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Water-energy-food nexus in Tigris and Euphrates river basin through systemic lenses

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ABSTRACT

This study investigates the systemic interconnections among the Water, Energy, and Food (WEF) sectors within the Tigris and Euphrates River (TigER) basin, focusing on the historical trajectories and resource competition among its four main riparian states: Turkey, Syria, Iraq, and Iran. It examines how domestic political decisions influence cross-sectoral dynamics and impact the ecological integrity of shared transboundary resources. The research employs a multifaceted approach, combining a comprehensive literature review with an in-depth examination of state-level statistical data, drawing from academic sources, policy documents, and reports. In parallel, sectoral data was collected from reputable international organizations and structured within the WEF nexus framework. Our study highlights the intricate interdependencies that govern resource management within complex systems. The findings indicate that unilateral infrastructure projects—particularly Turkey's GAP hydropower initiative aimed at energy supply and agricultural development—have substantially reduced downstream water availability, most notably affecting Iraq's agricultural productivity and food security. Crucially, the study demonstrates that WEF systems follow the ecological logic of the basin that transcends national boundaries. The study underscores the necessity of a cooperative, systems-based approach to resource management, emphasizing that ecological interdependence in the TigER basin requires regional coordination. Lasting stability depends on leveraging complementary sectoral strengths to achieve sustainable and equitable development.

1. Introduction

1.1. The water-energy-food nexus

The Water-Energy-Food (WEF) nexus highlights the complex interdependencies among water, food, and energy systems, recognizing that changes in one domain can significantly impact the others [1]. Rather than analyzing these systems in isolation, this holistic approach fosters a comprehensive and balanced understanding, improving resource management, promoting long-term sustainability, and helping assess system sustainability [2,3].

Since the origins of the WEF nexus have been comprehensively explored in earlier literature [4,5], this study refrains from revisiting its development and instead focuses on clarifying its relevance within the context of our research.

The emergence of the Nexus approach underscores the rising demand for interdisciplinary frameworks to tackle complex, cross-sectoral resource challenges [4], which often require integrated, large-scale analysis to capture their multifaceted interdependencies [6]. The sustainable management of cross-sectoral issues becomes even more complex when dealing with transboundary systems, particularly river systems, where differing national interests intersect with the supply and demand of ecosystem services [7]. In such a complex system, the WEF nexus approach provides a structured framework that helps us break down complexity into manageable components, facilitating the identification of relationships, the anticipation of trade-offs, and the development of integrated solutions [8].

Conflicts over water resources have intensified as societies seek to

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manage water for energy production, while agriculture—historically the largest consumer of water—faces growing competition. This interconnection between agriculture and energy sectors creates trade-offs that directly threaten water security, underscoring the need for a balanced, integrated management approach [9]. In such cases, unilateral policies can exacerbate resource conflicts and jeopardize regional stability and sustainability [2]. By recognizing the trade-offs and synergies between sectors, the Nexus framework promotes integrated resource management. With this approach, riparian states can shift from competitive resource exploitation to cooperative solutions, ensuring equitable access, environmental sustainability, and long-term resilience in shared river basins [10,11]. A comprehensive understanding of the interdependencies within the WEF Nexus serves as a foundation for sustainable regional development [12], as the concurrent development of these three resources has a direct influence on economic performance [13].

Without fully considering these dynamics in the WEF nexus, environmental issues such as desertification, drought, floods, and dust storms, will become more prevalent, intense, and challenging for sustainable policymaking [14]. In addition, the WEF nexus has critical social implications, including amplified social inequalities and unequal access to ecosystem services that expose millions of people to the risk of displacement [15,16]. For instance, the resulting environmental issues, particularly drought and sand and dust storms in Syria and Iraq, will significantly affect environmentally vulnerable neighboring countries, leading to increased migration. The signs of such crises are already appearing throughout the TigER region, for instance, in 2021, due to water scarcity in the southern areas of Iraq, over 20,000 individuals, a significant proportion of them women and children, have faced displacement [17].

Despite its growing use, the WEF Nexus framework faces criticism for limited effectiveness in politically sensitive contexts and its claimed neutrality. While promoting intersectoral integration, it often overlooks structural power asymmetries, historical injustices, and geopolitical realities affecting resource access and control [18,19]. Some critiques also highlight its technocratic, top-down nature, which risks depoliticizing the deeply political governance of water, energy, and food—especially in conflict-prone and fragmented regions [20–22]. Consequently, decontextualized Nexus strategies may unintentionally reinforce inequalities rather than foster inclusive governance.

This research adopts a novel approach by examining political decision-making in a transboundary context, highlighting how unilateral sectoral policies generate long-term trade-offs across interconnected ecosystems. Grounded in real-world data and cross-sectoral impacts, it frames the Nexus as a diagnostic tool that reveals tensions among governance priorities, environmental limits, and local livelihoods.

The study conceptualizes transboundary resource governance as shaped by two interlinked systems: sectoral institutions influenced by state priorities and an ecologically interconnected natural environment. It argues that political borders and institutional fragmentation frequently undermine ecological coherence. By incorporating historical-political analysis, the research uncovers how upstream unilateral decisions impose lasting negative impacts on downstream communities and ecosystems. Addressing these power dynamics, the paper responds to critiques of the Nexus's depoliticization and demonstrates its potential to promote more equitable, context-sensitive governance.

1.2. Tigris and Euphrates river basin

The Tigris and Euphrates River (TigER) basin is a water system formed by two major rivers, the Tigris and the Euphrates. Both rivers originate in Turkey, flow through northern Syria, and enter Iraq, where they merge in the south to form the Arvand Rud (Shatt al-Arab), which empties into the Persian Gulf. The Tigris also receives tributaries from Iraq and Iran. The region between them is historically known as Mesopotamia.

Covering 868,989 km^2, the TigER basin is one of the largest in the Middle East, home to at least 83 million people [23]. It is shared by Iraq (46%), Turkey (22%), Iran (19%), Syria (11%), Saudi Arabia (1.9%), and Jordan (0.03 %) [24].

The Tigris River is strategically vital for riparian states, especially Iraq, which depends on it for most of its freshwater. In Syria, the Euphrates is the most significant of seven basins due to its agricultural and hydropower potential. Though the Tigris is just one of 25 basins in Turkey, it supplies nearly a third of the country's surface water and a fifth of its irrigable land [25]. Iran also relies on Tigris tributaries to support agriculture and communities in its southwest. The control and allocation of these transboundary waters have become key political concerns.

Furthermore, the TigER basin is one of the most critical transboundary regions in the world, holding significant geopolitical importance and strategic value for Middle Eastern development, particularly for the main riparian countries [26]. Water scarcity in the region is intensifying ecological pressures, leading to severe environmental challenges, including land degradation; saltwater intrusion [24,27]; the drying of marshes and wetlands [28,29]; frequent and severe droughts [30]; desertification; and an increase in sand and dust storms [31]. Furthermore, climate change projections indicate a substantial decline in the runoff of the TigER in the future [32], exacerbating social crises such as migration [17]. These interconnected regional challenges in the Middle East are rapidly evolving into a global crisis, driven by geopolitical tensions, social insecurity, and the escalating threats of severe water shortages and prolonged droughts.

1.3. Water disputes in the TigER basin

Access to strategic water resources, particularly in the civilization-rich regions of the Middle East and the Fertile Crescent, has long been a source of conflict and struggle among the peoples of this area. Throughout history, especially in the eastern Mediterranean, numerous water-related disputes—both accidental and deliberate—have been recorded. In some cases, water has even been used as a weapon [33]. For example, around 2500 BCE, the Sumerians fought wars from Lagash against the cities of Ur and Uruk, using water as a tool or weapon to secure victory [34]. Between 1800 and 1750 BCE, wars occurred between the Sumerians (Larsa) and Babylon, as well as between the Babylonians and the Elamites; around 1790 BCE, ongoing disputes over water in Mesopotamia led Hammurabi (1792–1750 BCE) to include provisions in the Code of Hammurabi concerning irrigation neglect and water theft. Hammurabi's laws ensured farmers' involvement in infrastructure and the fair distribution of irrigation water to prevent conflict [35]. This is one of the earliest written legal texts, which is notable that it considered water rights. In 539 BCE, Cyrus the Great conquered Babylon, and after capturing Opis on the Tigris. His army built a bridge to cross the river, advanced to Sippar, and annexed all of Babylon into the Achaemenid Empire [36,37]. While records describe the conquest as largely bloodless, it also served as a strategic move to secure the water resources of the TigER, as well as the fertile lands of central Mesopotamia. Whoever controls the flow of water has dominion over the land.

In ancient wars, irrigation facilities were of strategic importance, and for this reason, their destruction became a military objective. In 851 BCE, after defeating Marduk-Bal-Usate and capturing Me-Turnat, Assyrian king Shalmaneser III recorded his victory: "I defeated him, massacred him, besieged his city, took his crops, destroyed his gardens, and blocked his river." His goal was to cut off agricultural water supplies, destroy land, and solidify control over the region. He also stated, "I blocked the Orontes River with their bodies like a bridge" [38]. Blocking or contaminating rivers with bodies was a common military tactic. For instance, Ashurbanipal blocked the Ulai River with the bodies of Elamite warriors, letting their blood flow instead of water for three days [17].

In the contemporary period as well, when ISIS took control of parts of Iraq, in 2014, they cut off water access to predominantly Shia areas, particularly in the south and center. By blocking rivers and irrigation channels, they aimed to exert pressure and create a humanitarian crisis [39]. These tactics, used as a military strategy, continued until 2017, when Iraqi forces, supported by an international coalition, launched operations to reclaim these territories [40].

Water-related challenges in the Fertile Crescent, particularly in Mesopotamian Iraq, remain ongoing geopolitical issues. Following World War II and the collapse of the Ottoman Empire, the formation of modern Turkey, Syria, and Iraq intensified conflicts over water, which continues to be a target and tool of war [41].

Turkey's water policies in the TigER basin have been influenced by broader state-building and modernization goals since the early 20th century [42]. Large-scale initiatives such as the Southeastern Anatolia Project (GAP) have aimed not only at economic development but also at reinforcing state authority and regional integration, particularly in southeastern provinces [40,43]. This sovereignty-centered stance is further reflected in Turkey's decision not to ratify the 1997 UN Watercourses Convention, which advocates for equitable and reasonable use of international watercourses [25]. In effect, this position aligns closely with the principles of the Harmon Doctrine, which asserts the absolute right of a state to exploit the natural resources within its territory regardless of transboundary impacts—a view that has influenced Turkey's hydropolitical approach in the region [44].

The role of water as the most crucial environmental factor, often used as a tool to pressure rival city-states or as the central element in conflicts, is both significant and undeniable in these historical struggles. The management and utilization of the TigER water resources have been a source of tension for over 3500 years. Despite human progress over these millennia, the biological functions of water and access to it have not yet been recognized as a fundamental right. Water continues to serve as a tool in conflicts.

Although the struggle over water resources in the TigER basin has been a historical constant since the dawn of civilization in the region, a key difference between modern conflicts and those of antiquity lies in the changing use of water. In the past, water served primarily for domestic use and agriculture, which was essential for both the development of power and economic prosperity. Today, however, the role of water extends far beyond domestic and agricultural needs, with tensions escalating particularly in areas where water is utilized for energy production [45]. In fact, the energy sector, as a significant tool of power in political relations, has become a major competitor to agriculture in terms of water usage. Therefore, analyzing water resources in the context of energy and agriculture (WEF nexus) is crucial.

Specifically, the construction of large dams in this region, aimed at hydropower generation, flood control, and water management for year-round agriculture, has been one of the main factors contributing to water disputes in this basin in recent decades [40,45,46]. The construction of dams in this basin began with the Dokan and Darbandikhan dams on the Tigris River, built by Iraq in 1959 and 1961, respectively. This was followed by Iran, which inaugurated the Dez Dam on the same river in 1962. Later, in the 1970s, the massive GAP in Turkey started, which included 22 large dams and 19 hydropower plants [43]. GAP has significantly reshaped the region's environment and socio-economic landscape by expanding irrigation, hydropower, and agricultural production [47,48]. While Turkey views boosting economic development, Iraq and Syria argue that it has severely reduced downstream water flow, threatening agriculture, drinking water supplies, and environmental stability, particularly in Iraq's southern marshlands [43,48]. Additionally, the construction of major dams such as the Tabqa Dam in Syria and Mosul Dam in Iraq has been significant in altering water flow patterns and exacerbating political, social, and ecological water tensions [25,45,49].

Numerous studies have examined the impacts of large dams on water flow in both upstream and downstream countries [47–49] indicated that the implementation of upstream dam projects significantly reduces water inflow to reservoirs in downstream countries. Some research, such as [50], has focused on the water-food nexus, specifically addressing issues of water scarcity and food security, but without incorporating the energy dimension directly. Similarly, Sabah et al. [51] analyzed the water-food nexus in the context of climate change, exploring how future population growth and climate variations affect water demand in the TigER basin. In a geopolitical context, Al-Muqdadi, [52] investigated the historical water-related relations among Iraq, Syria, and Turkey. His research examined the underlying causes of disputes and provided recommendations for riparian states, emphasizing that geopolitical relationships play a crucial role in shaping water resource management in the region. However, most of these studies have not considered the interlinkages within the WEF nexus.

On the global scale, the WEF nexus has become a key framework for understanding resource interdependencies, especially in regions facing increasing environmental and geopolitical stress. Studies have advanced this concept by modeling trade-offs and synergies at national and regional levels [8,53–55] while others have highlighted its relevance to transboundary water governance, where upstream-downstream dynamics shape outcomes across sectors [56,57]. However, while these studies provide valuable insights into the complexity of resource interlinkages, much of the literature remains conceptual or sector-specific, often lacking integrated, data-driven, cross-border perspectives.

Our study adopts a systemic, cross-border WEF nexus approach in a transboundary river basin, using global datasets to analyze how upstream hydropower links downstream agricultural and water security. This framework connects the WEF nexus to transboundary governance, offering a holistic, policy-relevant perspective for shared resource management. Linking evidence from the previous studies in the TigER basin that focus on isolated sectors or historical perspectives, this research discusses how human interventions—such as dam construction and agricultural expansion—have reshaped WEF dynamics via sectoral interdependence and how water scarcity drives a self-reinforcing cycle of vulnerability with cascading impacts on food and energy security.

Objective: This study aims to analyze the systemic interconnections between the WEF sectors and their entanglement with historical trajectories and resource competition among the four main riparian states of the TigER basin. It investigates how major developments in energy and agriculture within national borders influence cross-sectoral dynamics and the ecological integrity of shared resources.

To achieve this, the project focuses on three key objectives:

1. Assessing historical trends and current conditions of the WEF sectors in TigER countries, drawing on data from international organizations, particularly the FAO.
2. Analyzing the interlinkage of WEF sector dynamics in the region.
3. Exploring a holistic and integrated approach to develop policy recommendations for TigER countries.

Research Questions:

- What are the historical trends and current conditions of water, food, and energy sectors in the basin?
- How are WEF sectors interconnected in the TigER basin?
- How can a holistic and integrated approach be utilized to formulate effective policy recommendations for TigER countries?

The article is structured as follows: Section 2 presents the methodology and results, examining both the current state and historical trends of WEF resources in the riparian countries. Section 2.1 provides an overview of water resources in the region, highlighting trends over the past several decades. Section 2.2 focuses on food security and agricultural conditions, while Section 2.3 analyzes the energy landscape within the four countries of the TigER basin. Section 3 offers a comprehensive discussion, integrating historical events with the present status of water, energy, and food resources to uncover key underlying causes and interconnections. Finally, Section 4 presents conclusions and strategic recommendations aimed at enhancing cooperation, improving resource management, and addressing critical challenges in the region's water, energy, and food sectors.

2. Methodology and results

Our methodology involves a comprehensive literature review of historical events related to water resources among the riparian countries of the basin. Additionally, we conducted an in-depth analysis of statistical data at the state level, drawing from databases by reputable international organizations such as the Food and Agriculture Organization (FAO) [58], the International Energy Agency (IEA) [59], and various United Nations reports on water, energy, and food sectors across the four countries within the basin. The collected data was structured within the WEF framework to assess the impact of sectoral development on resource availability and distribution in the basin.

The study draws on data mostly from 1995 to 2021, that represent a range of cross-sectoral and geographic contexts covering four countries within the basin. The data are available at the state or administrative level, which allows for consistent integration across countries and sectors. We included only those variables for which data were available across all four countries to ensure comparability and consistency in the analysis. While not specific to the basin boundary, this resolution provides a basis for regional analysis and comparison. Basin-level assessments would require additional spatial disaggregation and ground-based validation, which are beyond the scope of this study but represent logical next steps for future research.

All data were obtained from internationally recognized sources, including the FAO, IEA, and UN databases. These datasets are subject to standardized validation protocols by their respective organizations. In line with common practice in multi-country assessments, we used these sources without additional independent verification, focusing instead on data integration and comparative analysis. Fig. 1 illustrates the overall process followed in this study, including data collection and analysis across sectors and countries within the TigER Basin.

2.1. Water resources and their historical trends in the TigER basin

Fig. 2 illustrates the trends of total annual renewable water resources (TRW) per capita for Iran, Iraq, Syria and Turkey (to make it short, hereafter, it will be referred as TigER countries). These values highlight both a marked disparity in water availability and a consistent decline across all four nations. From the mid-1990s to 2010, Iraq had the highest TRW per capita among the riparians. However, a sharp decrease since 2010 has seen Turkey surpass Iraq and maintain the lead in recent years (Fig. 2 and Table 1).

Since the total annual renewable water resources in these countries have been reported as relatively stable (Iran: 137, Iraq: 90, Syria: 17, Turkey: 212 billion cubic meters (BCM) per year) [58], the decrease in annual renewable water resources per capita can be attributed to the increase in population growth. Population growth is a key factor linking to environmental crises, water availability, food security, and energy resources [60]. Fig. 3 and Table 1 indicate that during 1995–2020, populations increased about 2.1 times in Iraq, 1.5 times in Syria, and 1.4 times in Iran, and Turkey. Syria had the highest growth rate (4.9%), followed by Iraq (2.3%), Iran (1.2%), and Turkey (0.4%) in 2023 [61].

Given that the population in each country has grown significantly in recent decades, corresponding increases in total annual water withdrawal can be expected. Fig. 4(a) highlights the trends of total annual water withdrawal in the riparian countries. Between 1995 and 2021, Turkey's total annual water withdrawal increased by 74%, similarly Syria and Iran saw increases of 24% and 12.4%, respectively (Fig. 4(a) and Table 1). In contrast, Iraq's withdrawal, while riging until 2000, eventually declined by 22% between 1995 to 2021.

In light of the rising population and declining total water withdrawal in Iraq, a sharp decrease in per capita water availability is unsurprising (Fig. 4(b)). Similarly, both Iran and Syria exhibit a downward trend in per capita water withdrawal. In contrast, despite Turkey's population growth, water withdrawal per person has increased.

Fig. 5 illustrates the trend of the National Rainfall Index (NRI) across the riparian countries. As shown in Fig. 5 and Table 1, precipitation has been declined meaningfully in Iran, Iraq, and Syria since 1967. These downward trends suggest a gradual decrease in rainfall over time. In contrast, Turkey has experienced only a slight decline in annual rainfall.

To better understand the changes in water flows within the basin, we examined the trends of data regarding constructed large dams in the TigER basin. Fig. 6 and Appendix I display the trends of total number of dams with a capacity exceeding one BCM constructed on the TigER basin. While the cumulative effect of smaller dams is not negligible, for the purposes of this article, we have excluded the examination of such dams and focused on dams with a capacity of more than one BCM. As shown in Fig. 6, more than 80% of the constructed dams that exist now were built and commissioned before the year 2000.

As shown in Fig. 7, more than 53% of the total dam capacities constructed on TigER is constructed by Turkey. Iraq follows with 20%, Syria 15%, and Iran 11%. Of the total capacity of operational reservoirs in the basin, nearly two-thirds (65%) are located on the Euphrates River, while about one-third (35%) in the Tigris basin. On the Euphrates, Turkey holds the largest share, with approximately 73% of the total reservoir capacity on the river. Syria follows with 21%, and Iraq holds only 6% of the Euphrates reservoirs. In contrast, in the Tigris basin, Iraq holds the largest share of water reserves, with around 47%. Iran and Turkey follow with 35% and 18%, respectively.

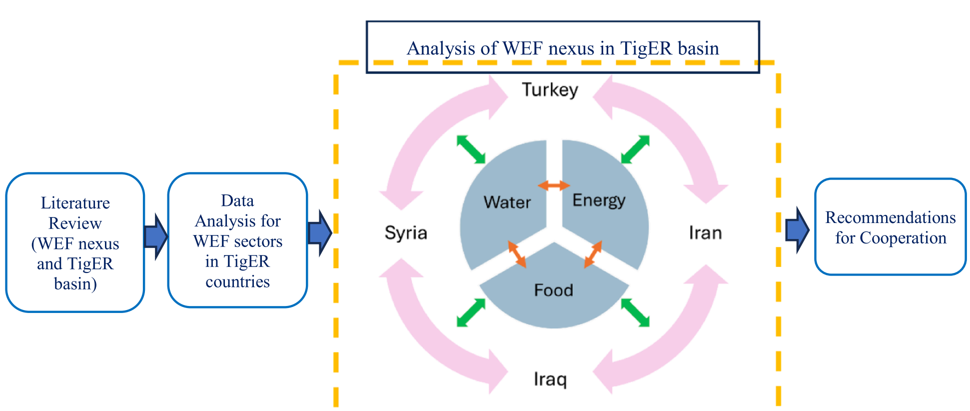

Fig. 1. Flowchart of analysis process for three sectors across four countries within the TigER Basin.

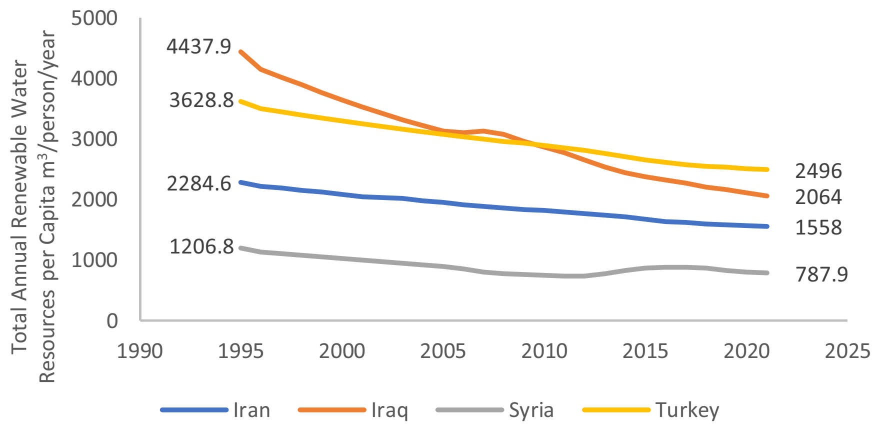

Fig. 2. Trends of total annual renewable water resources per capita (m^3/person/year) in TigER countries, 1995–2021 [58] .

Table 1
Comparing the historical trends of parameters related to water availability in TigER countries [58].

Country	TRW per capita (m^3/person/year)			Total Annual Water Withdrawal (BCM/year)			NRI (mm/year)		Population (1000 person)		
	1995	2021	% change	1995	2021	% change	1967–2021		1995	2021	Multiplier
							Rate of Change	p-value			
Iran	2285	1559	−31.8	83	93.3	12.4	−2.5	<0.05	62,206	87,923	1.4
Iraq	4438	2064	−53.5	54.4	42.4	−22.1	−2.5	<0.05	20,826	43,534	2.1
Syria	1207	788	−34.7	13.5	16.7	23.7	−2.1	<0.05	14,617	21,324	1.5
Turkey	3629	2496	−31.2	33.6	58.4	73.8	−0.3	>0.05	61,025	84,775	1.4

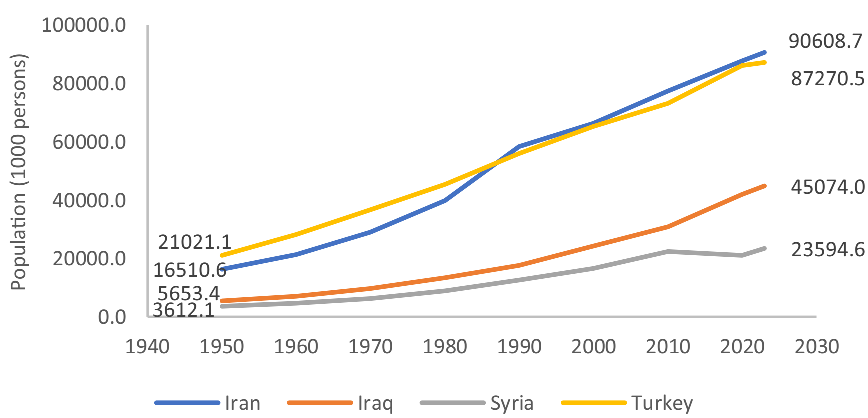

Fig. 3. Population growth trends (1000 person) in the TigER countries, 1950–2023 [58].

2.2. *Agriculture and food security*

2.2.1. *Historical trends and the current situation*

Securing sustainable peace centered around water among the TigER countries is essential. However, even with the realization of "water peace," water and ecological sustainability, particularly in downstream countries, cannot be fully achieved without addressing the agricultural sector, the largest water consumer in these countries. Therefore, in this section, we addressed the historical trends and the current situation of the agriculture sector in TigER countries.

In light of population growth, the global demand for food has increased significantly, leading many countries to expand agricultural land to meet rising consumption needs [58]. Fig. 8 shows that the area of land developed for expanding irrigated agriculture in the TigER countries increased 298%in Turkey, 182% in Iraq, 134% in Syria, and 102% in Iran between 1960 and 2021. This suggests that these countries are strategically investing in development of their agricultural sector, also to potentially reduce dependence on food imports.

Agriculture is the largest consumer of water globally. As illustrated in Fig. 9, agricultural water withdrawals in the TigER countries show a moderate rise in Iran and Syria and a sharper increase in Turkey since 1995. In 2021, Iran reported the highest agricultural water use at 86 BCM, followed by Turkey (45), Iraq (31), and Syria (15). Notably, Iraq's agricultural water withdrawal has been declining since 2000.

Fig. 10(a) illustrates the trends in water use efficiency (US$/$m^3$) across the TigER countries from 1994 to 2021. Turkey leads with $16.3 in 2021, indicating high agricultural efficiency, followed by Iran ($4.6) and Iraq ($4.2), which demonstrate moderate efficiency. Syria records the lowest profitability at $0.89, reflecting relatively low water use efficiency. These figures highlight significant regional disparities, with Turkey showing remarkable growth in efficiency over the past 15 years compared to the other countries.

As can be seen in Fig. 10(b), the trends of water use efficiency in agriculture exhibit significant fluctuations across nearly all riparian countries. In Iran, the trend was declining until 2010, after which it experienced rapid growth, ultimately achieving a higher ranking

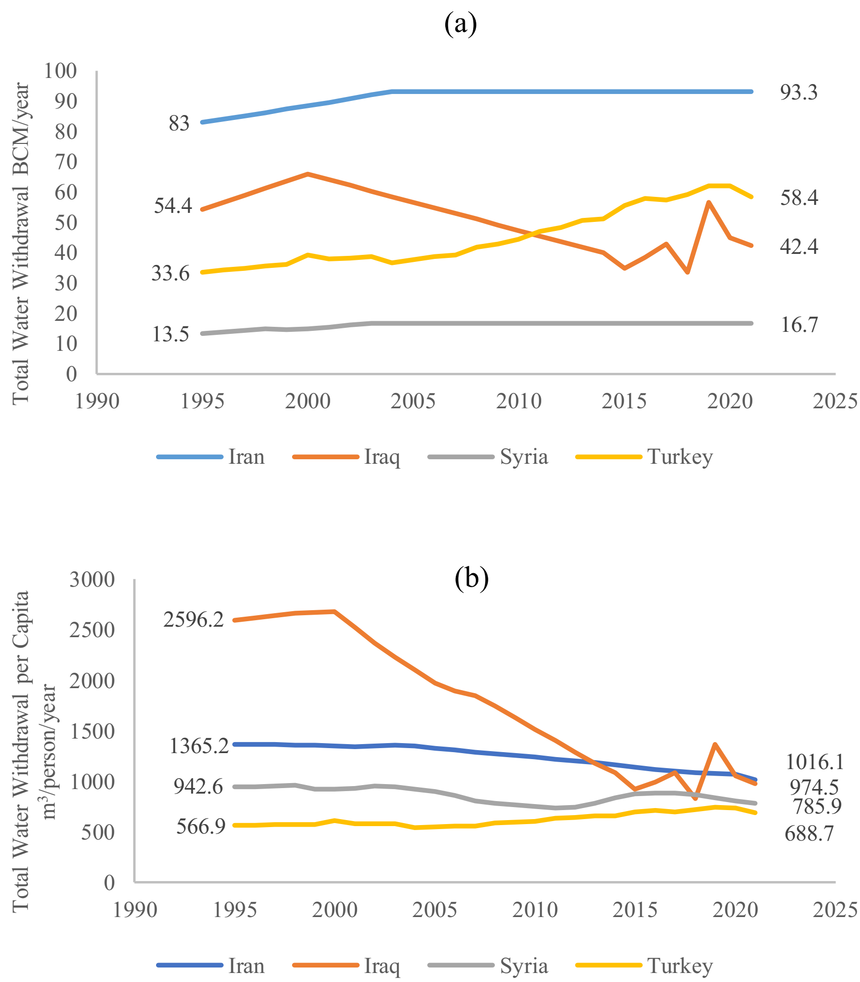

Fig. 4. (a) Trends of total annual water withdrawal (BCM/year); (b): Trends of total annual water withdrawal per capita (m^3/person/year) in TigER countries, 1995–2021 [58].

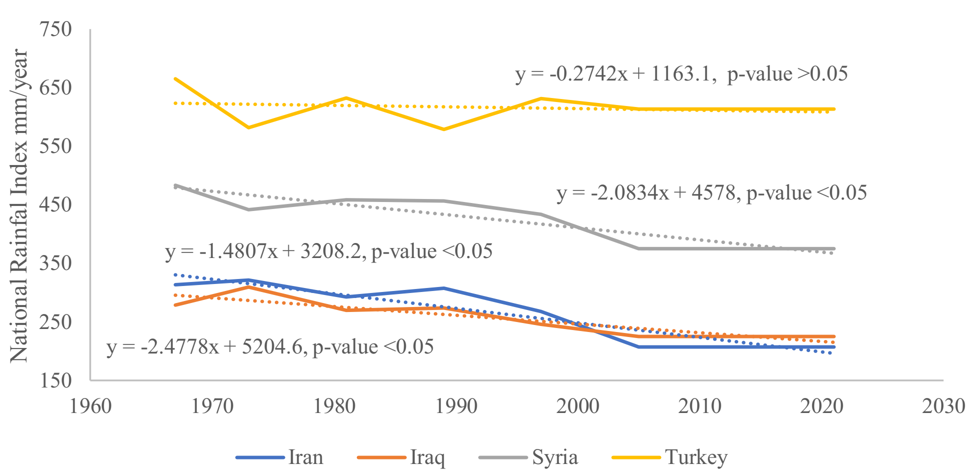

Fig. 5. Trends of national rainfall index (mm/year) in the TigER countries, 1967–2021 [58].

compared to other countries by 2021. In Turkey, a substantial upward surge occurred between 2000 and 2010, but the trend has since exhibited a pronounced decrease from 2010 onward. In Iraq, water use efficiency demonstrated a moderate upward trajectory until 2014, followed by a decline in 2017, and subsequently an increase thereafter. In Syria, the trend showed steady growth until 2010 but has since experienced a sharp decline.

To better understand how each country allocates water to agriculture, Fig. 11 presents the trend of agricultural water withdrawal as a percentage of total water withdrawal in the riparian countries.

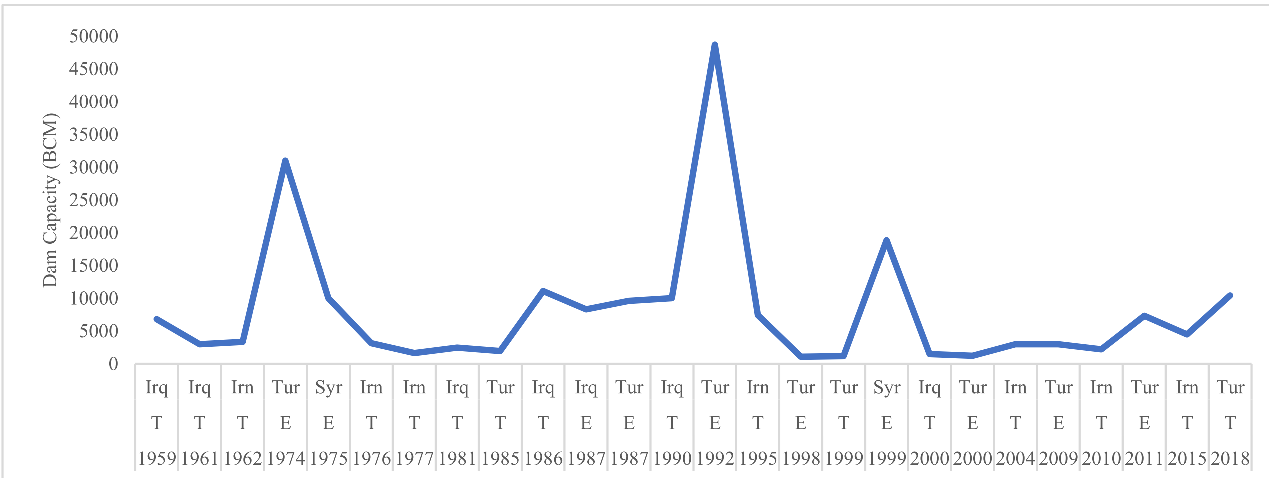

Fig. 6. The trend of constructed dams (< One BCM) on the Tigris (T) and Euphrates (R) river basin, (Appenix I).

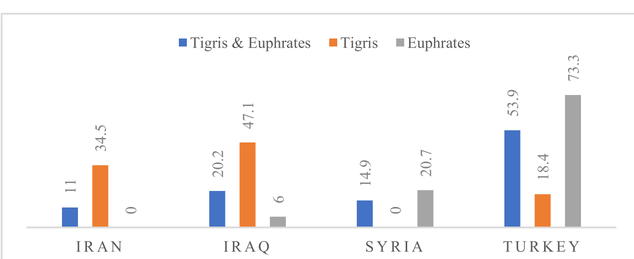

Fig. 7. Share (%) of each country in dams (<one BCM in capacity) across the TigER basin, (Appendix I).

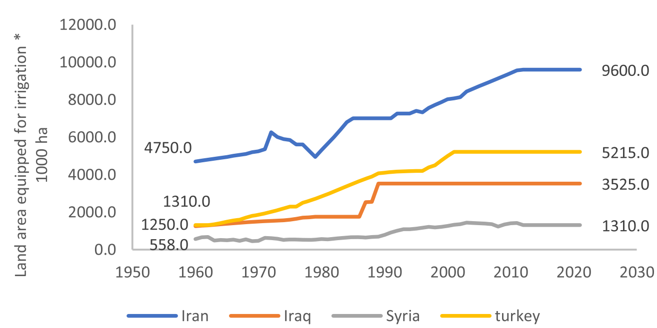

Fig. 8. Land development trends for expanding irrigated agriculture (*1000 ha) in TigER countries, 1960–2020 [58].

According to this figure, agriculture accounts for 92% of total water withdrawal in Iran in 2021 and 88% in Syria, indicating a heavy reliance on irrigation in these nations. In contrast, Turkey (77%) and Iraq (73%) have comparatively lower shares of water allocation to agriculture. These figures underscore the dominant role of agriculture in regional water use, with some countries facing greater pressure on their water resources due to their higher dependence on agricultural water withdrawals.

2.2.2. Food security situation in the riparian countries of the TigER basin

The first signs of human achievement in agriculture and animal husbandry were found in this “Fertile Crescent” region, where developments were closely linked to TigER water resources management. Despite this pioneering knowledge in agriculture, food security remains highly fragile and unstable in this region. In 1986, the United Nations defined food security as "the access of all people at all times to enough food for an active and healthy life" [62]. This definition highlights three main pillars of food security: food availability, access to food, and stability in food consumption.

As shown in Fig. 12, in 2024, more than 30 % of Syria’s population, 15% of Iraq’s population, 7% of Iran’s population, and 5% of Turkey’s population suffer from malnutrition [63]. Additionally, Fig. 12 illustrates that food insecurity in Iran, Iraq, and Turkey decreased between 2000 and 2024, while Syria experienced a significant increase during the same period, directly linked to the ongoing political and economic instability in the country [63]. This underscores the urgent need for regional stabilization to improve food security and promote sustainable development.

2.2.3. Soil salinity trends in the riparian countries of the TigER basin

Soil has played just as crucial a role as water in the emergence of

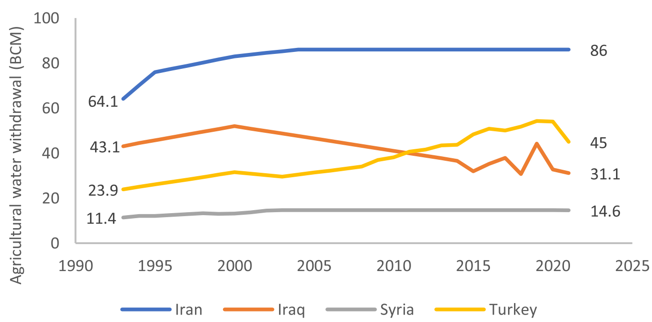

Fig. 9. Trends of total annual water withdrawal in the agricultural sector of the TigER countries (BCM), 1993–2021 [58].

civilizations. Even with access to the purest and most abundant water sources, agriculture, food security, and the rise of civilizations would not have been possible without fertile soil. Despite significant advancements in human knowledge, no substitute for soil has ever been discovered.

Although reliable data on soil salinity trends in Iran and Syria are lacking, the issue has been closely monitored and reported in Turkey and Iraq. According to FAO data, between 2004 and 2021, Turkey reduced its salinized agricultural land by over 1.5 million hectares, while Iraq saw an increase of more than 450,000 hectares of salinized farmland.

2.3. Energy resources and consumption in the TigER countries

After water and food, energy is the third most influential factor shaping the structure of individual and social life in the modern world. The role of energy, particularly since the onset of the Industrial Revolution, has expanded significantly [64]. Fig. 14 illustrates that fossil fuels—including natural gas, oil, and coal—account for at least 99% of Iraq, Syria and Iran's, and 82% of Turkey's total annual energy consumption [59]. It is worth noting that Turkey derived over 26% of its total energy from coal combustion, whereas Iran, Iraq, and Syria each sourced less than 0.7% of their energy consumption from coal. Given its lack of fossil fuel resources, Turkey has been able to meet over 18% of its energy needs through other sources such as wind, hydropower, and geothermal due to significant investments in energy infrastructure. In contrast, Iran has sourced 1.3%, Syria and Iraq less than 1% of their total

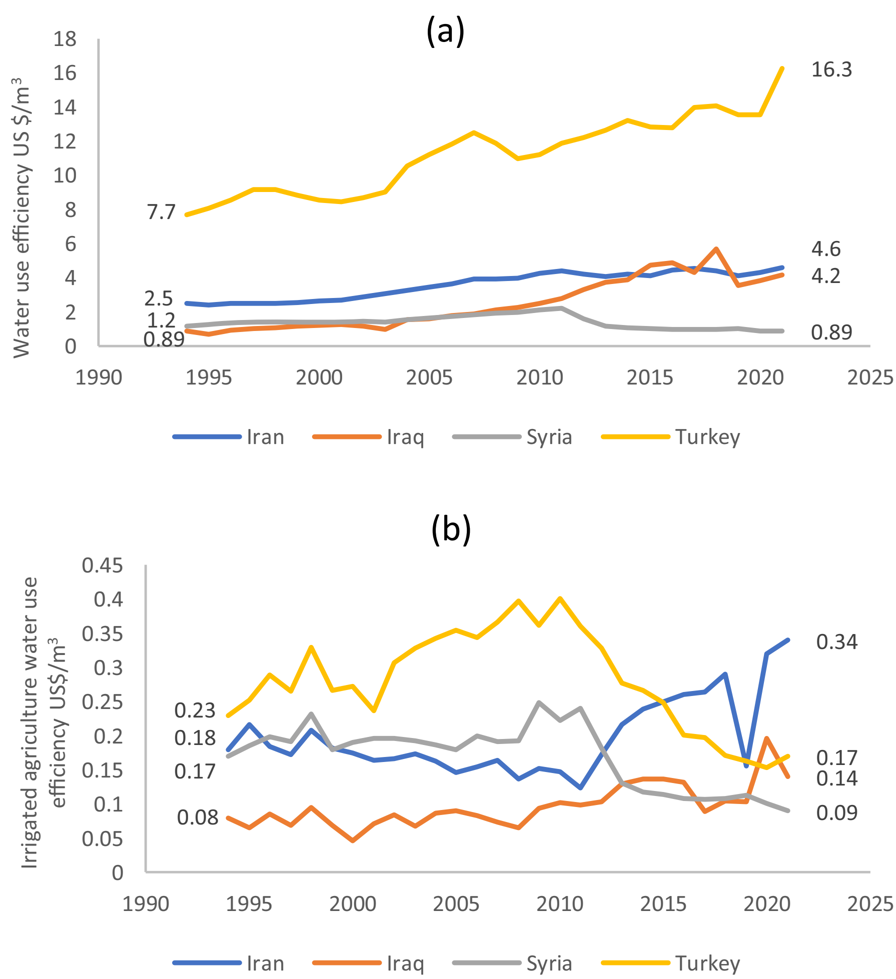

Fig. 10. (a): The trends of water use efficiency; including agriculture, industry and services (US$/m3); (b): The trends of irrigated agriculture water use efficiency (US$/m^3) in the TigER countries, 1994–2020 [58].

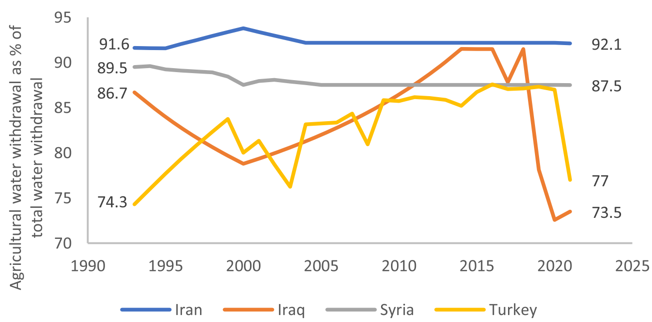

Fig. 11. Trends of agricultural water withdrawal as % of total water withdrawal for the TigER countries, 1990–2021 [58].

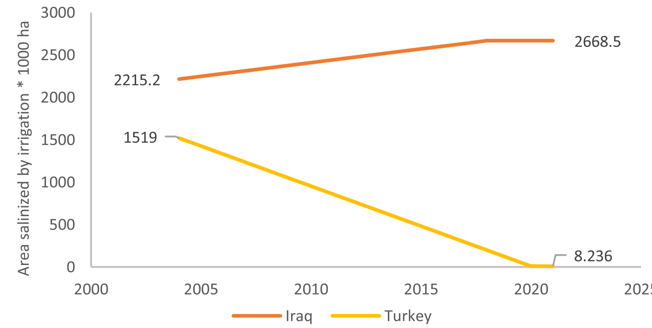

Fig. 13. Trends of soil salinization due to irrigation in Iraq and Turkey, 2004–2021 [58].

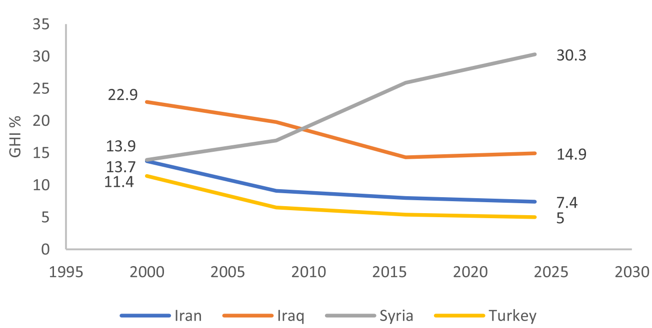

Fig. 12. Comparison of the GHI in the TigER countries, 2000–2024 [63].

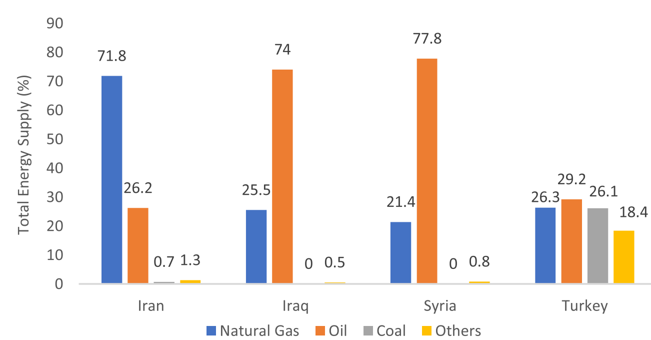

Fig. 14. Share of natural gas, oil, coal, and other energy resources in total energy production in TigER countries [59].

energy requirements from non-fossil fuel sources in 2022.

According to Figs. 15, 16 and 17 and Table 2, energy policies in the TigER countries exhibit notable changes. Between 2000 and 2022, hydropower production in Iran, Iraq, and Turkey increased by more than 117%, while Syria saw a 77% decrease, primarily due to internal security issues (Fig. 17 and Table 2). During this period, the share of natural gas in electricity generation rose by at least 62% in Iran, Iraq, and Turkey, while Syria experienced a 77% decrease. The share of oil in electricity production increased by 96% in Iran and Iraq. Meanwhile, Syria's oil share dropped by 9%, and Turkey's decreased significantly and very close to non-reliance on oil at all (Fig. 16 and Table 2).

3. Discussion

3.1. Water resources

Water scarcity is recognized as the most pressing environmental and security threat in the Middle East, with over 60% of the region's population living in areas already grappling with severe water crises or challenges [61]. By 2040, fourteen of the 33 countries projected to experience the most significant water stress will be in the Middle East [65]. Among these are the four TigER countries highlighting the urgent need for action to address water scarcity in the region. When evaluating the role of population, it is essential to consider not only the populations within the basin but also the broader national projections and growth rates [66]. The trend of water scarcity threatens the livelihoods of over 200 million people across these four countries, and its impact extends beyond these riparian nations, potentially affecting neighboring countries throughout the Middle East [47].

Iraq heavily relies on the TigER for about 98% of its surface water, but as the country lies at the lower end of the river basin, it now receives significantly less water than in the past [67]. As shown in Table 1, Iraq's total renewable water resources per capita have decreased by 53.5%

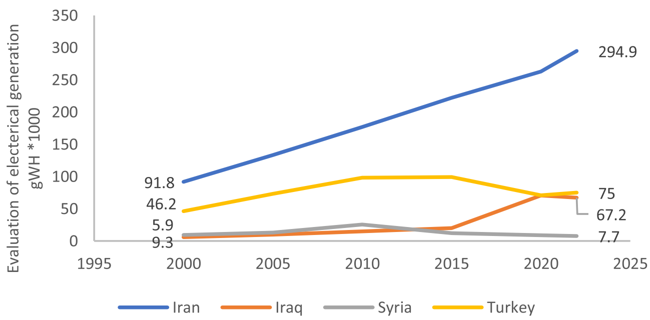

Fig. 15. The trends of natural gas consumption for electricity generation in TigER countries, 2000–2022 [59].

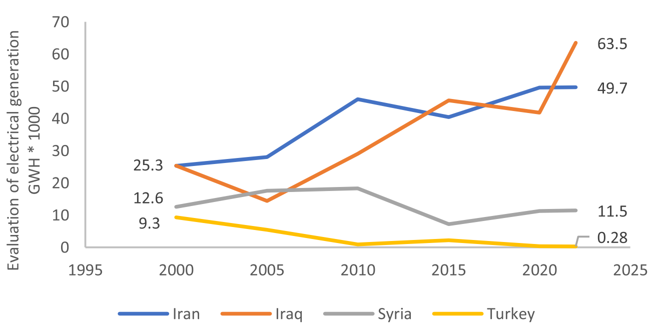

Fig. 16. The trends of oil consumption for electricity generation in TigER countries, 2000–2022 [59].

between 1995 and 2021, while Syria, Iran, and Turkey experienced reductions of 35%, 32%, and 31%, respectively. This decline is driven by several factors, including population growth, as well as decreasing precipitation and changes in the natural flow of water, all of which we address in the following sections.

In light of population growth, Iraq's population has increased 109% in 1995-2021 (Table 1). However, contrary to expectation, total annual water withdrawal has not risen; instead, it has declined approximately 22% (Fig. 4, Table 1). Meanwhile, total annual water withdrawal in Turkey has increased 74%. In Syria and Iran it has not changed much (24% and 12% respectively). This suggests that the drivers of the reduction in renewable water resources extend beyond increasing population number and water withdrawals.

Iraq has experienced a significant decline in rainfall (Fig. 5), but the overall reduction in renewable water resources cannot be attributed solely to precipitation levels. Similarly, Iran and Syria have also faced substantial declines in rainfall–due to their lower latitudes and more extreme climatic conditions compared to Turkey. As shown in Fig. 5 and

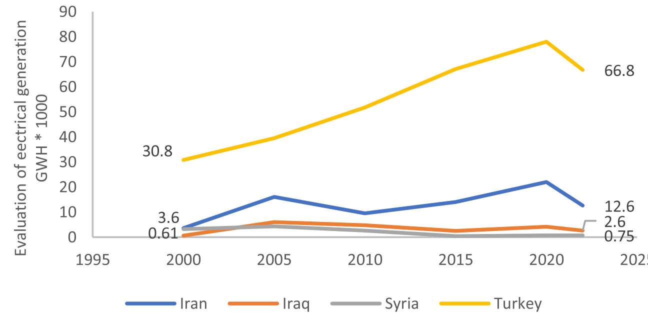

Fig. 17. The trends of hydropower electricity production in TigER countries, 2000–2022 [59].

Table 2
Changes in the share of natural gas, oil, and hydropower in electricity generation in the TigER countries (%), 2000–2022 [59].

Country	Natural Gas	Oil	Hydropower Electric
Iran	221.2	96.4	250
Iraq	1039	151	326.2
Syria	−17.2	−8.7	−76.6
Turkey	62.3	−97	116.9

Table 1, Turkey's decline in precipitation is notably less severe than that of these downstream countries. However, despite Iraq's higher population growth compared to Iran and Syria, its total annual water withdrawal has decreased.

As illustrated in Fig. 6, the most significant filling of large reservoirs in the Euphrates Basin occurred between 1990 and 2000. Notably, Turkey's largest dam, the Atatürk Dam, was completed in 1992, followed by Syria's Tashrin Dam in 1999. The implications of these developments became increasingly apparent in the subsequent decade, particularly from 2000 onward, as the downstream countries of the basin—Syria and Iraq—began to experience the full extent of their effects. The Atatürk Dam, as noted by Bayik et al. [68], is considered one of the central factors in the transformation of the water system in the Euphrates River Basin, specifically regarding the significant shift in displacement patterns caused by the dam. The consequences of these actions continue to impact the region today, through the complex interplay between national development, international cooperation, and environmental stewardship.

According to the Protocol on Matters Pertaining to Economic Cooperation Between Turkey and Syria in 1987, Turkey was committed to ensuring the release of at least 500 m^3 of water per second from the Euphrates River into Syria. However, after the Atatürk Dam's completion and filling, both Syria and Iraq were confronted with severe water shortages, exacerbating tensions and sparking protests from these nations against Turkey's water policies [45,49]. Furthermore, the impoundment of the Ilisu Dam on the Tigris River (2019–2021) has intensified water shortages and environmental challenges for Iraq as a downstream country [69].

3.2. Agriculture

Fig. 8 illustrates the increasing trend in the area allocated to irrigated agriculture across all riparian countries. However, this expansion has plateaued in Iraq since 1990 and Turkey since 2000. As depicted in Fig. 9, the total water withdrawal for agriculture has remained relatively stable in Iran and Syria. In contrast, Iraq has experienced a decline in agricultural water withdrawal since 2000, whereas Turkey has seen a substantial increase, particularly after 2005.

A closer examination of sectoral water allocation dynamics in Iraq reveals a paradoxical trend. The share of agriculture in Iraq's total water withdrawal rose significantly from 78% in 2000 to 91% in 2015, before falling to 73% in 2021 (Fig. 11). Despite this apparent prioritization of agricultural water use, the absolute volume of water withdrawn for agriculture in Iraq declined from 52 BCM in 2000 to 32 BCM in 2015, before slightly decreasing to 31 BCM in 2021 (Fig. 9)—a net reduction of 20 BCM. This suggests that while Iraq has allocated a larger proportion of its available water resources to agriculture, the overall quantity of water accessible for agricultural activities has markedly diminished.

In contrast, Turkey has increased its total annual agricultural water withdrawal from 32 BCM in 2000 to 48 BCM in 2015, a net increase of 17 BCM, before reaching 45 BCM in 2021 (Fig. 9). This significant expansion coincides with the large-scale development of dam infrastructure in Turkey (Fig. 6 and 7). The construction and operation of these dams have directly impacted the volume of water available downstream, particularly in Iraq, thereby exacerbating water scarcity in the country's agricultural sector, specifically since 2000 [49]. By comparison, the proportional share of agricultural water use and the absolute volume of water withdrawn for agriculture have remained relatively stable in Iran and Syria.

Fig. 10(a) highlights that Turkey has significantly higher overall water use efficiency compared to other countries. However, Fig. 10(b) reveals that despite agricultural expansion and increased water allocation to farming, Turkey's agricultural water efficiency showed substantial short-term growth from 2000 to 2005 but declined significantly after 2010. Nevertheless, this suggests that while Turkey has historically maintained high overall efficiency, its water use in industry and services has been particularly effective, not in agriculture. In 2021, Turkey reduced the share of agricultural water withdrawals relative to total water use (Fig. 9), thereby enhancing water use efficiency in the agricultural sector (Fig. 10(b)).

These findings may reflect a dynamic consistency with [70] observation that upstream regions are generally more suitable for reservoir development, while downstream areas are better suited for agriculture. The decline in Turkey's agricultural water use efficiency after 2010 may be linked to the expansion of cultivation into less productive or less water-efficient areas, suggesting that geographic suitability plays a critical role in determining economic water productivity. This could also help explain the observed reduction in agricultural water withdrawal as a percentage of total water use since 2020, as shown in Fig. 11.

While Iran and Iraq have made gradual strides in improving water use efficiency, the gap between these countries and Turkey remains substantial, (Fig. 10(a)). This disparity highlights the need for strategic reforms in water management policies across Iran, Iraq, and Syria. Despite these challenges, future development plans across all four countries suggest a shared ambition to expand agricultural production [71–73]. However, given the increasing trend of water scarcity, there is a growing recognition that a shift in focus or changing water management strategies in agriculture may be necessary.

The pressure on water resources, driven by goals such as agricultural self-sufficiency and the cultivation of water-intensive crops, is unsustainable in a region already facing limited renewable water resources [73]. Without significant policy adjustments, continued reliance on these practices could lead to severe water crises, ultimately affecting both agricultural and economic stability in the long term.

Inefficient water management practices, such as the continued use of flood irrigation and unlined or uncovered irrigation canals in Iraq, have exacerbated water scarcity [27]. Additionally, the extensive use of chemical fertilizers has contributed to the degradation of water quality in the region's rivers. Key developments, such as expanding irrigated land, upgrading irrigation systems, and providing essential agricultural inputs, are often not fully implemented [27]. Furthermore, wartime conditions have limited access to foreign markets, reducing agricultural exports and diminishing the economic return on water-intensive crops, (Fig. 10(b)).

Food security is a complex concept influenced by various factors, including political security and stability. A country experiencing a prolonged conflict and political instability is unlikely to achieve sustainable food security. Conversely, the absence of food security can exacerbate insecurity. Political stability and food security are deeply interconnected, each influencing and reinforcing the other [74]. For example, Soffiantini, [75] argues that rising food prices can exacerbate existing social unrest, further destabilizing political environments. The 2011 surge in food prices, in particular, sparked protests in Egypt, Syria, and Morocco, with the potential to affect the broader Middle East and North Africa. In Syria, agricultural water efficiency has also dropped sharply since 2010 (Fig. 10(b)), a trend linked to the outbreak of the Syrian Civil War. The link between the Syrian civil war and water-related conflicts aligns with the perspectives of [76] and [77] who argue that water issues were among the contributing factors to the onset of the conflict. This example also underscores the critical connection between internal political instability and food security [78].

This connection between political stability and food security is further emphasized by [79], who identified seven of the most food-insecure developing countries based on FAO data, highlighting a significant positive correlation between political stability and food security. In line with this, Van Dijk & Djindil, [80] explains that political instability and conflicts diminish people's ability to access healthy diets. Similarly, [81] examined the relationship between political and security stability and food security across 83 developing countries in Africa, Asia, Latin America, and the Caribbean, finding that greater political and security stability significantly enhances food security. Khan et al. [82] found that weak central governance and political instability disrupt food supply chains, foster food smuggling, and push societies toward hunger and food insecurity.

3.3. Soil salinization

Brown, [83] underscores the critical role of soil in the rise of civilizations, stating, *"The thin layer of soil covering the Earth's surface is the foundation of civilization."* Emphasizing the deep interconnection between soil, nature, and human societies, Brown warns, *"First, the trees disappear, then the soil, and finally, the society itself"* [83].

The challenge of increasing soil salinity in Iraq, particularly in Mesopotamia, is not a new issue. Jacobsen & Adams, [84] identified several historical periods in which soil salinity contributed to the decline of civilizations in this region. Different parts of Mesopotamia were affected in each period, including the southern, central, and eastern regions of present-day Iraq. For instance, rising soil salinity in southern Mesopotamia led to the collapse of irrigated agriculture after nearly five thousand years, which in turn contributed to the fall of the Sumerian civilization [84].

Additionally, [85] documents the collapse of civilizations due to soil erosion, degradation, or salinization. For instance, the decline of early civilizations—such as the Maya—is attributed to soil erosion and declining food production [85]. Furthermore, the collapse of the Akkadian civilization in Mesopotamia, in present-day Iraq, over 4200 years ago has been attributed to a decline in access to sustainable water resources, which subsequently led to increased soil salinity in agricultural lands [86].

The increase in soil salinity, caused by poor-quality water, high groundwater levels, heavy soil texture, improper soil structure, and lack of proper drainage, reduces fertility and crop yields. To prevent these effects, proper water management, infrastructure maintenance, and suitable drainage equipment are essential. In the later years of the Sassanian Empire, due to military conflicts and the Arab invasion, the government neglected water infrastructure in Mesopotamia, leaving the task to local communities. Lacking the necessary capabilities, the locals failed to maintain it, leading to agricultural damage, food insecurity, social instability, and migration (Jacobson & Adams, 1958).

A look at history tells us that people in the Fertile Crescent have always struggled with soil salinity. For example, in the year CE 870, thousands of enslaved Black individuals assigned to cleanse the saline lands of the government estates along the Karun and Arvand (Tigris) rivers in Khuzestan, Iran, revolted and killed the Abbasid Caliphate's governor. This uprising, known in history as the Zanj Rebellion, was far greater and more impactful than the Roman slave revolt led by Spartacus, as 120,000 slaves participated in the Spartacus revolt, while the Zanj Rebellion, led by Ahmad from Ray and supported by over 500,000 slaves along with the Banu Tamim tribe from the Mesopotamian region of Iraq, succeeded [87].

History of Mesopotamia might repeat itself after over four thousand years. The rising soil salinity in Iraq, for any reason, threatens the country's agricultural infrastructure and food security. In the long term, this could lead to the collapse of food production, environmental damage, including dust storms affecting neighboring countries like Iran, forced migration, and the spread of inscurity and terrorism in the region.

Irrigation practices under GAP, located in arid and semi-arid zones, have led to increasing soil salinity and drainage issues. These challenges have become a critical concern, particularly in Southeastern Anatolia, placing salinity management at the forefront of Turkey's agricultural policy agenda [88].

In response, Turkey has prioritized long-term investments in land drainage infrastructure to mitigate salinity and enhance soil productivity. The first major drainage project began in the Tarsus Plain in the late 1960s, initially covering 3000 hectares. By 2015, this expanded to 170,000 hectares. Ongoing projects target an additional 10,000 hectares, with plans for over 50,000 more, and projections estimate that more than 2.5 million hectares of irrigated land will eventually be equipped with drainage systems [89]. These efforts have significantly reduced saline soil areas (Fig. 13)—from over 1.5 million hectares in 2005 to about 820,000 hectares in 2015. Effective drainage has proven vital in preventing further salinization.

3.4. Water flow and energy

Iran, Iraq, and Syria rely heavily on fossil fuels for their energy needs (Fig. 14). While Turkey has a significant share (over 18%), of its energy from other sources such as hydropower (via the GAP project), geothermal, wind, and solar energy. Through GAP, Turkey increased its hydropower production from 125 in 2000 to 326 (GWh) in 2023, a 61% increase, making it the third-largest electricity producer in Europe [59]. The TigER basin is estimated to contribute 28% of Turkey's total runoff and accounts for 31% of the country's national gross hydropower potential, generating approximately 433 GWh per year [90].

Turkey reduced dependence on fossil fuels and utilizing shared surface waters for other source of energy. From national perspective, Turkey's energy policies are based on a foresight, sustainability-driven approach designed to avoid significant dependence on a single energy source. As shown in Fig. 14, Turkey has successfully diversified its energy mix, distributing its reliance across four energy sources in a balanced and nearly equal manner. This strategy helps mitigate the risks associated with energy dependence and minimizes the potential for widespread energy crises in the country. In contrast, Iran, Iraq and Syria, with their significant reliance on natural gas and oil as their primary energy sources, have not equally and systematically distributed their energy supply sources. Additionally, due to the lack of investment in clean energy production, these countries have increased their vulnerability to unforeseen energy crises.

From an ecological perspective, the classification of hydropower as a clean and sustainable energy source remains a subject of considerable controversial debate [91–93]. One of the primary criticisms stems from the fact that hydropower development often neglects a systemic approach to ecosystem management, particularly in transboundary river systems. The implementation of upstream dam project can significantly reduce water inflow to reservoirs in downstream countries, potentially rendering parts of its hydropower and reservoir capacity ineffective, while causing hydrological drought [49].

Rivers are not confined by national borders; they are part of an interconnected ecological and hydrological system that spans multiple countries. When an upstream nation constructs large hydropower dams to meet its energy demands, it might offer certain sustainable developments goals, but unilateral actions sometimes fail to account for the broader ecological and socio-economic impacts on downstream countries, which are equally dependent on the shared water resources. By disregarding this systemic approach, hydropower development often exacerbates regional water stress, disrupts aquatic ecosystems, and undermines agricultural and economic stability in neighboring states, leading to tensions and regional instability. A sustainable approach requires acknowledgment that water resources transcend political boundaries. Without such an integrated perspective, the long-term consequences of hydropower development may prove to be more damaging than beneficial, undermining both regional stability and environmental sustainability.

As [94] indicated in their study hydropower can be one of the most environmentally damaging renewable energy source, causing habitat destruction, altered river ecosystems, and biodiversity loss. In contrast, wind and solar energy have become more economically attractive alternatives, with costs significantly decreasing, and less environmental harm. The price of solar photovoltaic energy dropped from $0.417 per kilowatt-hour in 2010 to $0.048 in 2021, while onshore wind and offshore wind costs declined by 68% and 60%, respectively. Given their lower environmental impact and increasing affordability, solar and wind energy present more sustainable alternatives to hydropower.

Furthermore, the viability of hydropower itself is increasingly uncertain due to shifting climate patterns. Recent trends in precipitation suggest growing variability in rainfall, making water availability less predictable. As shown in Fig. 17, Turkey's share of hydropower in electricity generation steadily increased from 2000 to 2020 but began to decline after 2020. This decline may be linked to fluctuations in the country's total rainfall since 1970. As illustrated in Fig. 5, Turkey's annual rainfall, which averaged 665 mm in the 1960s and 1970s—often referred to as the GAP expansion era—has decreased over time. Between 1965 and 2020, annual rainfall declined by at least 51 mm. This instability in rainfall and the resulting decrease in hydropower generation suggest that Turkey's water policies may not unfold as originally planned under the GAP, which in turn may and cause cumulative impact on downstream countries.

Moreover, true sustainability requires that present development does not compromise the needs of future generations. In regions with significant uncertainties surrounding long-term water availability, hydropower carries risk of not offering a fully reliable source of energy for future generations, as it fails to guarantee stable resource access over time.

3.5. Systemic approach

Managing water resources in the TigER basin involves significant water control on water flow through dam construction [95]. This has contributed to political instability, food insecurity, rising poverty, and heightened regional tensions [40,45]. TigER countries have built at least 56 major dams that exacerbat water scarcity and increasing security risks [49].

Water governance remains constrained by political boundaries, increasing the likelihood of conflicts. Addressing these challenges requires a shift toward a systemic and holistic approach that views water as part of an interconnected system rather than a national asset [96,97]. Sustainable governance must recognize the interdependence of water, energy, and food security within broader ecological boundaries, ensuring long-term stability and resource equity in the region.

A systemic approach to hydropower development necessitates international agreements and cooperation between shared-resource countries. Countries within a shared river basin must come together to develop frameworks that promote joint management, ensure equitable distribution, and prevent conflicts [98]. The absence of agreements over shared river basins heightens the likelihood of tensions by disrupting water access, potentially exacerbating inequalities among ethnic groups, displacing communities, and reducing water supplies for downstream regions [99,77].

In 1997, with the adoption of the United Nations Convention on the Law of Non-Navigational Uses of International Watercourses, which sought to regulate the use of shared water resources, Turkey stood among the three countries that voted against the resolution. This opposition further highlighted the growing divide between Turkey and its neighbors over water rights and resource management. Turkey's refusal to sign the 1997 convention reflects a water policy that prioritizes self-interest over regional cooperation. This stance hinders equitable water governance, increasing conflict risks and undermining sustainability [46,100]. The absence of a legal framework limits integrated management, potentially leading to over-extraction, downstream neglect, and environmental degradation. Without multilateral cooperation, water insecurity in the region will worsen amid climate change [101,102].

Water is more than a biological necessity; its role in food and energy security makes it a critical factor in social and political stability. Research has long highlighted water scarcity as a potential driver of unrest. Gleick, [78] predicted that limited rural access to water would accelerate urban migration, fueling social tensions and intensifying political tensions in Syria. Similarly, Bulloch & Darwish, [103] warned of water's potential to ignite future conflicts.

While some scholars argue that fears of water-induced instability are rooted in pessimistic assumptions [100,104,105], others, such as [70], contend that water is a double-edged sword—it can either fuel disputes or serve as a catalyst for cooperation. Our analysis underscores that without equitable access to sustainable and safe water at the basin level, water remains a source of political tensions, rather than a unifying force.

The WEF nexus needs to be embeded within its political and historical context, particularly in transboundary settings where governance is complex and contested. As pointed by Srivastava & Mehta, [21], Allouche et al., [20], Warner et al., [22], and Baranyai, [101] unilateral decisions by upstream actors often produce long-lasting trade-offs, exacerbating inequalities and undermining ecological coherence downstream.

Furthermore, Urbinatti et al., [19] emphasize that Nexus frameworks often overlook underlying political and power relations. Turkey's upstream position influences the political capacity and resource management of downstream countries, Syria and Iraq [49].

The absence of coordinated, integrated management mechanisms has exacerbated asymmetries—reinforcing upstream dominance and limiting the capacity of downstream countries to secure water, energy, and food resources [101]. Ultimately, neglecting political power relations within Nexus frameworks constitutes a significant shortcoming, with the potential to propel rather than resolve existing inequalities.

In line with the fundamental distinction of the WEF Nexus approach, in this study we discussed both the interrelations within each sector and the cross-sectoral interactions among them. Rather than treating the sectors in isolation, our analysis incorporates key linkages—such as the implications of water use for energy production and agricultural development on downstream agricultural capacity, and transboundary feedbacks across food systems. This integrated perspective is conceptually aligned with the frameworks proposed by [106] and [107], both of which emphasize the importance of addressing intra- and inter-sectoral dynamics in Nexus-oriented studies. These relationships have been explicitly captured in our model design and analysis.

Given the interconnected nature of regional security, instability within the TigER basin can easily extend beyond national borders, affecting neighboring countries. Socio-environmental challenges in the region are increasingly difficult to contain and risk evolving into a broader crisis, marked by large-scale migration and heightened geopolitical tensions.

4. Conclusion

This study underscores the urgent need for more integrated and holistic governance approaches that reflect the basin's environmental interdependence and the cross-sectoral nature of its challenges.

We highlighted the complex and interdependent nature of WEF systems within the TigER basin, emphasizing the necessity of a Nexus-based approach to resource governance. Evidence suggests that upstream energy demands—particularly Turkey's hydropower and agricultural development under the GAP project—have significantly altered downstream water availability specifically in Iraq, with far-reaching implications for agricultural productivity, food security, and regional stability [45,49]. These unilateral infrastructural interventions have disrupted the natural flow regime, exacerbating environmental issues such as soil salinization and drought, and in a long-term contributing to socio-economic challenges including unemployment and displacement [17].

This research highlights that the WEF nexus functions within an ecological framework that transcends political boundaries. The interconnections among WEF sectors follow the natural logic of the basin as an integrated ecosystem rather than the territorial limits of nation-states. This ecological reality requires political cooperation rather than nationally isolated strategies focused on unilateral gains. In the long term, mutual benefits can be found in cooperation. Each country—-whether upstream or downstream—possesses distinct ecological capabilities. For example, while Turkey has greater access to water for hydropower and agriculture, historical evidence confirms that the plains on both sides of the TigER basin have long benefited from fertile soils, primarily due to the seasonal flooding of these rivers. Although these soil resources are currently undergoing salinization as a result of the declining quantity and quality of water in the TigER—a consequence of both unilateral water management policies by upstream countries, particularly Turkey, and local mismanagement—this region was historically one of the cradles of agriculture [47]. Despite current challenges, vast areas of the region still possess significant potential for the development of modern and efficient agriculture aimed at meeting the growing food demands of the local population. Sustainable water management in the TigER basin requires a systemic approach that recognizes the interdependence of the WEF and regional security. A cooperative framework aligning national policies with shared environmental and social priorities is essential to prevent instability and ensure lasting peace.

In light of these findings, we offer and highlight recommendations for policy which may already be made by various experts and international organizations:

Turkey is encouraged to consider recognizing and acceding to the United Nations Convention on the Law of the Non-Navigational Uses of International Watercourses (1997), while engaging in constructive dialogue with downstream countries. Utilization of the waters of the TigER rivers would benefit fromcloser coordination with Syria and Iraq, guided by the principles of equitable and reasonable use, the avoidance of significant harm, and the persuit of mutual benefit. Developing a cooperative framework—ideally with a legal foundation—could support the sustainably and fair management of transboundary water resources and contribute to enhancing regional stability and water security.

Given the extensive dam construction by Turkey on the TigER and its notable downstream implications, it would be advisable for Turkey to carefully evaluate the potential impacts of new dam projects. Conducting environmental impact assessments—ideally in consultation with downstream countries—could help ensure that potential adverse effects are minimized. Enhanced coordinated in water management may contribute to protecting regional water resources and easing tensions.

Enhancing economic cooperation among TigER countries can strengthen interdependence and support sustainable resource management. Iran and Iraq's oil wealth and Turkey's upstream water and agricultural capacity offer complementary advantages that can be leveraged through expanded trade in energy, agriculture, and infrastructure development. Promoting trilateral and basin-wide partnerships will improve resource allocation, build diplomatic trust, and contribute to greater regional stability and resilience [108,109].

One possible approach could be to establish a TigER Basin Organization, or alternatively to strengthen existing mechanisms for transboundary water governance, to facilitate joint planning, data sharing, dispute resolution, and integrated basin-level management. Such an institute could be grounded in systemic thinking and management principles, thereby supporting long-term sustainability and fostering cooperation among all riparian states.

Iraq is increasingly challenged by rising soil salinity, posing serious risks to its agricultural productivity and long-term food security. Turkey, having achieved notable success in mitigating soil salinity through effective drainage systems and sustainable land management practices, is well-positioned to share its technical expertise and operational best practices. Likewise, Iran's agricultural sector—shaped by years of working with saline water and soil resources—has conducted extensive research in the field of saline soil and water management, with a particular emphasis on biosaline agriculture. This has yielded a substantial body of knowledge and practical experience that holds significant relevance for Iraq, especially given the shared geographic latitude of the two countries, which enhances the feasibility and effectiveness of applying Iran's innovations in the Iraqi context. Advancing bilateral and multilateral cooperation focused on knowledge exchange, joint research initiatives, and capacity-building programs would not only bolster Iraq's efforts in soil reclamation but also generate mutual economic and environmental benefits for the region as a whole.

Given the high number of sunny days across the TigER countries, they have a significant opportunity to expand solar energy production. Shifting toward renewable sources—such as solar and wind, which in compare to hydropower have fewer direct impact on neighboring countries—can help reduce reliance on hydropower and fossil fuels. While these alternatives also come with their own challenges, integrating solar energy into national energy strategies could nonetheless strengthen energy security, support environmental sustainability, and help mitigate some of the regional tensions linked to water scarcity and transboundary resource competition.

Future research should focus on collecting geographically explicit data at the basin level for each country. While this study analyzed data at the national level—an important perspective for understanding broader trends—examining data at the basin or even provincial level will provide deeper insights and a more precise understanding of regional water dynamics.

CRediT authorship contribution statement

Elham Sedighi: Writing – original draft, Validation, Project administration, Methodology, Investigation, Data curation. **Hanifreza Golzar:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Brian D. Fath:** Writing – review & editing, Supervision. **Ali Kharrazi:** Writing – review & editing, Supervision. **Elena Rovenskaya:** Writing – review & editing, Supervision.

Declaration of competing interest

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

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Appendix I. Dams (sorted by year) with a capacity of more than 1000 million cubic meters (MCM) in the Tigris and Euphrates basins

Year	Country	Name of Dam	Basin	Volume (MCM)
1959	Iraq	Dukan	Tigris	6800
1961	Iraq	Darbandikhan	Tigris	3000
1962	Iran	Dez	Tigris	3340
1974	Turkey	Keban	Euphrates	31,000
1975	Syria	Tabag	Euphrates	10,000
1976	Iran	Karun 1	Tigris	3139
1977	Iran	Lower Gotvand	Tigris	1620
1981	Iraq	Hamrin	Tigris	2450
1985	Turkey	Kralkizi	Tigris	1920
1986	Iraq	Mosul	Tigris	11,100
1987	Iraq	Haditha	Euphrates	8280
1987	Turkey	Karakaya	Euphrates	9580
1990	Iraq	Badush	Tigris	10,000
1992	Turkey	Ataturk	Euphrates	48,700
1995	Iran	Karkheh	Tigris	7400
1998	Turkey	Ozluce	Euphrates	1070
1999	Turkey	Batman	Tigris	1180
1999	Syria	Tashrin	Euphrates	18,830
2000	Turkey	Biyecik	Euphrates	1220
2000	Iraq	Aladheem	Tigris	1500
2004	Iran	Karun 3	Tigris	2970
2009	Turkey	Alpaslan 1	Euphrates	2993
2010	Iran	Karun 4	Tigris	2190
2011	Turkey	Silvan	Euphrates	7300
2015	Iran	Upper Gotvand	Tigris	4500
2018	Turkey	Ilisu	Tigris	10,410
Future	Iraq	Bekhme	Tigris	17,000

(*continued on next page*)

(*continued*)

Year	Country	Name of Dam	Basin	Volume (MCM)
Future	Iraq	Badush	Tigris	10,000
Future	Turkey	Silvan	Tigris	7300
Future	Turkey	Alpaslan-2	Euphrates	2430

Data availability

Data will be made available on request.

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