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Posted Date: July 8th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9408620/v1

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Additional Declarations: No competing interests reported.

Blue Water Footprint of Hydropower Generation under Arid and Semi-Arid Climatic Conditions

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ABSTRACT

Hydroelectric power plants are key sources of electricity globally and are typically built with dams that store river water in reservoirs. However, significant water loss occurs through evaporation from these open surfaces, reducing availability for other sectors. This study aims to quantify the blue water footprint of hydropower generation in Iran by applying the concept of the blue water footprint to assess evaporation-related water consumption in 25 hydroelectric power plants across the country from 2004 to 2021. Data on evaporation volume (cubic meters, m^3) and electricity generation (terajoules, TJ) were analyzed. Results showed wide variation in water footprints among plants. The Golab plant had the highest at 283852.15m^3/TJ, while the Shah Qasim in Yasuj had the lowest at 323.22 m^3/TJ. Annually, the blue water footprint peaked in 2021 (11136.44m^3/TJ) and was lowest in 2008 (3690.31m^3/TJ), with an average of 7313.3 m^3/TJ across all plants. Hydropower plants in hot and dry regions showed the highest rates of water loss (BWF), indicating the need for improved reservoir management in water-scarce regions. This methodological approach provides a comprehensive framework for linking hydropower water use to climatic variability, offering a novel perspective for assessing the sustainability of energy–water interactions under changing climate conditions. Evaporation rates were strongly influenced by climate conditions such as high temperatures, drought, and climate variability intensified water losses. These values are generally higher than those reported in studies from other regions, mainly due to the arid climate and high evaporation rates from reservoirs in Iran. These findings highlight the critical need to consider evaporation impacts and climate variability when assessing the sustainability of hydropower in water-scarce regions like Iran. Future studies are recommended to integrate climate projections and operational optimization to reduce water losses in similar arid regions

Keywords: "Hydropower", "Blue Water Footprint", "Sustainability", "Evaporation", "Climate Variability", "Iran"

1. Introduction

Freshwater resources are a fundamental basis for human welfare, ecosystem functioning, and economic development, yet their availability is increasingly constrained at global and regional scales. Growing water demand driven by population growth, economic expansion, and changing consumption patterns, together with the impacts of climate change on hydrological systems, has intensified pressure on limited freshwater resources (Gleick, 2018). These challenges are particularly pronounced in arid and semi-arid regions, such as Iran, where the need for innovative approaches to monitor and assess water consumption is more urgent than ever. A key indicator in evaluating water use is the Water Footprint (WF), which quantifies the amount of direct and indirect water consumed in the production of goods or services. Among its three components: blue, green, and grey; the blue water footprint specifically represents the volume of surface and groundwater consumed and not returned to the same catchment. This metric is especially important in water-intensive sectors such as energy production (Hoekstra, 2017). The water footprint can be assessed at individual, sectoral, or national levels and serves as an analytical tool for demand management, resource optimization, and water policy planning. In countries facing water scarcity and climatic stress, integrating water footprint analysis into resource management is essential for ensuring sustainability and improving water-use efficiency (Zhang et al., 2022). Among energy sources, hydropower plants play a vital role in providing renewable and relatively clean electricity. However, these facilities often rely on large reservoirs, from which considerable volumes of water are lost through evaporation. In warm and dry climates, this evaporation loss can significantly increase the water footprint of electricity generation and pose challenges for the long-term sustainability of hydropower. Assessing the water footprint of hydropower systems offers a clearer picture of the hidden water costs associated with electricity production and can help inform efficiency improvements and sustainable development strategies (Pfister et al., 2017). Numerous global studies have investigated the water footprint of electricity production.

Several studies conducted in Brazil have further advanced the assessment of hydropower water footprints, particularly by addressing evaporation losses from large multipurpose reservoirs in tropical climates. Early efforts to quantify the water footprint of hydropower systems highlighted the significant role of reservoir evaporation in determining water consumption associated with electricity generation. One of the pioneering studies in this field was conducted by Herath et al. (2011), who introduced a methodological framework for estimating the water footprint of hydropower by allocating reservoir evaporation losses to electricity production. Their study demonstrated that, particularly in large reservoir-based hydropower systems, evaporation can constitute a dominant component of consumptive water use and should be explicitly accounted for in water footprint assessments. This work provided an important foundation for subsequent studies aimed at refining allocation methods and improving the accuracy of hydropower water footprint calculations (Herath et al., 2011).

For example, Mekonnen and Hoekstra (2012) compared the water footprint of different energy sources on a global scale and reported that hydropower has the highest water consumption per kilowatt-hour of electricity generated (Mekonnen & Hoekstra, 2012). Similarly, Zhao and Liu (2015) introduced innovative methods for allocating water footprints among the multiple functions of reservoir systems (Zhao & Liu, 2015). Delgado (2012) emphasized the utility of water footprint analysis as a policy-making tool in regions with high water stress by analyzing future scenarios (Delgado, 2012). Zhang et al. (2019) emphasized the importance of properly allocating evaporation losses in multi-purpose reservoirs when estimating the blue water footprint of hydropower. Their study on the Miyun Reservoir Hydropower Station (1985–2013) showed that neglecting the multiple ecological and service functions of reservoirs can lead to a significant overestimation of hydropower-related water use. By applying an allocation coefficient to distribute evaporation losses among different water uses, they demonstrated a more realistic evaluation of water consumption (Zhang et al., 2019). These findings highlight the need to consider reservoir multifunctionality and temporal variability in hydropower water footprint assessments, aspects often overlooked in large-scale national studies. Vaca-Jiménez et al. (2019) investigated the interdependence between water availability and electricity generation dynamics, emphasizing how fluctuations in freshwater resources influence the blue water footprint (WF) of national electricity mixes. Using Ecuador's Amazon and Pacific basins as case studies, they demonstrated that variations in hydropower output due to changing water availability lead to significant temporal fluctuations in the overall WF of electricity generation (Vaca-Jiménez et al., 2019). Their findings underscore the importance of integrating water–energy nexus assessments into energy planning, particularly in countries where hydropower dominates electricity production. Hogeboom et al. (2018) conducted a comprehensive global assessment of the blue water footprint of artificial reservoirs, quantifying evaporation losses and attributing them to multiple reservoir purposes such as hydroelectricity generation, irrigation, domestic and industrial water supply, and flood control based on their economic value. Their analysis of over 2,200 reservoirs showed that hydropower and water supply are the largest contributors to the global reservoir-related blue water footprint, which totals approximately 66×10^9 m^3 per year (Hogeboom et al., 2018). The study highlighted how the primary purpose of reservoirs shifts with increasing water scarcity—from hydropower generation in water-abundant basins to water supply and irrigation in more arid regions such as emphasizing the need for integrated water and energy management. In Iran, although research in this area is relatively limited, several studies have addressed aspects of the water footprint in the energy sector. For instance, Golabi et al. (2019) analyzed the water footprint of electricity produced by domestic hydropower plants (Golabi et al., 2019). Sadeghi et al. (2016) employed a social accounting matrix approach to assess water footprints across various economic sectors (Sadeghi, 2016). Mousavi Reine and Yousefi (2020), focusing on renewable energy, found that water consumption costs in wind, gas, and photovoltaic power plants are lower than in thermal and combined-cycle plants—highlighting the significance of choosing appropriate cooling systems to reduce water use (Mousavi Reine & Yousefi, 2020). Razavi Kahnamuee (2020) also pointed out challenges in fully implementing the water footprint framework in Iran, such as limited local data

and a lack of foundational studies, which hinder the development of effective and quantitative water reduction policies (Razavi Kahnamuee, 2020). Given the scarcity of comprehensive case studies in this area and the identified research gap, the present study quantifies and analyzes the blue water footprint associated with evaporation losses from 25 hydropower plants across Iran during the period 2004–2021. The results aim to provide actionable insights into regional water-use efficiency and practical guidance for improving the sustainability of hydropower under increasing climatic stress and water scarcity conditions.

2. Material and Methods

This study is applied in nature and employs a descriptive-analytical approach. The statistical population comprises 73 active and operational hydroelectric power plants across Iran. From this population, 25 power plants were purposively selected based on their consistent operation throughout the study period (2004–2021).

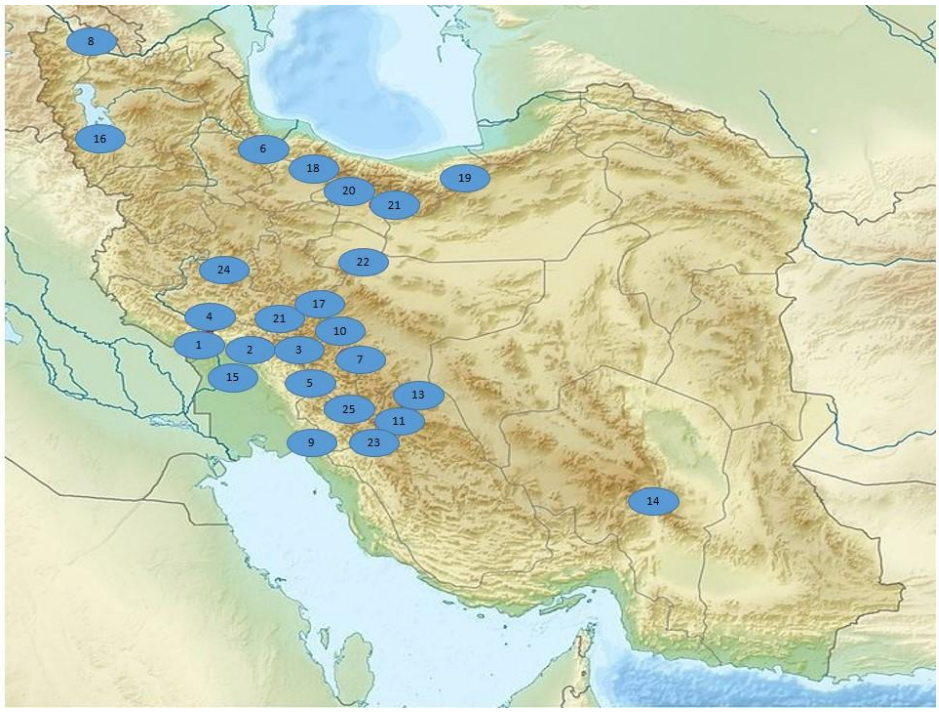


Figure 1. Location map of the study area showing the selected dams and associated hydropower plants.

1.Karkheh , 2. Shahid Abbaspour , 3. Karoon 3 , 4. Dez , 5. Karoon 4 , 6. Sefid Rood, 7. Zayandeh Rud , 8.Aras, 9. Maroon , 10. Golab, 11.Dorudzan, 12. Lar, 13.Mollasadra, 14.Jiroft, 15. Masjed

Soleiman, 16.Mahabad , 17.Rudbar Lorestan, 18.Amir Kabir, 19. Shahid Rajaei, 20. Latian, 21.Kouhrang, 22.Vefarqan, 23.Shahid Talebi, 24.Gamasiyab, 25. Shahgasem

The required data, including annual electricity production (in terajoules, TJ) and annual evaporation volumes from reservoir surfaces (in cubic meters, m^3), were obtained from official annual reports of the national electricity sector.

Specifically, statistical information was sourced from the national energy balance sheets, detailed statistical reports published by the Iran Water Resources Management Company, and data provided by the Hydropower Plants Management Center of Iran (IWPRD, 2021; SIN, 2021; WRM, 2021).

Calculation of Water Footprint in Hydroelectric Power Generation

Most hydroelectric power plants derive their energy from the potential energy stored in water retained behind a dam. The total water footprint of electricity generation ($WF_{e,\ otal}$) is calculated using Equation (1), as proposed by (Mekonnen et al., 2015):

$$WF_{e.Total} = WF_{e.c} + WF_{e.o} \qquad (1)$$

Where:

- $WF_{e,c}$ = Water footprint related to the construction phase of the dam and power plant
- $WF_{e,o}$ = Water footprint related to the operation phase of the hydropower plant

Due to the lack of detailed technical data and construction specifications for each of the dams included in this study, it was not feasible to calculate the exact construction-phase water footprint for each plant. Therefore, the average construction-phase water footprint reported by Golabi et al. (2019) was used as a proxy. According to their findings, the average water footprint associated with the construction of various types of hydropower plants is approximately 0.3 m^3/TJ. Based on this value, the total water footprint of electricity production was estimated for each plant in the current study.

The operational-phase water footprint of hydroelectric power generation from reservoir surfaces ($WF_{e,o}$) was calculated using Equation (2):

$$WF_{e.o} = \frac{E_o}{P} \qquad (2)$$

Where:

- E_o = Annual volume of water evaporated from the open surface of the reservoir (m^3)
- P = Annual electricity production by the hydropower plant (TJ)

This equation quantifies the volume of evaporated water per unit of energy produced, providing a measure of water use efficiency during the operation of the hydropower plant.

It is important to note that many reservoirs are designed and operated for multiple purposes, including hydropower generation, agricultural irrigation, flood control, and more. Attributing the entire volume of reservoir evaporation solely to hydropower generation would result in an overestimation of the water footprint. To avoid this error, the allocation approach proposed by (Scherer & Pfister, 2016) was employed.

In this approach, an "allocation factor" is determined based on the priority ranking of hydropower among the multiple objectives of the reservoir. For instance, if a reservoir has five purposes and hydropower is ranked third in priority, only 20% (1 divided by the rank of 5) of the total evaporation is allocated to hydropower. This ratio, referred to as the allocation factor (f_A), was calculated for each reservoir by identifying its objectives, assigning a rank to hydropower generation, and computing the corresponding share of evaporation. The identified purposes and benefits of the reservoirs included hydropower generation, irrigation, aquaculture, tourism development, flood control, and domestic water supply.

The allocation factor was calculated using Equation (3):

$$f_A = \frac{n + 1 - r}{\sum_{i=1}^{n} i}$$

Where:

- f_A: Allocation factor
- n: Total number of objectives of the reservoir
- r: Rank of hydropower generation among the objectives

The denominator represents the sum of the integer series from 1 to n, accounting for all objectives

Reservoir objectives and their priority rankings were identified from official dam operation reports published by the Iran Water Resources Management Company and the Iran Water and Power Resources Development Organization. The ranking assigned to hydropower generation reflected its operational priority relative to other reservoir functions. This approach follows the allocation principles proposed by Scherer and Pfister (2016) and has been adopted in previous water-footprint assessments of multipurpose reservoirs.

Sensitivity Analysis of Allocation Assumptions

The allocation of reservoir evaporation among competing reservoir purposes represents one of the major sources of uncertainty in hydropower water footprint assessments. To evaluate the influence of allocation assumptions on the estimated blue water footprint (BWF), a sensitivity analysis was performed using three alternative allocation approaches.

The first scenario corresponds to the ranking-based allocation method adopted in this study, following Scherer and Pfister (2016), in which reservoir evaporation is distributed according to the relative priority of hydropower among reservoir purposes. The second scenario assumes equal allocation of evaporation losses among all reservoir purposes, where the allocation factor is calculated as: fA = 1/n

where n represents the total number of reservoir purposes. The third scenario assumes full allocation of reservoir evaporation to hydropower generation (fA = 1.0), representing the upper-bound estimate of the blue water footprint.

For each allocation scenario, the operational blue water footprint was recalculated while maintaining the same reservoir evaporation and electricity production values. Because only the allocation factor was modified, the blue water footprint under each scenario was estimated as:

$$WF_{scenario} = WF_{baseline} \times \frac{FA_{scenario}}{FA_{baseline}} \qquad (4)$$

where WFscenario is the recalculated blue water footprint under the alternative allocation assumption, WFbaseline is the blue water footprint obtained using the ranking-based allocation approach adopted in this study, FAscenario is the allocation factor associated with the alternative scenario, and FAbaseline is the allocation factor used in the baseline calculation.

The resulting BWF values were then compared to evaluate the sensitivity of the estimates to alternative allocation assumptions.

In this study, the Kolmogorov–Smirnov test was used to assess the normality of the data. All statistical analyses were conducted using SPSS version 23, and Excel was used for computations and generating visualizations.

Figure 1 shows the flow chart of the overall study process, including data collection, processing, water footprint calculation, evaporation allocation to hydropower plants, statistical analysis, and interpretation of results. This diagram presents the methodological framework adopted to assess the water footprint of hydropower plants in this study step by step.

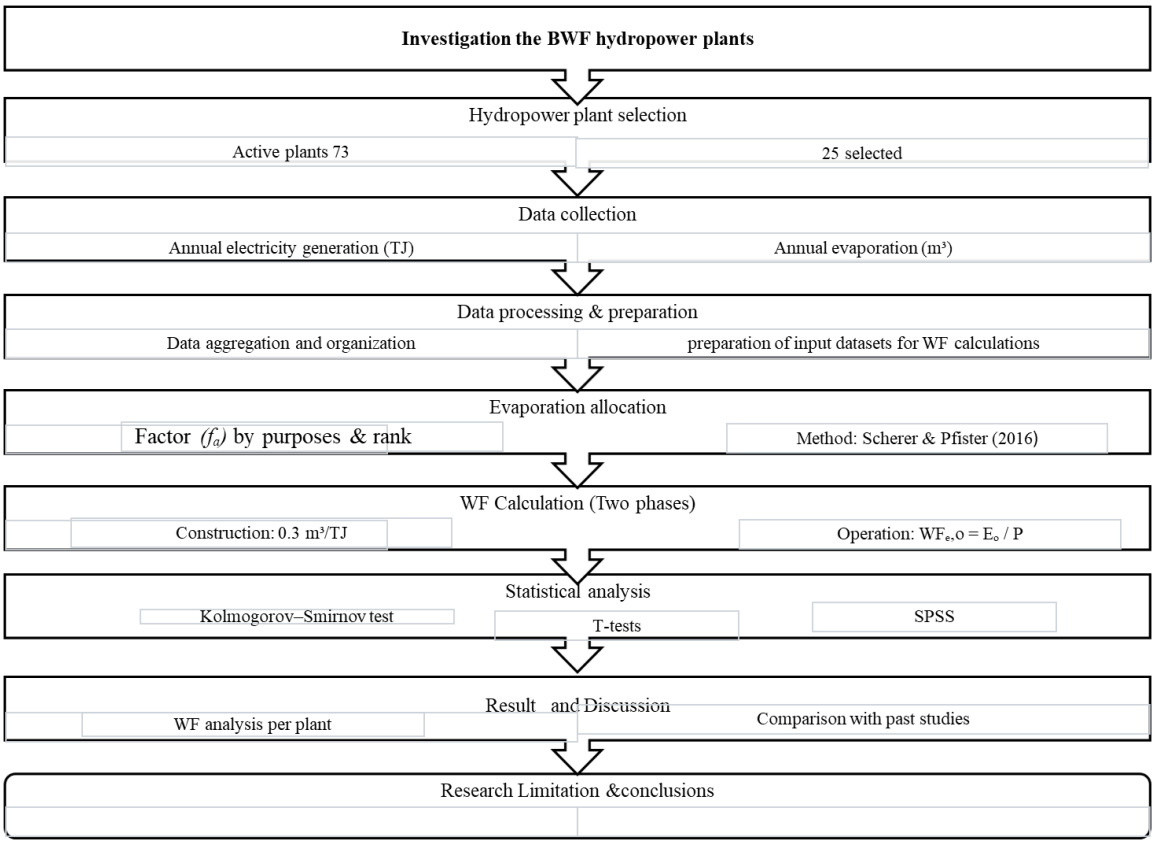


Figure 2: Flowchart of the Research Methodology

3. Results

Table 1 presents a summary of the main features of the studied hydropower plants, including their reservoir purposes, hydropower ranking, and the applied allocation factors. It also provides the components of the water footprint associated with electricity generation. The blue water footprint, calculated considering the allocation factor, is expressed both in cubic meters per megawatt-hour (m³/MWh) and cubic meters per terajoule (m³/TJ), representing the consumptive use of surface water resources for hydropower production.

Table 1. Summary of reservoir purposes, hydropower ranking, allocation factors, and water footprint components for the studied hydropower plants

No.		Reservoir Purposes	Reservoir objectives (n)	Hydropower rank (r)	allocation factor (F_A)	(WFe.o) (unadj. F_A) (m³/GWh)	Op. WF (WFe.o) (m³/GWh)	Construction phase $WF_{e.c}$	(WFe.o) (unadj. F_A) (m³/TJ)	(WFe.o) (m³/TJ)	Water Footprint $WF_{e.Total}$ (m³/TJe)

								(m^3/TJe)			
1	Karoon 1	AGR-HYD-FC	3	2	0.33	14046.5116	4635.34883	0.30	3901.8088	1287.596904	1287.896904
2	Karoon 3	FC-DWS-AGR-HYD	4	4	0.1	14851.3902	1485.13902	0.30	4125.3862	412.53862	412.83862
3	Masjed Soleiman	HYD	1	1	1	3151.3514	3151.3514	0.30	875.3754	875.3754	875.6754
4	Karoon 4	HYD-IND-AGR-FC	4	1	0.4	26688.8046	10675.52184	0.30	7413.568	2965.4272	2965.7272
5	Dez	HYD-FC-AGR	3	1	0.5	45916.9938	22958.4969	0.30	12754.4205	6377.21025	6377.51025
6	Karkheh	AGR-HYD-FC	3	2	0.33	170171.3062	56156.531046	0.30	47269.8073	15599.03631	15599.33631
7	Maroon	FC-DWS-AGR-HYD	4	4	0.1	67428.5714	6742.85714	0.30	18730.1587	1873.01587	1873.31587
8	Lar	AGR-DWS-HYD	3	3	0.16	193533.333	30965.333328	0.30	53759.2593	8601.481488	8601.781488
9	Aras	AGR-HYD	2	2	0.33	1360465.1163	448953.488379	0.30	377906.9767	124709.302311	124709.602311
10	Rudbar	HYD-TD	2	1	0.66	200408.1633	132269.387778	0.30	55668.9342	36741.496572	36741.796572
11	Zayandeh Rood	HYD-FC-AGR	3	1	0.5	134920	67460	0.30	37477.7778	18738.8889	18739.1889
12	Jiroft,	AGR-HYD-FC	3	2	0.33	186875	61668.75	0.30	51909.7222	17130.208326	17130.508326
13	Sefidrud	AGR-FC-HYD-DWS	6	3	0.19	168433.3333	32002.333327	0.30	46787.037	8889.53703	8889.83703

		- IND-FA									
14	Kouhrang	HYD	1	1	1	22421.875	22421.875.00	0.30	6228.2986	6228.2986	6228.5986
15	Ve-Furghan (Saveh)	HYD - DWS	2	1	0.66	27222.2222	17966.666652	0.30	7561.7284	4990.740744	4991.040744
16	Mollasadra	HYD - FC-DWS - AGR - IND	5	1	0.33	28647.0588	9453.52940	0.30	7957.5163	2625.980379	2626.280379
17	Latian	AGR - DWS - HYD	3	3	0.16			0.30	15793.6508	2526.984128	2527.284128
18	Amir Kabir	DWS - FA-HYD - TD	4	3	0.20	24866.6667	4973.33334	0.30	6907.4074	1381.48148	1381.78148
19	Shahid Rajaee	AGR - TD-FC-DWS - HYD	5	5	0.06	70645.1613	4238.709678	0.30	19623.6559	1177.419354	1177.719354
20	Golab	AGR - IND-DWS - HYD	4	4	0.16	6386666.6667	1021866.666672	0.30	1774074.0741	283851.851856	283852.151856
21	Doroudzan	DWS - AGR – FA-HYD	4	4	0.16	1012527.4725	162004.3956	0.30	281257.66313	45001.2261008	45001.52261008
22	Mahabad	HYD - FA	2	1	0.66	64470588.23532	42550588.235298	0.30	179084.9673	118196.078418	118196.378418
23	Gerin	DWS - HYD	2	2	0.33	134615.3846	44423.076918	0.30	37393.1624	12339.743592	12340.043592
24	Sheshpir (Shhid Talebi)	AGR - DWS - HYD	3	3	0.16	100000	16000	0.30	27777.7778	4444.444448	4444.744448
25	Shahghasem Yasouj	DWS - AGR - TD-FC-HYD	5	5	0.06	19375	1162.5	0.30	5381.9444	322.916664	323.216664

Note: AGR: Agriculture; FC: Flood control; HYD: Hydroelectric energy production; DWS: Drinking water supply; IND: Industry; FA: Fisheries and aquaculture; TD: Tourism development.

According to Table 2, the selected hydroelectric power plants were classified into three categories based on their generation capacity: large, medium, and small. The majority of the plants (11 out of 25) fall into the medium-capacity category.

Table 2. Classification of Selected Hydroelectric Power Plants Based on Generation Capacity

Power Plant Group	Number of Plants	Capacity (MW)	Plant Names
Large Power Plants	8	>100	Karoon 1, Karoon 3, Masjed Soleiman, Karoon 4, Dez, Karkheh, Marun, Lar
Medium Power Plants	11	10-100	Mollasadra, Amir Kabir, Sefidrud, Zayandeh Rood, Rudbar, Latian, Kouhrang, Jiroft, Aras, Shahid Rajaee, Saveh (Al-Ghadir)
Small Power Plants	6	<10	Doroudzan, Mahabad, Yasouj, Golab, Gerin, Shahid Talebi

As shown in Figure 3, among the selected hydropower plants, the largest reservoir capacities belong to Karkheh Dam (5,575 MCM), Karoon-1 (Shahid Abbaspour) with 3,139 MCM, and Karoon-3 with 2,970 MCM. The smallest reservoir capacity is associated with Shah Ghasem Yasouj Dam, with only 9 MCM.

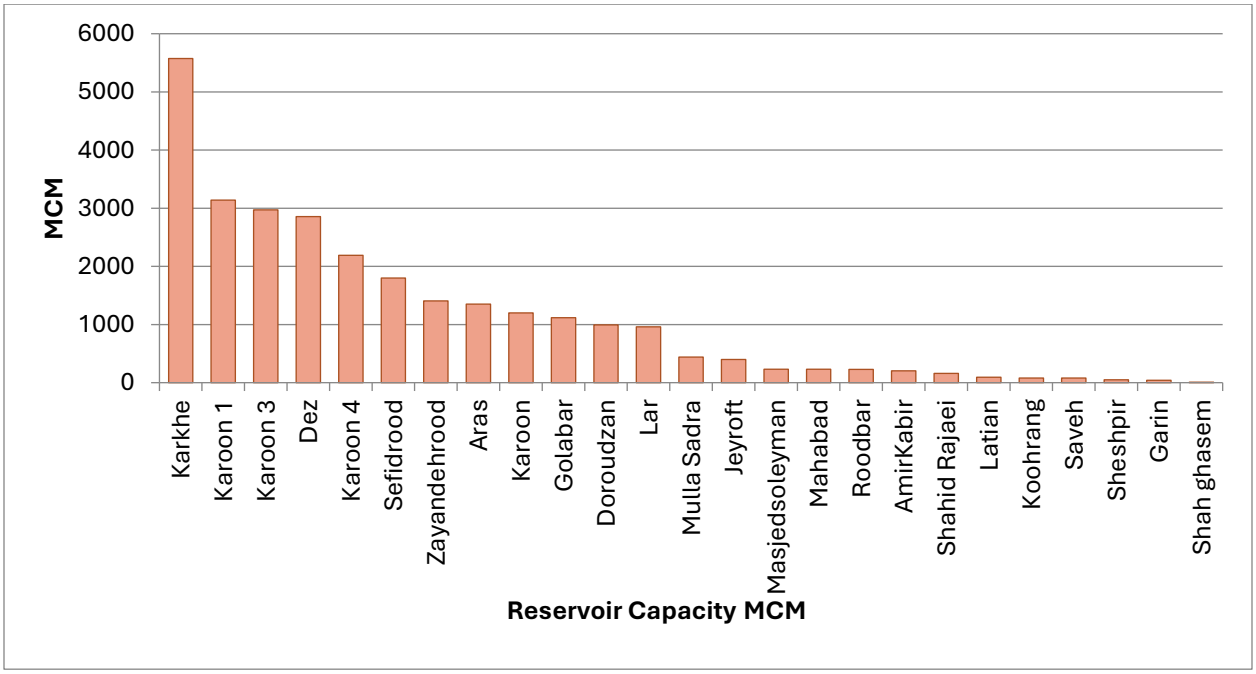


Figure 3: Storage Capacities of the Studied Hydropower Plant Reservoirs

According to Figure 4, the highest installed generation capacity among the selected hydropower plants belongs to Karoon-1 (Shahid Abbaspour), Karoon-3, and Masjedsoleyman, each with a capacity of 2,000 MW. The lowest capacity is associated with the Shahid Talebi hydropower plant, with a total generation capacity of 2.25 MW

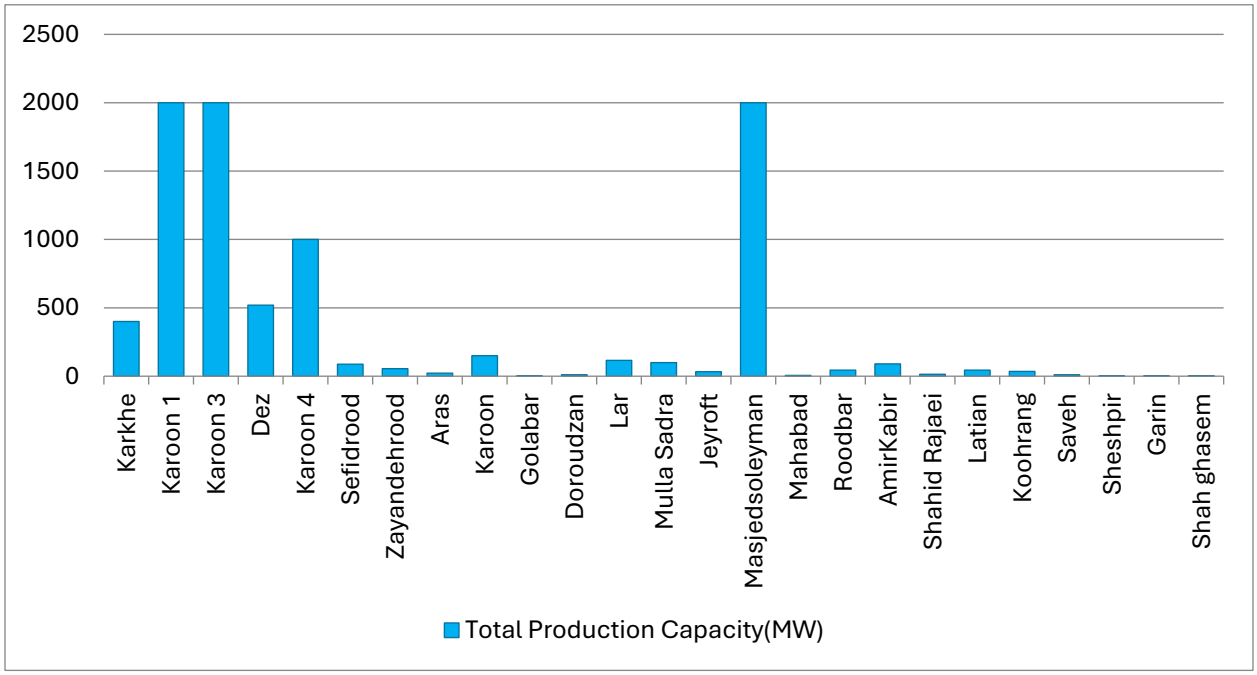


Figure 4. Total Generation Capacity of the Studied Hydropower Plants

According to Figure 5, the highest average annual electricity production among the selected hydropower plants belongs to Karoon-1 (Shahid Abbaspour) with 4300 GWh, followed by Karoon-3 with 4172 GWh, and Masjed Soleyman with 3700 GWh. The lowest average annual production is observed at the Golab hydropower plant, with only 4.5 GWh.

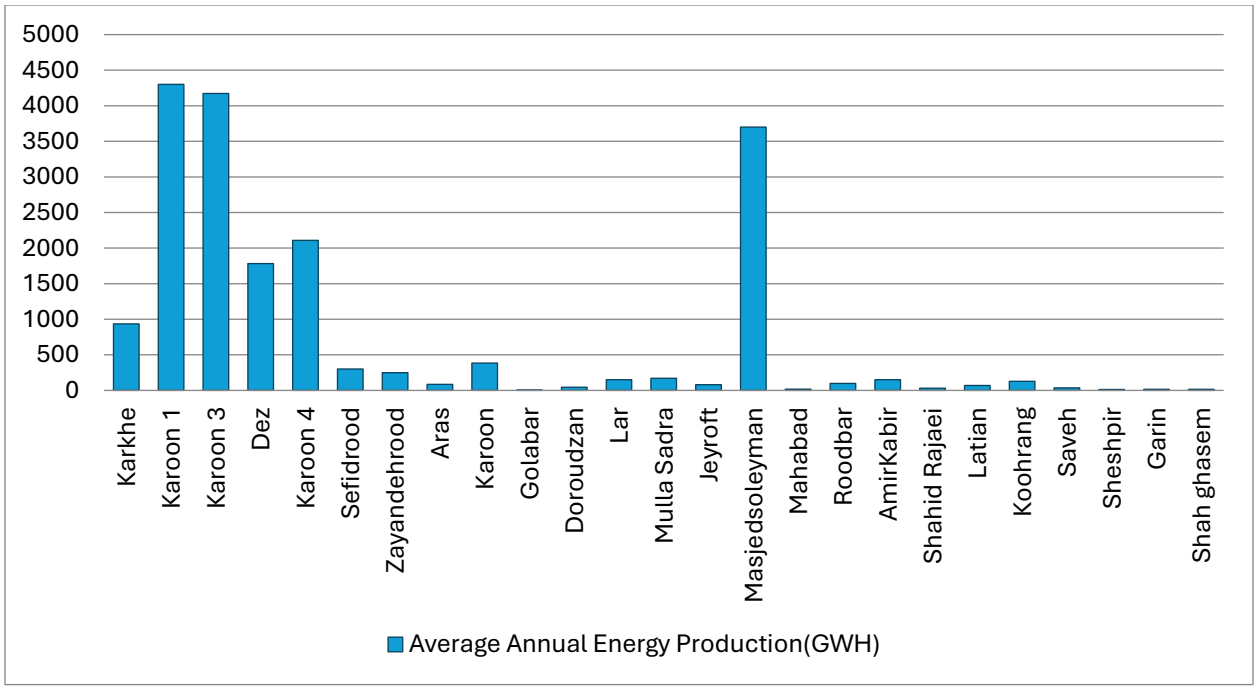


Figure 5: Average annual energy production of the studied hydropower plants

According to Figure 6, the highest average annual evaporation volumes among the reservoirs of the selected hydropower dams are observed in Karkheh (158.94 MCM), Aras (117 MCM), and Dez (81.87 MCM). The lowest evaporation volume is recorded at the Shah Ghasem Yasouj reservoir, with only 0.31 MCM annually.

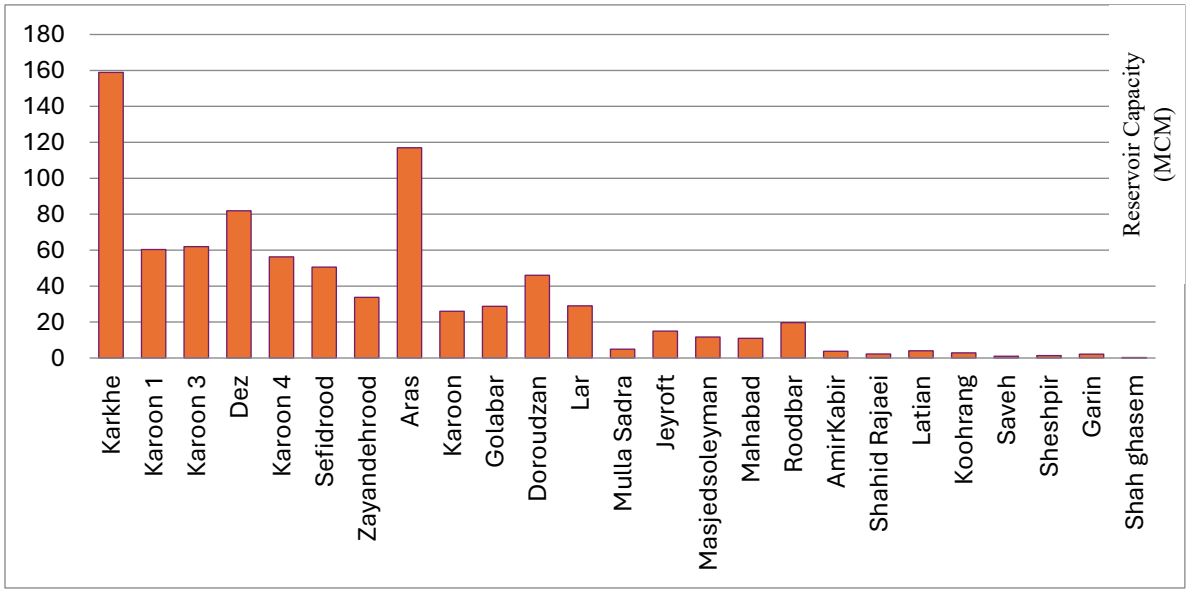


Figure 6: Average annual evaporation volumes in the reservoirs of the selected hydropower dams

The classification of the selected large, medium, and small hydropower plants based on generation capacity is presented in Tables 2, 3, and 4, respectively.

Table 3. *Blue water footprint in large hydropower plants*

Rank	Large hydropower Plants	BWF (m^3TJ^{-1})
1	Karkheh	15599.3363
2	Lar	8601.7815
3	Dez	6377.5103
4	Karoon 4	2965.7272
5	Maroon	1873.3159
6	Karoon 1	1287.8969
7	Masjed Soleiman	875.6754
8	Karoon 3	412.8386

Table 3 presents the blue water footprint (m^3/TJ) of large hydropower plants with an installed capacity of more than 100 MW.

Table 3 presents the ranking of large hydropower plants (capacity >100 MW) based on total blue water footprint. Karkheh has the highest footprint (15599.3363 m^3/TJ), while Karoon-3 has the lowest (412.8386 m^3/TJ).

Table 4. *Blue water footprint in medium hydropower plants*

Rank	Medium hydropower Plants	BWF (m^3TJ^{-1})
1	Aras	124709.6023
2	Rudbar	36741.7966
3	Zayandeh Rood	18739.1889
4	Jiroft	17130.5083
5	Sefid Rood	8889.8370
6	Kohrang	6228.5986
7	Ve-Furghan	4991.0407
8	Mullasadra	2626.2804
9	Lattian	2527.2841
10	Amir Kabir	1381.7815
11	Shahid Rajaie	1177.7194

As shown in Table 4, medium-sized hydropower plants (with 10 < MW < 100) are ranked by total blue water footprint. The highest value belongs to Aras (124709.6023), and the lowest to Shahid Rajaee (1177.7194) m^3/TJ.

Table 5: *Blue water footprint in small hydropower plants*

Rank	Small hydropower Plants	BWF (m^3TJ^{-1})
1	Golab	283852.1519
2	Mahabad	118196.3784
3	Dorudzan	45001.5226
4	Garin	12340.0436
5	Shahid Talebi	4444.7444
6	Shah Qasem Yasouj	323.2167

According to Table 5, small hydropower plants (with generation capacity < 10 MW; n = 6) are ranked based on total blue water footprint. The highest value is for Golab (283852.1519), and the lowest for Shah Ghasem–Yasouj (323.2167) m^3/TJ.

Based on the calculations, the highest total blue water footprint across all hydropower plants was recorded in 2021 (11136.44 m^3/TJ), while the lowest occurred in 2008 (3690.31 m^3/TJ). The annual trend of blue water footprint for the period 2004–2021 is illustrated in Figure 6.

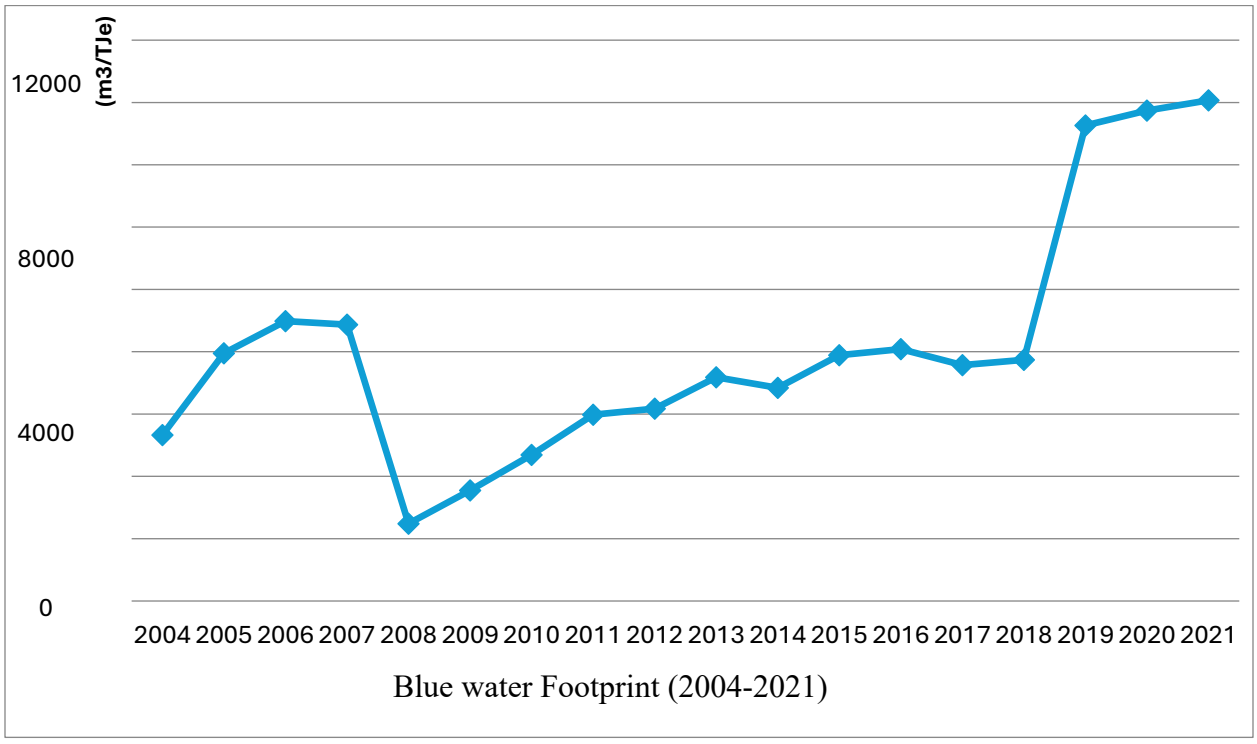


Figure 7. Trend of total blue water footprint in the studied hydropower plants during 2004–2021

As shown in Figure 7, the blue water footprint of power plants in 2021 increased significantly compared to other years. This can be attributed to the specific climatic conditions of the hydrological year ending in the summer of 2021. During this period, Iran experienced one of the driest years of the past half-century, with average precipitation about 50% lower than the previous year and 40% below the long-term mean. In many regions, rainfall shortages ranged from 50% to 85%, while air temperatures in the spring of 2021 were about 2–3°C higher than the long-term average (ISNA, 2021).These conditions led to increased evaporation and reduced surface water resources, resulting in a substantial rise in the blue water footprint of power plants in that year. To examine the relationships between the variables, the normality of the data was first tested using the Kolmogorov–Smirnov test.

Sensitivity Analysis of Allocation Assumptions

To evaluate the influence of reservoir evaporation allocation on the estimated blue water footprint (BWF), a sensitivity analysis was performed using three alternative allocation approaches. The first approach corresponds to the ranking-based allocation method adopted in the present study. The second assumes equal allocation of reservoir evaporation among all reservoir purposes (fA = 1/n), while the third assigns all evaporation losses exclusively to hydropower generation (fA = 1.0). Representative hydropower plants covering a wide range of BWF values were selected to illustrate the impact of alternative allocation assumptions. The results are presented in Table 6.

Table 6. Comparison of blue water footprint estimates under alternative reservoir evaporation allocation assumptions

Hydropower Plant	Reservoir Purposes (n)	Baseline Allocation (Current Study) (m^3/TJ)	Equal Allocation (fA = 1/n) (m^3/TJ)	Full Allocation (fA = 1.0) (m^3/TJ)
Karoon 3	4	412.84	1,032.10	4,128.39
Karkheh	3	15,599.34	15,756.91	47,269.81
Aras	2	124,709.60	188,953.98	377,906.98
Shahid Rajaee	5	1,177.72	3,925.73	19,623.66
Golab	4	283,852.15	443,518.99	1,774,074.07
Shah Ghasem Yasouj	5	323.22	1,076.39	5,381.94

Note: Baseline values represent the ranking-based allocation approach adopted in this study. Equal allocation assumes that reservoir evaporation is distributed equally among all reservoir purposes (fA = 1/n), whereas full allocation assumes that all evaporation losses are attributed to hydropower generation (fA = 1.0).

The sensitivity analysis confirms that the estimated blue water footprint is strongly influenced by the selected allocation approach. As expected, assigning all reservoir evaporation losses to hydropower generation produced the highest BWF estimates, while equal allocation among

reservoir purposes resulted in intermediate values. For example, the estimated BWF of the Golab hydropower plant increased from 283,852 m^3/TJ under the baseline scenario to 1,774,074 m^3/TJ under full allocation. Similarly, the BWF of Aras increased from 124,710 m^3/TJ to 377,907 m^3/TJ. Despite these differences in magnitude, the relative ranking of hydropower plants remained generally unchanged, indicating that the principal conclusions of the study are robust with respect to alternative allocation assumptions. These findings highlight the importance of allocation choice in hydropower water footprint studies and support the need for transparent reporting of allocation procedures.

5. Discussion

This study assessed the Blue Water Footprint (BWF) associated with electricity production from 25 operational hydropower plants in Iran over the period 2004–2021. The selected power plants were classified into three categories based on their installed capacity: large (>100 MW), medium (10–100 MW), and small (<10 MW). The results demonstrated that small-scale hydropower plants, despite their relatively low energy output, exhibited the highest BWF per terajoule (TJ) of electricity produced. Among the large plants, the Karkheh hydropower facility exhibited the highest BWF, while Karoon 3 had the lowest. In the medium-size category, the Aras plant showed the highest BWF, while Shahid Rajaee had the lowest. Similarly, among the small-scale facilities, Golab recorded the highest BWF at 283852.15 m^3/TJ, and Shah Ghasem Yasouj exhibited the lowest at 323.22 m^3/TJ. These findings highlight the critical influence of local climatic conditions, reservoir design, and dam operation strategies on water use efficiency.

Interpretation of Spatial Variations in Blue Water Footprint

The observed differences in the blue water footprint among hydropower plants across Iran can be attributed to a combination of climatic, morphological, and operational factors. Plants located in arid and semi-arid zones, such as Golab and Karoon-3, are exposed to higher potential evaporation due to elevated temperatures, low humidity, and prolonged dry seasons, resulting in greater evaporative losses from their reservoirs. In contrast, plants situated in relatively humid regions, such as Shah Qasem Dam, experience lower evaporation rates and consequently smaller water footprints. The morphology of the reservoirs also plays a decisive role: dams with large surface areas but shallow storage depths tend to have disproportionately high evaporation losses per unit of stored water. Furthermore, operational efficiency and the hydropower generation capacity factor influence the footprint intensity. Plants with irregular inflow regimes or low annual generation efficiency exhibit higher water footprints per megawatt-hour (MWh) of electricity produced.

When compared with global benchmarks, the estimated blue water footprints for Iranian hydropower plants are generally higher than those reported for temperate regions (e.g., Europe or North America) but are consistent with findings from other arid and semi-arid areas such as

southern Spain, South Africa, and northern China (Berger et al., 2016; Liu et al., 2024; Mekonnen & Hoekstra, 2012). This consistency suggests that the high evaporation rates typical of dry climates, combined with specific design and operational characteristics of reservoirs, are the primary determinants of water footprint magnitude in these contexts.

Mekonnen and Hoekstra (2012), for instance, reported a global blue water footprint (BWF) range of 0.3 to 846 m^3/GJ across 35 hydropower plants, emphasizing the influence of local environmental and technical conditions. Their results demonstrated that evaporation losses are a dominant factor shaping the BWF of hydropower, particularly in hot and arid climates. Higher evaporation rates in such regions lead to considerably larger water footprints per unit of electricity generated, as significant volumes of stored water are removed through surface evaporation. This pattern is consistent with the elevated BWF values observed for reservoirs located in Iran's arid and semi-arid zones, where limited precipitation and high potential evaporation substantially increase water consumption associated with hydropower generation. These observations highlight the necessity of explicitly accounting for climatic variability when evaluating the sustainability of hydropower systems in water-scarce environments. Similarly, Li et al. (2022) reported an average BWF of approximately 1.2 m^3/GJ in the Yalong River Basin, China—significantly lower than the values recorded in this study—due to wetter climate conditions and more efficient reservoir infrastructure (Li et al., 2022). Hoekstra et al. (2017) also noted that run-of-river systems tend to have minimal BWF values because of the absence of large reservoirs, which minimizes evaporation—a pattern consistent with the lower BWFs observed in small-scale facilities like Shah Ghasem Yasouj and Shahid Rajaee. Furthermore, an analysis of annual trends revealed considerable inter-annual variability in BWF across all studied plants. The highest annual BWF was recorded in 2021 at 11136.44 m^3/TJ, while the lowest was in 2008 at 3690.31 m^3/TJ. These fluctuations may be linked to a combination of factors, including climatic variability, drought conditions, declining reservoir levels, and changes in electricity production.Warmer and drier years lead to higher evaporation losses, while years with greater inflow or cooler conditions reduce evaporation and, consequently, the BWF. Similar observations have been reported by Gerbens-Leenes et al. (2018) and Wang et al. (2018), who emphasized the impacts of climate change and hydrological variability on the water footprint of energy production systems (Gerbens-Leenes et al., 2018; Wang et al., 2018).

Overall, this study underscores that beyond the installed capacity of hydropower plants, multiple factors such as the multi-purpose use of reservoirs, climatic conditions, local hydrology, and operational management play a significant role in determining the blue water footprint of electricity generation. These insights suggest that BWF should be incorporated as a key indicator in sustainability assessments and water resource planning, particularly in arid and semi-arid regions with high evaporation potential. The findings can serve as a valuable input for policymakers in developing sustainable hydropower strategies and promoting integrated water-energy management.

From a theoretical perspective, this study contributes to the broader discourse on the water-energy nexus by establishing a conceptual link between climatic variability and hydropower water-use

efficiency. The results demonstrate that evaporation-related water losses are not merely operational outcomes but are shaped by systemic climatic and management factors, thereby expanding the understanding of sustainability assessment in hydropower systems. From a policy standpoint, our findings underscore the need for integrating water footprint analysis into national energy planning frameworks. Practical strategies such as adopting run-of-river designs, applying evaporation control technologies, and aligning hydropower operations with climate adaptation plans can substantially reduce blue water footprints and enhance resilience in water-scarce regions.

Policy Implications and Mitigation Strategies

The findings of this study reveal that evaporation-related water loss constitutes a significant component of the blue water footprint (BWF) of hydropower generation in Iran, particularly under conditions of high temperature and climatic variability. These results have important implications for energy and water resource planning, highlighting the need for strategic interventions to enhance water-use efficiency in the hydropower sector. The following policy directions and mitigation strategies are proposed based on the study's outcomes:

(a) Prioritization of run-of-river and small-reservoir systems:

Future hydropower development should prioritize *run-of-river* configurations or smaller reservoirs with limited surface area-to-volume ratios. These systems inherently reduce evaporative losses while maintaining renewable energy generation capacity. Such approaches can be especially effective in arid and semi-arid basins where evaporation rates are high.

(b) Implementation of evaporation suppression techniques:

Adopting innovative methods to minimize open-surface evaporation can substantially reduce blue water losses. Possible measures include the use of floating solar panels or modular floating covers, which simultaneously enable hybrid solar-hydro power generation and minimize water loss. Additionally, optimizing reservoir geometry—by increasing depth and reducing exposed surface area—can improve storage efficiency.

(c) Integration of climate variability projections into hydropower design and operation:

Long-term climate projections should be systematically incorporated into hydropower scheduling, design, and management. Incorporating parameters such as drought frequency, temperature anomalies, and evaporation trends can improve adaptive capacity and ensure stable electricity production under changing climatic conditions.

(d) Promotion of integrated water–energy planning through the IWRM framework:

Given the strong interdependence between water availability and energy production, the *Integrated Water Resources Management (IWRM)* framework should be institutionalized in hydropower planning and operation. Coordinated governance between the water and energy

sectors can facilitate more equitable allocation of water resources, improve resilience to climate-induced stress, and support national sustainability objectives.

Collectively, these policy-oriented strategies provide a foundation for reducing the blue water footprint of hydropower systems while enhancing their long-term sustainability. Integrating these measures into Iran's energy planning frameworks can serve as a model for other arid regions facing similar trade-offs between renewable energy development and freshwater conservation.

Limitations and Uncertainties

Although this study provides valuable insights into the blue water footprint (BWF) of hydropower generation in Iran, several limitations and uncertainties should be acknowledged. First, the analysis relied on secondary data sources, including national reports and statistical yearbooks, which may contain inconsistencies or gaps in temporal and spatial coverage. Variations in measurement techniques and data reporting among different institutions could introduce uncertainty into the calculated evaporation volumes and energy production figures. Second, the allocation of reservoir evaporation to hydropower generation was based on a simplified ranking approach that may not fully capture the dynamic interactions among multiple reservoir functions, such as irrigation, flood control, and recreation. Third, the evaporation data represent long-term averages and do not account for short-term climatic fluctuations, such as heatwaves or extreme droughts, which can substantially alter actual evaporation losses. Fourth, spatial heterogeneity in meteorological parameters—such as temperature, wind speed, and humidity—was not explicitly modeled, potentially leading to regional bias in evaporation estimates. Finally, uncertainties also arise from the use of average construction-phase water footprint values reported in global studies (e.g., Mekonnen et al., 2015), which may not precisely reflect local construction materials, technologies, or environmental conditions. Future studies could reduce these uncertainties by integrating remote sensing observations, high-resolution meteorological data, and process-based hydrological models to better capture spatial and temporal variability in evaporation and water use efficiency.

Although the present study focused on estimating the blue water footprint of hydropower generation under current climatic and operational conditions, it is important to acknowledge that climate and hydrological variability can substantially influence both evaporation losses and hydropower production capacity. Future temperature increases and changes in precipitation and inflow regimes may alter reservoir storage dynamics, surface evaporation rates, and consequently, the magnitude and temporal distribution of the blue water footprint. Therefore, future research should integrate climate projection scenarios and hydrological modeling approaches to assess how long-term climate variability could affect the sustainability of hydropower-related water consumption.

The choice of allocation method is a critical source of uncertainty in hydropower water footprint assessments, as different allocation approaches can lead to substantially different estimates of blue water footprint values. Previous studies have shown that the allocation of reservoir evaporation losses can substantially influence the estimated blue water footprint of hydropower, and that

simplified allocation approaches may lead to an overestimation of hydropower-related water scarcity impacts compared to multi-criteria, expert-based methods such as the Fuzzy Analytic Hierarchy Process (Golabi & Radmanesh, 2020). Similarly, Ansorge et al. (2021) systematically compared multiple allocation approaches and showed that the resulting water footprint values are highly sensitive to the chosen allocation scheme. In this context, the simplified ranking-based allocation applied in the present study should be interpreted as one plausible representation among several alternatives, and the resulting blue water footprint estimates should be considered within this methodological uncertainty range.

To further evaluate the influence of allocation uncertainty on the study results, a sensitivity analysis was conducted using alternative allocation assumptions, including equal allocation of reservoir evaporation among all reservoir purposes and full allocation of evaporation losses to hydropower generation. The analysis showed that the absolute magnitude of the blue water footprint estimates varied considerably across allocation scenarios. However, the overall pattern of results and the relative ranking of hydropower plants remained broadly consistent. These findings suggest that, despite the acknowledged uncertainty associated with allocation procedures, the principal conclusions of the study are reasonably robust with respect to alternative allocation assumptions.

Conclusion

This study quantified and analyzed the blue water footprint (BWF) associated with electricity generation from 25 operational hydropower plants across Iran during the period 2004–2021. The results revealed substantial variation in BWF values across different plant scales and climatic zones, emphasizing that small-scale facilities, despite their lower generation capacity, exhibit disproportionately high-water footprints per unit of electricity due to higher evaporation to production ratios. Conversely, large-scale hydropower plants tend to be more water-efficient, benefiting from greater generation efficiency and reduced relative evaporation losses. Spatial analysis indicated that climatic and morphological factors are the principal drivers of BWF variability. Hydropower plants located in arid and semi-arid regions of Iran characterized by high temperatures, low humidity, and limited precipitation experience considerably higher evaporation losses compared to those situated in more humid areas. These findings align with global evidence showing that hydropower systems in dry climates generally have much larger blue water footprints than those in temperate or humid regions. From a sustainability perspective, the study underscores that evaporation induced water loss constitutes a critical environmental trade-off in hydropower development, particularly in water-scarce regions. The magnitude of these losses challenges the conventional perception of hydropower as a universally renewable energy source. In countries like Iran, where many regions are characterized by arid and desert climates, the construction of large reservoirs for hydropower generation is often not environmentally justified. In such areas, the high evaporation rates, coupled with limited water availability, make large-scale hydropower projects unsustainable from a water-resource management perspective. Therefore, future hydropower

planning in Iran should adopt a regionally differentiated approach. Moreover, diversifying the renewable energy portfolio through greater investment in solar and wind energy can reduce reliance on water-intensive power sources while enhancing energy security and climate resilience. Overall, this research contributes to a deeper understanding of the water-energy nexus in arid environments and highlights the necessity of incorporating blue water footprint analysis into hydropower planning and policy. By acknowledging the strong influence of climatic and operational factors on water-use efficiency, policymakers can better balance the dual goals of renewable energy expansion and sustainable water resource management in water-limited regions such as Iran.

Author Contributions Statement

Mousavi: Conceptualization, Data curation, Writing- Original draft preparation, Software.

Farrokhian: Investigation, Methodology, Supervision, Validation, Writing- Reviewing and Editing.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval

This is not applicable.

consent to participate

This is not applicable.

Consent to publish

This is not applicable.

Competing interests

The authors declare no competing interests.

Human and animals' participants

This is not applicable.

Clinical trial number

This is not applicable.

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