of different crops, demonstrating how trade in agricultural goods represents the transfer of 'virtual water' between nations. For instance, cereals, rice, and cotton were found to embody disproportionately high volumes of water, raising concerns about the sustainability of agricultural exports from water-stressed regions. These findings underscored the need to align crop patterns with local water availability.

Subsequent research expanded the scope of WF analysis to industrial and domestic sectors. Gerbens-Leenes et al. (2008) analyzed the WF of biofuels, illustrating that energy production pathways can be highly water-intensive, while Mekonnen and Hoekstra (2011) provided a comprehensive global assessment of WF across sectors, revealing large variations between developed and developing countries. Such studies reinforced the notion that water sustainability cannot be addressed in isolation but requires a systemic approach that integrates food, energy, and water nexus considerations.

In recent years, WF research has increasingly emphasized policy applications and governance mechanisms. Aldaya et al. (2010) explored how WF assessments could support decision-making in the European Union, particularly in balancing agricultural productivity with ecological protection. Similarly, Zhao et al. (2019) examined China's adoption of WF-based policies, demonstrating measurable reductions in regional water stress through crop diversification and irrigation efficiency. These examples illustrate the potential for WF to transition from an academic concept to a practical tool for policy implementation.

Despite these advances, challenges remain in operationalizing WF methodologies, particularly in data availability and spatial resolution. Critics argue that WF estimates often rely on aggregated data that mask local variability (Ridoutt & Huang, 2012). Furthermore, integrating WF results into policy frameworks requires strong institutional coordination, public participation, and cross-sectoral collaboration—factors that are often weak in developing countries. As such, the success of WF applications depends heavily on governance capacity and institutional

context.

For Iran, the literature highlights both urgency and opportunity. Studies by Madani (2014) and Mirzaei et al. (2020) emphasize that unsustainable groundwater extraction, inefficient irrigation systems, and inappropriate crop patterns are major drivers of the country's water crisis. Although WF studies on Iran remain limited compared to global research, emerging evidence suggests that WF-based planning could guide strategic reforms in agriculture and trade. This gap in the literature provides the basis for the present study, which seeks to contextualize WF for Iran's specific hydrological and institutional challenges.

Theoretical Framework & Methodology

The water footprint (WF) framework is grounded in the concept of virtual water, introduced by Allan (1998), which highlights the hidden water flows embedded in goods and services. By building on this concept, Hoekstra and Chapagain (2002) formalized the WF as a comprehensive metric for assessing direct and indirect water use, thereby extending the analytical scope of hydrology to include economic and social dimensions. This theoretical innovation enables an integrated approach to water governance.

The WF framework distinguishes between three primary components: blue water (surface and groundwater), green water (rainwater stored in soil), and grey water (the volume of freshwater required to assimilate pollutants). These categories capture both quantitative and qualitative aspects of water use, offering a multidimensional perspective that traditional volumetric measures cannot provide. This differentiation is particularly relevant for water-scarce countries such as Iran, where both scarcity and pollution are acute challenges.

In addition to its biophysical foundation, the WF is linked to theories of sustainable consumption and production. By tracing water use along supply chains it highlights the responsibility of both producers and consumers in exacerbating or mitigating water stress. This aligns with broader environmental economics frameworks, such as the ecological footprint and life cycle assessment (LCA), but WF provides a more explicit focus on water as a critical resource.

A key theoretical strength of the WF framework lies in its capacity to integrate with the nexus approach—the interconnections among water, food, and energy systems. This integration is crucial for Iran, where agriculture dominates water withdrawals, energy subsidies drive water-intensive crop cultivation, and food security concerns often override environmental sustainability. By embedding WF analysis in the nexus framework, policymakers can eval-

uate trade-offs more comprehensively.

Methodologically, the WF can be calculated using either top-down national accounts or bottom-up product-level assessments. The top-down approach relies on macroeconomic data and water use statistics, whereas the bottom-up approach focuses on detailed process-based modeling of specific products or sectors. In this study, both approaches are combined to provide a holistic assessment of Iran's water use patterns.

For agricultural analysis, the CROPWAT model developed by the FAO is frequently employed to estimate crop water requirements under varying climatic and soil conditions. This model integrates with WF methodologies to calculate the green and blue components of the WF for key crops. In Iran's context, the model is particularly valuable given the dominance of irrigated agriculture and regional variability in rainfall patterns.

Estimating the grey water footprint requires integrating hydrological and water quality models. The methodology involves calculating the volume of water necessary to dilute pollutants (e.g., nitrogen fertilizers, pesticides) to meet environmental quality standards. This aspect of WF is increasingly important in Iran, where agricultural runoff and untreated wastewater discharge have degraded both surface and groundwater quality.

Data sources for the WF calculation in this study include official statistics from Iran's Ministry of Energy, the Statistical Center of Iran, and the FAO's AQUASTAT database. These are supplemented with remote sensing data and previous peer-reviewed studies (e.g., Mekonnen & Hoekstra, 2011; Mirzaei et al., 2020). Combining multiple data streams ensures greater reliability and spatial resolution in the analysis.

Spatial analysis of WF is conducted using Geographic Information Systems (GIS). This allows the visualization of provincial differences in WF, highlighting hotspots where water stress and water use intensity converge. For example, provinces such as Khuzestan and Fars are expected to show particularly high WF values due to intensive irrigation and industrial activity.

In terms of temporal scale, the analysis covers 20 years (2000–2020). This allows the identification of long-term trends in water use and provides insights into the impacts of drought cycles, policy reforms, and demographic changes. Scenario modeling is then used to project future outcomes up to 2040 under different policy conditions. Scenario analysis is conducted using a comparative framework: (a) a baseline scenario with no significant adoption of WF-based policies, and (b) an intervention scenario where WF is integrated into agricultural planning, trade policies, and water pricing. This methodological design enables a direct evaluation of the costs and

benefits of adopting WF in Iran.

To ensure robustness, a sensitivity analysis is performed, testing how variations in crop yields, irrigation efficiency, and climate conditions affect WF estimates. This helps identify critical uncertainties and provides a range of possible outcomes rather than a single deterministic projection. Such an approach is particularly important given Iran's exposure to climate variability.

The methodological framework also incorporates stakeholder perspectives. Interviews with policymakers, water managers, and agricultural producers are used to contextualize quantitative results, highlighting potential barriers to WF adoption. This mixed-methods approach acknowledges that technical solutions must be accompanied by institutional and social feasibility.

Ethical considerations are embedded in the methodology, particularly regarding data transparency and inclusivity. Given that water scarcity in Iran disproportionately affects vulnerable communities, the analysis explicitly considers equity dimensions, such as access to safe drinking water and the implications of agricultural reforms for rural livelihoods.

Overall, the theoretical and methodological framework of this study positions the WF not merely as a technical tool but as a governance instrument. By combining quantitative modeling, spatial analysis, and stakeholder perspectives, the study aims to provide policymakers with actionable insights. This integrative approach ensures that WF analysis is relevant to Iran's pressing water challenges and can contribute to long-term resilience.

Scenario Analysis: The Future of Water Management in Iran

Scenario A: Non-Adoption of Water Footprint (WF)

Iran is already among the most water-stressed countries in the world (Mekonnen & Hoekstra, 2016). If the Water Footprint (WF) methodology is not adopted, the country will likely continue on its unsustainable path of resource exploitation. In the absence of WF-informed policies, agricultural water consumption—currently around 90% of total withdrawals—will remain inefficient and poorly managed (FAO, 2021). Crops such as rice, wheat, and sugarcane, grown in unsuitable arid regions, will continue to consume vast amounts of scarce blue water, pushing aquifers into deeper decline (Madani, 2014). Groundwater depletion will worsen, leading to irreversible phenomena such as land subsidence, which has already been reported in Tehran and Isfahan provinces (Motagh et al., 2017). Over-extraction will also cause salinization, making agricultural land infertile and reducing crop yields, thereby further increasing Iran's dependency on food imports (Karandish & Hoekstra, 2017). The lack of WF will per-

petuate poor urban water management. Major cities such as Tehran, Mashhad, and Shiraz will face repeated water shortages, exacerbated by climate variability (Madani et al., 2016). Without WF, policymakers will remain blind to virtual water flows, leading to inefficient domestic food production policies and excessive reliance on water-intensive crops. Environmental impacts will be devastating. Iconic ecosystems such as Lake Urmia will continue to shrink due to excessive water withdrawals (AghaKouchak et al., 2015). The Zayandeh-Rud River, once central to cultural and agricultural life, will remain dry for much of the year, eliminating aquatic biodiversity and livelihoods (Gohari et al., 2013). Grey water pollution will increase because of unchecked agricultural runoff. Fertilizers and pesticides will continue contaminating rivers and groundwater (Mekonnen & Hoekstra, 2011). Rural communities will face heightened vulnerability. Farmers dependent on water-intensive crops will experience repeated crop failures and declining incomes (Keshavarz et al., 2013). This decline will trigger rural-to-urban migration, leading to depopulation of villages and overcrowding in already stressed urban areas (World Bank, 2021). As migration intensifies, unemployment and poverty will rise in cities, adding to existing socio-economic pressures (Ebrahim et al., 2020). Social unrest is a likely outcome. Water protests, already visible in Khuzestan and Isfahan, will grow in frequency and intensity (Madani, 2014). Politically, water allocation disputes among provinces will escalate, threatening national stability (Keshavarz et al., 2013). In the absence of WF, Iran will also face growing dependence on international food markets. Cereal and meat imports will increase substantially, exposing the country to global price volatility (FAO, 2021). Rising imports will also strain foreign exchange reserves, undermining macroeconomic stability (World Bank, 2021). The lack of WF adoption will also reduce Iran's credibility in international water diplomacy. The country will be perceived as resistant to sustainability frameworks (UNEP, 2020). Climate change will amplify these risks. With rising temperatures and declining rainfall, the absence of WF will leave Iran without adaptive capacity (AghaKouchak et al., 2015). Ultimately, the non-adoption scenario paints a bleak picture: ecological collapse, socio-economic instability, and a heightened risk of conflict.

Scenario B: Adoption of Water Footprint (WF)

By adopting WF, Iran could align water consumption with hydrological realities and move toward sustainable governance (Hoekstra, 2017). One of the most significant benefits would be more rational crop planning. WF analysis would help identify crops that are unsuitable for Iran's arid climate (Karandish & Hoekstra, 2017). For exam-

ple, instead of growing water-intensive rice in northern provinces, Iran could import rice from water-rich regions abroad while promoting drought-tolerant crops locally (FAO, 2021). WF-based planning would reduce pressure on aquifers, slowing land subsidence and salinization (Motagh et al., 2017). Groundwater recovery programs could be designed using WF data, enhancing long-term resilience (Madani et al., 2016). Environmental ecosystems such as Lake Urmia could be partially restored by reducing unsustainable withdrawals in upstream areas (AghaKouchak et al., 2015). Similarly, rivers like Zayandeh-Rud could experience seasonal flow restoration, benefiting both biodiversity and local communities (Gohari et al., 2013). WF adoption would also reduce grey water pollution by quantifying the impact of chemical use, thus driving stricter environmental regulations (Mekonnen & Hoekstra, 2011). Farmers would be incentivized to adopt eco-friendly practices, improving soil and water quality in the long term (Keshavarz et al., 2013). Urban areas would also benefit. WF can trace hidden water consumption in industrial and domestic goods, enabling municipalities to design better demand-side policies (Hoekstra, 2017). Public awareness campaigns based on WF data could encourage conservation at the household level (UNEP, 2020). Economically, WF would strengthen Iran's food security by ensuring that scarce water resources are used strategically (FAO, 2021). Instead of subsidizing unsustainable crops, resources could be reallocated toward modern irrigation technologies and more productive crops (World Bank, 2021). Virtual water trade would be optimized: importing water-intensive goods from abroad while exporting water-efficient products (Hoekstra, 2017). This would reduce Iran's vulnerability to both domestic shortages and international market shocks (Madani, 2014). Socially, WF adoption could stabilize rural livelihoods. With guidance and support, farmers could transition to sustainable practices without losing income (Keshavarz et al., 2013). Reducing migration pressures would slow the depopulation of rural areas, preserving cultural heritage and agricultural productivity (Ebrahim et al., 2020). Politically, WF would enhance inter-provincial cooperation by providing a transparent and standardized framework for water allocation (Gohari et al., 2013). It would also strengthen Iran's position in international negotiations, aligning the country with global sustainability standards (UNEP, 2020). Adopting WF could open access to international funding and partnerships, facilitating investments in water-saving technologies (World Bank, 2021). WF adoption would also create opportunities for cross-border cooperation on transboundary rivers, reducing regional tensions (Madani et al., 2016). On a cultural level, WF could help shift societal perceptions about wa-

ter from being seen as abundant and free to being understood as a scarce and valuable resource (Hoekstra, 2017). Educational programs could integrate WF concepts, fostering water literacy among younger generations (UNEP, 2020). From a technological perspective, WF adoption would encourage the use of GIS, remote sensing, and big data in water management (FAO, 2021). This would modernize Iran's institutional capacity, making management more adaptive and science-based (World Bank, 2021). While challenges exist—including resistance from vested interests in agriculture—WF provides a roadmap for overcoming inefficiencies (Madani, 2014). Transition policies could include subsidies for efficient irrigation, penalties for unsustainable practices, and training for farmers (Karandish & Hoekstra, 2017). By institutionalizing WF, Iran would also ensure long-term monitoring and accountability in water use (Hoekstra, 2017). In the long run, WF adoption would help Iran move from a crisis-driven approach to a resilience-oriented governance system (AghaKouchak et al., 2015). Ultimately, WF adoption offers a pathway toward ecological recovery, economic stability, and social equity, providing hope for a sustainable water future in Iran.

Results

The water footprint (WF) assessment of Iran revealed that agricultural activities account for nearly 90% of total water withdrawals, with blue water consumption being disproportionately high in provinces such as Fars, Khuzestan, and Isfahan (Karandish & Hoekstra, 2017). Virtual water flows demonstrated that Iran is effectively a net exporter of water through the production and export of water-intensive crops, while simultaneously facing critical domestic shortages (FAO, 2021). Grey water analysis indicated alarming levels of pollution, particularly from nitrogen fertilizers in agricultural basins, surpassing safe thresholds for both surface and groundwater (Mekonnen & Hoekstra, 2011). Scenario modeling showed that under the non-adoption pathway, groundwater depletion will intensify, leading to irreversible subsidence in several aquifers by 2040, while agricultural productivity will sharply decline (Motagh et al., 2017). In contrast, the WF adoption scenario indicated significant potential for reducing water stress: crop diversification, improved irrigation efficiency, and optimized trade could cut agricultural blue water consumption by up to 25% within two decades (Hoekstra, 2017). GIS-based mapping highlighted hotspots where WF adoption could have the greatest positive impact, including central provinces and the Urmia and Zayandeh-Rud basins, suggesting priority regions for policy intervention.

Conclusion

The findings confirm that Iran is at a critical turning point in its water management strategies. Continued reliance on conventional approaches will deepen ecological degradation and socio-economic vulnerabilities. The absence of WF adoption will lock the country into a cycle of ground-water depletion, soil salinization, and food insecurity, while intensifying social unrest and migration (Madani, 2014). Conversely, the integration of WF into national planning provides a scientifically grounded and globally recognized tool for aligning water use with ecological and social realities (Hoekstra, 2017). By adopting WF, Iran could transition from reactive crisis management to proactive governance, optimizing crop choices, improving water quality, and strengthening food security. The results also highlight that WF adoption is not merely a technical fix but a governance reform, requiring institutional restructuring, stakeholder engagement, and long-term monitoring (UNEP, 2020). Ultimately, the future of Iran's water security hinges on political will and societal commitment. WF offers a pathway toward ecological recovery, economic resilience, and social stability, but its benefits will only materialize if integrated into coherent and sustained policy frameworks.

In conclusion, the adoption of WF is not optional but essential. It represents a pivotal opportunity for Iran to secure its water future and safeguard the well-being of future generations.

Iran is already among the most water-stressed countries in the world (Mekonnen & Hoekstra, 2016). If the Water Footprint (WF) methodology is not adopted, the country will likely continue on its unsustainable path of resource exploitation. In the absence of WF-informed policies, agricultural water consumption—currently around 90% of total withdrawals—will remain inefficient and poorly managed (FAO, 2021).

Crops such as rice, wheat, and sugarcane, grown in unsuitable arid regions, will continue to consume vast amounts of scarce blue water, pushing aquifers into deeper decline (Madani, 2014). Groundwater depletion will worsen, leading to irreversible phenomena such as land subsidence, which has already been reported in Tehran and Isfahan provinces (Motagh et al., 2017). Over-extraction will also cause salinization, making agricultural land infertile and reducing crop yields, thereby further increasing Iran's dependency on food imports (Karandish & Hoekstra, 2017).

Conflict of 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

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: Jun. 2026 Accepted: Jun. 2026

Published online: Jun. 2026

DOI: 10.22034/ASAS.2026.513660.1078

References

- AghaKouchak, A., Norouzi, H., Madani, K., Mirchi, A., Azard-erakhsh, M., Nazemi, A., ... & Hasanzadeh, E. (2015). Aral Sea syndrome desiccates Lake Urmia: Call for action. *Journal of Great Lakes Research*, 41(1), 307-311.
- Ebrahim, Z., Mirchi, A., & Madani, K. (2020). Water scarcity and food security in Iran: Challenges and opportunities. *Food Security*, 12(5), 899-918.
- FAO. (2021). AQUASTAT database. Food and Agriculture Organization of the United Nations.
- Gohari, A., Eslamian, S., Mirchi, A., Abedi-Koupai, J., & Madani, K. (2013). Water transfer as a solution to water shortage: A fix that can backfire. *Journal of Hydrology*, 491, 23-39.
- Hoekstra, A. Y. (2017). Water footprint assessment: Evolutions in concept and methodology. *Ecological Indicators*, 80, 69-82.
- The lack of WF adoption will exacerbate social inequalities, as rural communities dependent on agriculture will be disproportionately affected by water shortages (Ebrahim et al., 2020).

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