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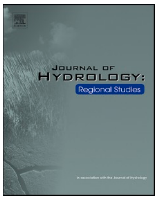

The impact of Turkey's water resources development on the flow regime of the Tigris River in Iraq

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ABSTRACT

Study region: Once, the Tigris River (with its twin, the Euphrates) was the remarkable river in the west of Asia, making Mesopotamia a cradle of civilization thousands of years ago. Upstream anthropogenic activity has choked the Tigris River, the connecting lifeline across Iraq, and, due to droughts and desertification, caused the country to be plagued by poverty.
Study focus: Here, we give a perspective on flow regime alteration in the main corridor of the Tigris River at five crucial points (Cizre, Mosul, Baiji, Baghdad, and Kut) before and after the planned water resources development in Turkey. Turkey's Tigris River regulation goal is to generate about 7247 GWh of energy and irrigate over 640,000 ha of farmlands.
New hydrological insights for the region: We reconstructed the natural flow along the Tigris River. In addition, to evaluate hydrological droughts, we proposed a modified streamflow drought index (MSDI) and compared it with the original streamflow drought index (SDI). The results show that the worst hydrological conditions could be found below the Samarra barrage in Iraq before the Tigris River regulation in Turkey. This negative hydrological condition will be extended to the whole corridor of the Tigris River in Iraq after the implementation of Turkey's goal. As a result, for example, Cizre and Mosul will experience extreme conditions in 37.5–87.5% of the years; this means a considerable reduction in the Mosul reservoire's inflow (135–326 m^3/sec). Consequently, some parts of Mosul's hydropower and reservoir capacity will be useless, and hydrological drought upstream of the Samarra barrage will be dominated.

1. Introduction

A series of dams and hydropower stations have been constructed upstream of the Tigris and Euphrates Rivers (TERs) by the

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southeastern Anatolia project, titled Güneydoğu Anadolu Projesi (GAP). Through this project, Turkey has control of about 45% of both rivers' water resources (Unver, 1997; Tilmant and Kelman, 2007). In addition, Iraq and Syria's governmental policies rely on river regulation to improve farming and other sectors of their economy (Daggupati et al., 2017). River regulation, combined with demographical and climatological changes in the Middle East (Milly et al., 2005; Chenoweth et al., 2011; Danandeh Mehr and Kahya, 2017; Akbari et al., 2020), has worsened the environmental conditions in the TERs basin. In addition to the drying of Mesopotamian marshlands (Richardson et al., 2005), there is a positive correlation between a reduction in fish stocks and a decline in the TERs inflow into the northwestern part of the Persian Gulf (Al-Husaini et al., 2015; Ben-Hasan et al., 2018). The deterioration in the water quality of the TERs has been widely reported (Richardson et al., 2005; Yesilnacar and Uyanik, 2005; Odemis et al., 2010; Al-Ansari et al., 2018). Groundwater overexploitation in the TER region has drastically depleted aquifers and dried soil moisture (Voss et al., 2013). Dust from dried marshlands has also severely affected human health in Iran and Iraq (Hamidi, 2020).

Since 1997, Turkey's Tigris River regulation has generated about 7247 GWh of renewable energy and irrigate over 640,000 ha of farmland. Tigris River regulations have been accelerated by impounding the Ilisu dam (the second largest dam in the GAP, 10.4 km^3) in

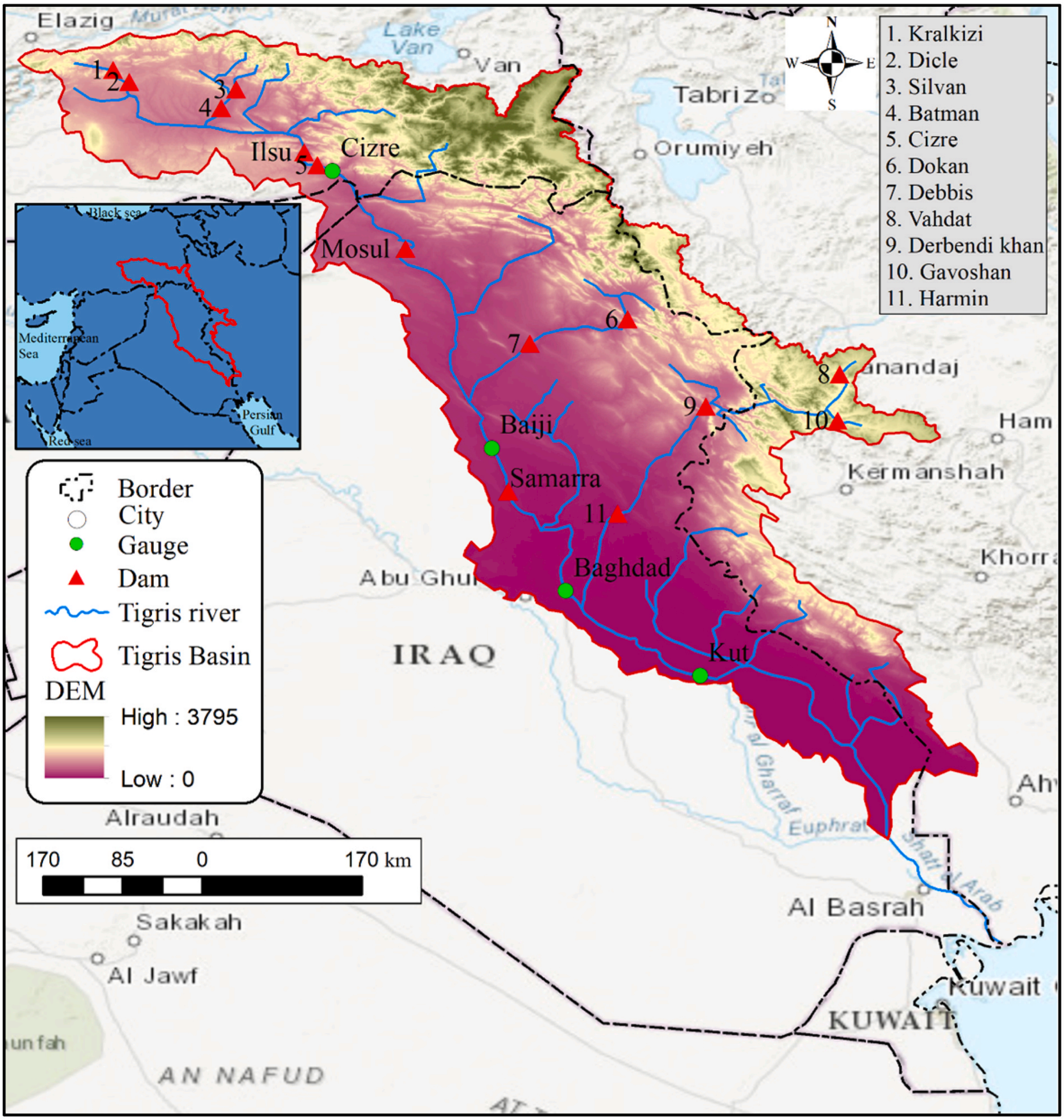

Fig. 1. The Tigris River basin, gauges, and location of Major dams.

2020 and will be completed with the Silvan dam (storage capacity of 7.4 km^3) in 2023. Although these projects generate considerable profits in agricultural and hydropower production, their consequences are somewhat contradictory, resulting in a wide national dispute (Morvaridi, 2004; Ronayne, 2006; Eberlein and Ayboga, 2007; Harris, 2008; Eberlein et al., 2010). For example, Ilisu's impounding led to the flooding of 15 cities and 52 rural areas, including some parts of the ancient city of Hasankeyf (Ronayne, 2006; Eberlein et al., 2010). Beyond the national consequences of Tigris River regulation in Turkey, it has also been a source of conflict between Turkey and riparian countries. Turkey argues that the dam's construction serves downstream interests too. They argue that by regulating the Tigris River flow, the dam mitigates the impact of droughts and floods and improves the timing of the river flow to be in accord with downstream agricultural demands (Bilen, 2000). Iraq's government has warned that the project's negative impact will be seen as far downstream as the Mesopotamian marshlands (Janabi, 2009) and will dramatically influence downstream agricultural production (Declaration et al., 2006).

The limited access to hydrological data in the Tigris River basin has caused researchers difficulties when discussing how the damming of the river influences the downstream environment (Kavvas et al., 2011). While several studies have focused on the flow regime of the Tigris River (or the Tigris and Euphrates Rivers together), most of them have primarily examined the consequences of flow regime alterations in lower lands, such as the Mesopotamian marshlands (Richardson et al., 2005; Altinbilek, 2004; Jones et al., 2008; Al-Quraishi and Kaplan, 2021) and the Arvandroud estuary (Torabi Haghighi et al., 2020). Ali and Al-Ansari (2012) conducted a study on the morphology of the Tigris River with a focus on Baghdad city. Al-Hasani (2021) provided a trend analysis to detect abrupt changes in the lower Tigris River. However, to the best of our knowledge, no comprehensive study has yet been conducted on the alteration of the river regime along the Tigris River while considering water resource development in Turkey.

This research aims to give a perspective of flow regime alteration in the main corridor of the Tigris River at five crucial points (Cizre, Mosul, Baiji, Baghdad, and Kut) before and after the operation of three planned irrigation scenarios in Turkey. To evaluate the hydrological droughts before and after irrigation scenarios, we proposed modifying the streamflow drought index (SDI) proposed by Nalbantis and Tsakiris (2009).

2. The Tigris River and its flow regulation

The Tigris is a transboundary river with a basin area of approximately 221,000 km^2. At 1800 km, it is the second-longest river in Western Asia. The river originates from the Taurus Mountains in Turkey and is fed by tributaries in the Zagros Mountains. It flows south into Iraq and finally discharges into the Persian Gulf via the Arvandroud. The basin of this transboundary river extends into four riparian countries, Iraq (56.1%), Turkey (24.5%), Iran (19%), and Syria (0.4%). The Tigris flows 400 km across Turkey, making up 44 km of the border between Turkey and Syria. The major tributaries of the Tigris River are the Greater Zab (25,810 km^2), the Lesser Zab (21,475 km^2), the Al-Adhaim (13,000 km^2), and the Diyala (31,896 km^2) (Fig. SM1).

Turkey and Iraq have constructed fourteen dams and barrages on the Tigris River and its tributaries since 1941 (Fig. 1 and Table SM1). The river regulation in the Tigris River basin can be divided into two main periods (Table SM1). Before 1996, significant regulations were implemented in Iraqi territory (starting with Kut in 1940 and ending with Mosul in 1982), while after 1994, Turkey started to regulate major river and highland tributaries. This regulation continued with the commissioning of the Ilisu dam in 2020 and will end (or reach a near maximum regulation capacity) by impounding the Silvan dam in 2023. These dams increase the available water for irrigation by storing seasonal runoff released and then diverted from the river downstream at the planned Cizre Dam (Frucht and Williams, 2006). After completing the Cizre project below the Ilisu dam, 121,000 ha will be irrigated. In addition to the Cizre project, 138,000 ha of irrigated areas are currently in use or under construction. It will reach 520,000 ha after all dams and irrigation projects are completed. Therefore, based on the possible water consummation of irrigation, three irrigation scenarios were considered to analyze the flow regime alteration (Frucht and Williams, 2006): Scenario 1: 259,000 ha, including 121,000 ha downstream and 138, 000 ha in use or under construction upstream; scenario 2: 421,000 ha, including 121,000 ha downstream and 300,000 ha upstream; and scenario 3: 641,000 ha consisting of 121,000 ha downstream and 520,000 ha upstream. The estimated monthly crop demand (Frucht and Williams, 2006) has been taken into account to calculate the impact of the irrigation scenarios on the Tigris monthly flow (Table S2). The available monthly flow data at the Cizreh gauge (1969–2005, basin area: 38295 km^2), Mosul (1931–1997, 56000 km^2), Baiji (1930–2005, 107600 km^2), Baghdad (1930–2004, 134000 km^2), and Kut (1931–2005, B.A: 173000 km^2) hydrological stations are used as the reference for this study.

3. Methodology

To evaluate the impact of river regulation on the Tigris flow regime, we used five sets of monthly flow (N and S0-S3) in five locations. N is a reconstruction of the natural flow and S0 is the monthly flow regime at different points of the Tigris River from 1982 to 1995. As the last commissioned dam (Mosul) on the Tigris was constructed before this period, any impact assessment based on S0 will reflect the influence of water resource development in Iraq on the Tigris flow regime. S1-S3 are the possible altered flow regimes for implementing irrigation scenarios in Turkey.

3.1. *Reconstructed monthly natural flow at crucial points of the Tigris River*

Naturally, adjacent stations should have the most correlation along a river. Therefore, an annual and monthly correlation analysis between flow data at successive stations during an unregulated period (see Torabi Haghighi and Kløve, 2013) was applied to reconstruct the natural flow along the Tigris River. After that, an annual and monthly developed linear regression was applied to fill in missing values in the natural condition (Figs. SM2-SM5).

3.2. River regime alteration assessment

In order to evaluate the impact of Turkish irrigation scenarios on the flow regime of the Tigris River in Iraqi territory, we utilized the river impact (RI) factor introduced by Torabi Haghighi et al. (2014). The RI method quantifies the impact of changes in three key flow features: magnitude (MIF), variability (VIF), and timing (TIF). To calculate the RI value (Eq. 1), we considered all three factors (MIF, VIF, and TIF):

$$\mathrm{RI} = \mathrm{MIF} \times (\mathrm{TIF} + \mathrm{VIF}) \tag{1}$$

$$\mathrm{MIF}_2 = \mathrm{A.F.}_{\mathrm{Post}} / \mathrm{A.F.}_{\mathrm{Pre}} \tag{2}$$

$$\mathrm{VIF} = \left(50 - \frac{|\mathrm{IRR}_{\mathrm{Pre}} - \mathrm{IRR}_{\mathrm{Post}}|}{\mathrm{IRR}_{\mathrm{Pre}}} \times 50\right) \times 100 \tag{3}$$

$$\mathrm{TIF} = \left(50 - 0.274 \times \left(\frac{|\mathrm{DT}_{\max}| + |\mathrm{DT}_{mix}| + |\mathrm{DT}_{median}|}{3}\right)\right) \Big/ 100 \tag{4}$$

where $\mathrm{AF}_{\mathrm{Post}}$ and $\mathrm{AF}_{\mathrm{Pre}}$ are the pre and post impact annual flow rate. The IRR is the river regime index introduced by Haghighi and Kløve (2015). The IRR is dependent on the annual flow hydrograph fluctuation varied between 0 (uniform flow) and 1200 (strongly seasonal flow regime). A calculator tool for the RRI can be found in the Supplementary Material in Haghighi and Kløve (2015). $\mathrm{DT}_{\mathrm{max}}$, $\mathrm{DT}_{\mathrm{min}}$, and $\mathrm{DT}_{\mathrm{median}}$ are the time shifts in monthly maximum discharge, minimum discharge, and cdf50 timing values, respectively.

The RI varies between 0 (wholly changed river flow) and 1 (natural river flow). According to the value of RI, the impact is categorized into five classes: low, incipient, medium, severe, and drastic impact (more detail on the method, refer to Torabi Haghighi et al., 2014). We have provided a graphical demonstration of the impact analysis (Fig. SM6) based on the values of two terms, namely MIF and (TIF+VIF), in Eq. (1). The five impact levels are represented by different colors in the figure: white for low impact, yellow for incipient impact, orange for moderate impact, red for severe impact, and black for drastic impact.

We designed two sets of river regime impact analyses (including 35 individual river impact assessments, Table SM3) based on five flow time series (N and S0-S3). First, S0-S3 was compared with the reconstructed natural flow (1940–1995) to see the overall influence of river regulation on different river points. Second, we compared S1-S3 with S0 to reveal the influence of Turkish regulations on the Tigris River's lower section. To this end, each river impact assessment has been given a name including two parts, X and YZ (Table SM3). X indicates the location of analysis (e.g., C for Cizre or Ba for Baghdad), and YZ includes the name of two compared flow regimes, pre (Y: N or S0) and post-impact (Z: S0-S4). For example, M-NS1 indicates the river regime impact at Mosul (M) by comparing the flow regime of natural conditions (N) with the altered flow regime created by the implementation of the first irrigation scenario (S1).

3.3. Modified streamflow drought index

The streamflow drought index (SDI), developed by Nalbantis and Tsakiris (2009), addresses hydrological droughts.

$$\mathrm{SDI} = \frac{\mathrm{Q} - \overline{\mathrm{Q}}}{\sigma_Q} \tag{5}$$

where, Q, $\overline{\mathrm{Q}}$, and σ_Q are the monthly flow, mean monthly (or annually) flow, and standard deviation of monthly (or annually) natural flow.

The Standardized Drought Index (SDI) is calculated based on flow characteristics such as the mean and standard deviation of the entire flow time series. However, in cases where anthropogenic factors, such as river regulation by dams and hydropower, have led to flow alteration, the flow time series may include pre- and post-alteration flows, which can affect the flow characteristics (mean and standard deviation) and thus may not accurately reflect the natural flow characteristics. To ensure an accurate evaluation of hydrological changes, such as droughts, we recommend comparing the altered flow with the natural flow characteristics rather than the flow time series that includes altered flow. In order to assess hydrological drought in the river, we propose a modification to the SDI by introducing the Modified Streamflow Drought Index (MSDI). MSDI involves using the flow characteristics of the pre-alteration period (or natural flow if it can be determined) in Eq. (5) and modifying it as shown in Eq. (6):

$$\mathrm{MSDI} = \frac{\mathrm{Q} - \overline{\mathrm{Q}}_{\mathrm{Nat}}}{\sigma_{\mathrm{Q}_{\mathrm{Nat}}}} \tag{6}$$

where, Q, $\overline{\mathrm{Q}}_{\mathrm{Nat}}$, and $\sigma_{\mathrm{Q}_{\mathrm{Nat}}}$ are the monthly flow, mean monthly natural (or pre-impact) flow, and standard deviation of monthly natural (or Pre-impact) flow, respectively.

Based on the value of SDI or MSDI, we can classify hydrological drought as "No Drought", "Mild Drought", "Moderate Drought", "Severe Drought" and "Extreme Drought" (Table SM4) (Torabi Haghighi et al., 2020).

4. Results

4.1. Estimation of the Tigris River's natural flow

To evaluate the impacts of scenarios S0 and S1-S3 on the flow regime of the Tigris River, the annual and monthly natural flow at key points of the Tigris River is required. For this purpose, the natural flow of the Tigris at Kut, Baghdad, Baiji, Mosul, and Cizre (the location of stations shown in Fig. 1) was reconstructed from 1930 to 1995 (Fig. 2). The monthly natural flow was estimated based on the correlation of available flow data between successive stations and the history of river regulation (Table SM1). The river regulation history helped specify a period for each pair of successive stations with the most negligible impact from river regulation. These periods

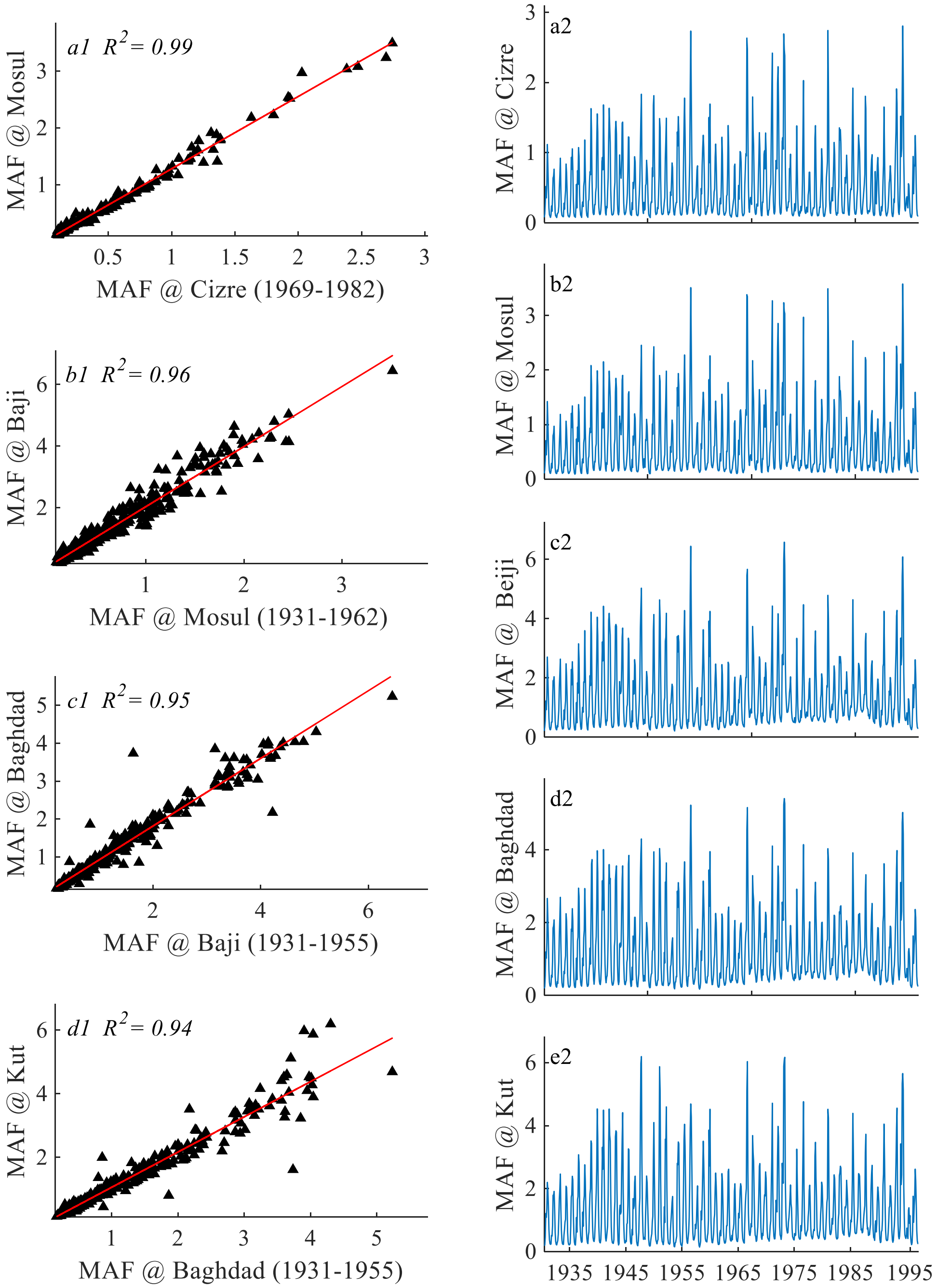

Fig. 2. a1-d1: The cross-correlation in mean annual flows (MAF, 1000 m^3s^{-1}) between the successive stations and a2-e2: the reconstructed monthly natural flow (RCMNF) of the Tigris River at Cizre (a2), Mosul (b2), Baiji (c2), Baghdad (d4), and Kut (e2) for the period of 1930–1995.

were chosen as 1931–1955, 1931–1955, 1931–1962, and 1969–1982 for reconstructed natural flow between Kut-Baghdad, Baghdad-Baiji, Mosul-Baiji, and Mosul-Cizre, respectively (Figs. SM2-SM5). There is a significant correlation between annual flow in each successive station for the specified periods (Fig. 2a1-d1). The monthly natural flow for 1930–1995 (Fig. 2a2-e2 and Fig. 3a1-e1) was reconstructed based on the monthly correlation between the selected successive stations.

4.2. Altered monthly flow along the Tigris River

To evaluate RI, the mean monthly flow was required from five locations (Fig. 3a-e, a-e refers to the gauges at Cizre, Mosul, Baiji, Baghdad, and Kut, respectively) to compare with the reconstructed natural flow (N, Fig. 3a1-e1). The monthly flow for scenario S0 was directly obtained from observed flow (1982–1995) at each gauge (Fig. 3a2-e2). The monthly flow in scenarios S1-S3 refers to the possible reduced flow in the different gauges caused by implementing irrigation scenarios (S1-S3) in Turkey (Fig. 3a3-e3, a4-e4, and a5-e5). These intra-annual hydrographs were obtained by subtracting associated monthly irrigation demands in three irrigation scenarios (see Table SM2) from scenario S0.

4.3. The impact of river regulation on the flow regime of the Tigris River

In this part, we first assess the overall spatial impact of river regulation along the Tigris River by comparing scenarios S0 and S1-S3 with natural flow (N); then, we present the influence of water resource development in Turkey on the Tigris flow regime in Iraq.

4.3.1. The impact of river regulation on the Tigris flow regime compare with the natural flow

Before intensive river regulation in Turkey (S0, 1982–1993), the RI (River Impact) varied from 0.97 to 0.27, reflecting the low to severe conditions along the river (C, M, Bi, Ba, and K-NS0 in Fig. 4a, Table SM5). The lowest impact (RI: 0.97, C-NS0) was found at Cizre on the Iraq-Turkey border, which indicates that the flow regime there (Fig. 3a2) is very close to the natural condition (Fig. 3a1). Below the Mosul dam, the RI reduced to 0.73, and the impact class declined to incipient (Fig. 4a, Table SM5) due to the dam performance and its influence on the timing impact factor TIF (0.29 out of 0.50) and negligible influence on changes in MIF (0.97 out of 1) and VIF (0.47 out of 0.5) (Table SM5). At Baiji, the next station after the Mosul dam, the RI increased to 0.83, reflecting the low impact class (Bi-NS0, Fig. 4a, Table SM5). This recovery in flow regime is the result of discharging two considerable sources of freshwater (the Greater and Lesser Zabs) into the main corridor of the Tigris River. A severe impact on the flow regime was observed in two lower

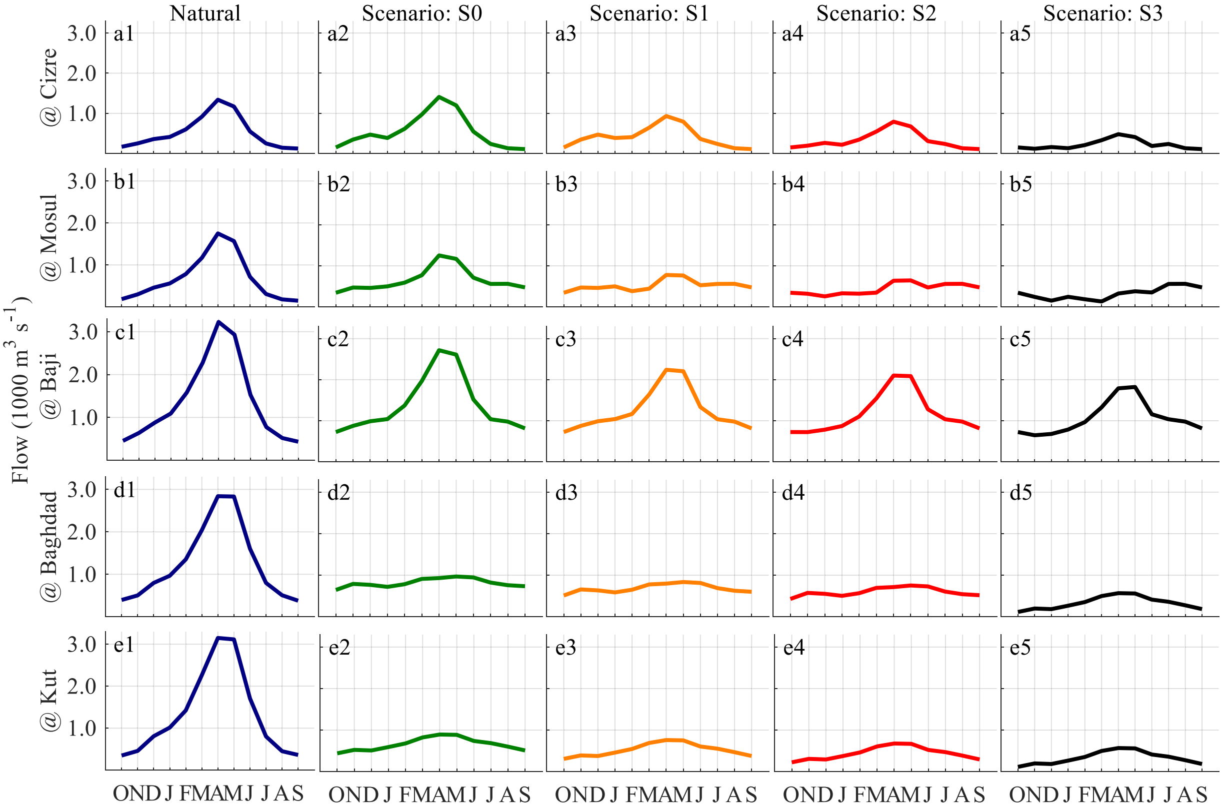

Fig. 3. The monthly flow of the Tigris River at a) Cizre, b) Mosul, c) Baiji, d) Baghdad and Kut gauge in 1) reconstructed natural flow, 2) scenario S0 (1982–1997), 3–5) different irrigation scenarios S1-S3 conditions.

stations, Baghdad and Kut, with RI values of 0.36 and 0.32, respectively (Ba-NS0 and K-NS0, Fig. 4a, Table SM5). The leading cause of this decline in the Flow regime is the significant water diversion at the Samarra barrage, which results from the contribution of all three impact factors (MIF, VIF, and TIF, Fig. 4a and Table SM5).

The rest of the analysis in this part is the impact assessment of water resource development in Turkey on the Tigris flow regime in Iraq (Irrigation scenarios 1–3) compared with the natural flow. The most significant impact in all stations was in Scenario 3 (followed by Scenario 2 and 1) due to there being the highest amount of water consumption in this scenario (Fig. 4a). The greatest decline in RI value and change in impact class was seen at Cizre (ΔRI =0.60 (0.97 ($RI_{C\text{-}NS0}$) - 0.37 ($RI_{C\text{-}NS3}$)) and Mosul (ΔRI =0.48), followed by Baiji (ΔRI =0.28), Baghdad (ΔRI =0.21) and Kut (ΔRI =0.17) (Table SM2). At Cizre, Low impact flow in S0 (RI: 0.97, C-NS0) declined to incipient (RI: 0.72, C-NS1), moderate (RI: 0.59, C-NS2), and severe (RI: 0.37, C-NS3), respectively; this was due to irrigation scenarios S1-S3 (Fig. 4a and Table SM5). Likewise, A similar pattern of variation in impacts was observed in Mosul (from an incipient to severe impact in S0 and S3 scenarios, Fig. 4a and Table SM5). The flow regime at Baiji in the worst-case scenario (S3 irrigation scenario) shows a moderate impact (RI: 0.55) and reflects the lowest impacted point along the Tigris River (Fig. 4a and Table SM5). The flow regime alteration in the two lower stations (Baghdad and Kut) was quite similar, and in the worst cases, the RI declined (RI=0.17 and 0.15) to below the drastic impact threshold (0.2) at Kut and Baghdad gauges after the implementation of the third irrigation scenario (Ba-NS3 and K-NS3, Table SM5). For the rest of the scenarios, the flow regime impact is classified as severe (Table SM5, RI: 0.21–0.34). Out of all the scenarios and stations, the lowest declines in RI (ΔRI: 0.06–0.21) due to Turkish modification were estimated in Baghdad and Kut (Table SM5).

4.3.2. The Impact of river regulation in Turkey on the Tigris flow regime

In the second set of analyses, the impact of river regulation in Turkey was aggregated with the impact of river regulation in Iraq (Fig. 4b). The altered flow regimes caused by Turkish developments were compared with the flow regime in the period 1982–1993 (S0) after the ending of water development in Iraq on the main corridor of the Tigris River. The flow regimes at Cizre and Mosul show the highest impact (Fig. 4b and Table SM6). Due to the implementation of the first irrigation scenario (S1), the flow regime impact was

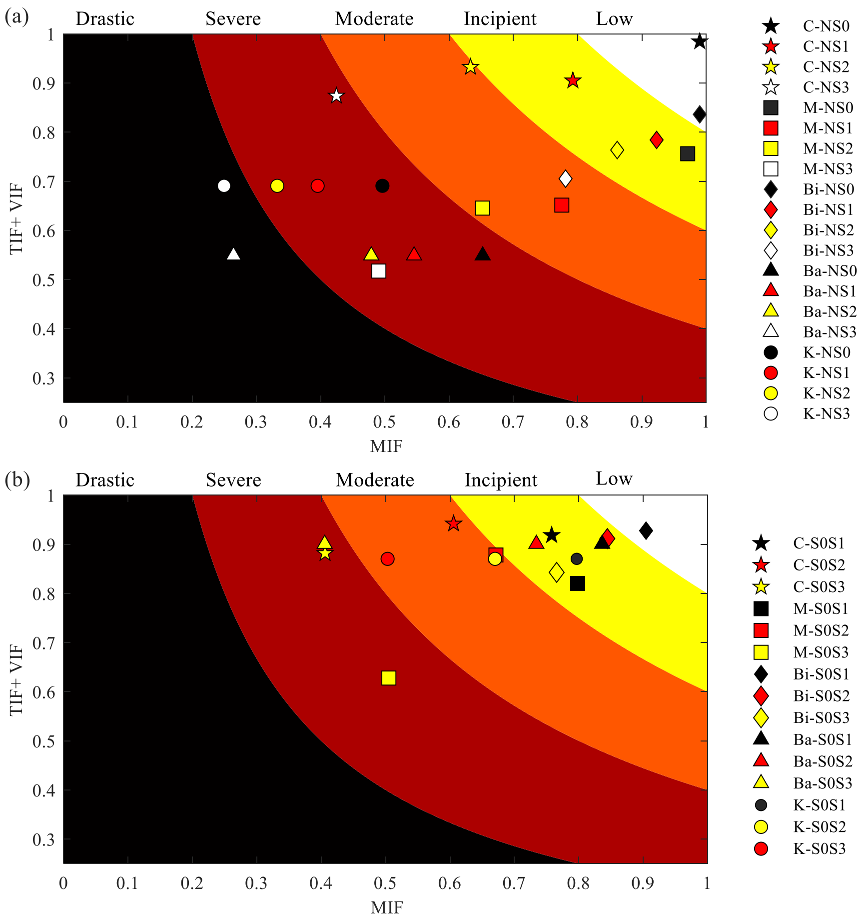

Fig. 4. Flow regime Impact class at different points and in different conditions along the Tigris River, C, M, Bi, Ba, and K stand for Cizre, Mosul, Baiji, Baghdad, and Kut, respectively, N, S0, S1, S2, and S3 stand for Natural flow, Scenario S0, Scenario S1, Scenario S2, and Scenario S3 conditions, respectively.

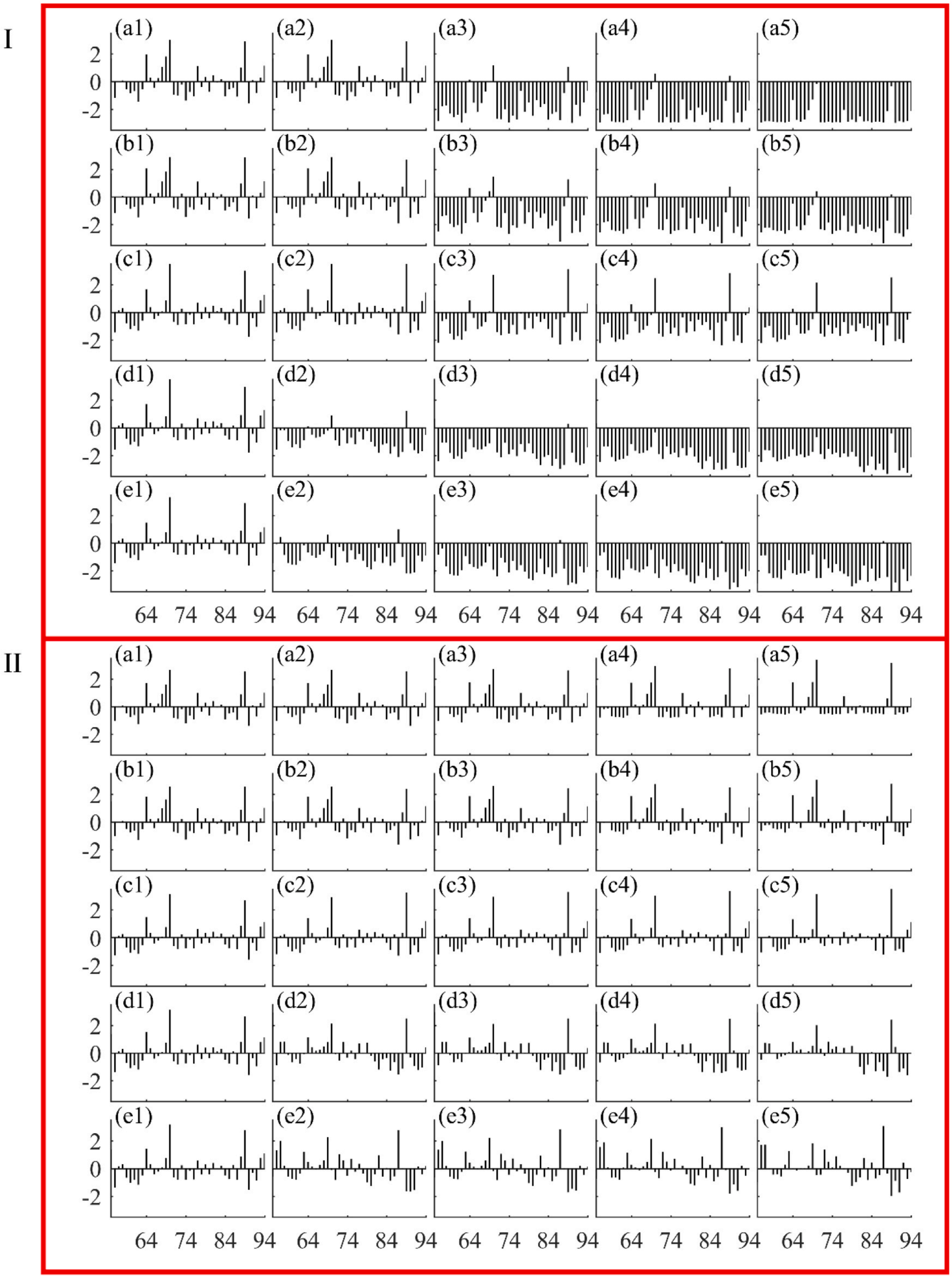

Fig. 5. Hydrological drought along the Tigris River at a) Cizre b) Mosul c) Baiji d) Baghdad and e) Kut, Based on I) modified streamflow drought index (MSDI) and II) streamflow drought index (SDI) in different conditions: 1) natural flow, 2) Scenario S0, 3) Scenario S1, 3) scenario S3 and 4) scenario S4.

classified as having an incipient impact at Cizre (RI=0.73, CS0S1, Table SM6, Fig. 4b) and Mosul (RI=0.67, MS0S1, Table SM6, Fig. 4b). After implementing S2 and S3, the flow regime impact declined to moderate and severe (RI=0.33–0.57, Table SM6 and Fig. 4b) in Mosul and Cizre. The minimal flow regime impact was observed in the Baiji gauge upstream from the Samarra barrage (RI=0.62–0.87). The impact of the three irrigation scenarios on the flow regime of the Tigris at the lower parts of the basins (Baghdad and Kut) is classified as moderate (RI 0.42–0.58) (Table SM6 and Fig. 4b).

4.4. Hydrological drought along the Tigris River

In natural flow conditions, the values of MSDI showed no droughts (MDSI>0) for about half of the years in all gauges as an expected pattern for natural flow (Fig. 5-I a1-e1, Table SM7, and SM8). In Scenario S0 flow conditions (before irrigation scenarios S1-S3), the Tigris river is divided into two parts at the Samarra barrage when considering hydrological drought (Fig. 5-I a2-e2). As the main water consumers are placed below the Samarra barrage, the number of hydrological droughts increased considerably at the Baghdad and Kut gauges (Fig. 5-I d2 and e2). In 90% of the analyzed years, a negative value was reported for MDSI (hydrological drought) in these two gauges (Fig. 5-I d2-e2 and Table SM8). In contrast, in the upstream gauges (Baiji, Mosul, and Cizre, Fig. 5-I a2-c2), about 55% of the years were detected as having hydrological droughts (Table SM8). These results are consistent with RI assessment results, indicating a moderate impact for Baghdad and Kut (Scenarios Ba-NS0 and K-NS0, Table SM3) and low impact for Baiji, Mosul, and Cizre (Scenarios Bi-NS0, M-NS0, and C-NS0, Table SM3). When considering the impact of the irrigation scenario (S1-S3) on annual flow, it can be seen that the number of hydrological droughts also increased in the gauges above the Samarra Barrage (e.i, Baiji, Mosul, and Cizre, Table SM7, Fig. 5). Based on the MSDI value, the implementation of irrigation Scenarios S2 and S3 meant that, in more than 90% of the years, hydrological droughts can be seen in all gauges except Baiji (Table SM8, Fig. 5). The lowest number of hydrological droughts was detected for the Baiji gauge due to the Great and Lesser Zab tributaries meeting the river above this station and discharging a considerable amount of freshwater to the main channel of the Tigris River (Table SM8, Fig. 5).

Regarding the drought categories, the most extreme droughts were observed at Cizre in 50%, 75%, and 87.5% of the analyzed years after the implementation of S1, S2, and S3, respectively (Table SM8, Fig. 5). In terms of MDSI value, after Irrigation scenarios in Turkey, the dominant hydrological drought condition below Samarra gauge will extend to the whole river in Iraqi territory (Table SM7, Fig. 5). In addition to the number of years affected, the frequency of extreme droughts will also increase significantly (Table SM7, Fig. 5). Droughts (extreme drought) were detected in 87.5% (37.5%), 90% (52%), and 95% (72.5%) of the years at the Mosul gauge for scenarios S1, S2, and S3, respectively (Tables MS5 and MS6). The percentages detected drought (extreme droughts) at the Cizre, border gauge was 92.5% (50%), 95% (75%), and 100% (87.5%). As seen, the conditions at Mosul (below Cizre) are better, as several small tributaries join the Tigris River in the mid-basin between Cizre and Mosul.

Likewise, with the pre-impact flow condition, the Tigris River at Baiji has better conditions than other gauges; the number of years with extreme drought was 4, 6, and 6 years for the three irrigation scenarios, while for other gauges, it was at least 15 years. In the lower part of the basin at Baghdad (Kut), droughts occurrence increased from 36 (37) years in pre-impact flow conditions to 38 (39), 39 (39), and 40 (39) years in S1, S2, and S3, respectively (Tables SM7 and SM8). It is worth noting that while hydrological drought was dominant, the precipitation pattern in different parts of the basin during the last 40 years followed the natural fluctuation, the variation of the Standardized Precipitation Index (SPI) presented in the Supplementary Material (Fig. SM7).

5. Discussion

5.1. Justification of the selected period for the reconstruction of natural flow data

The last two stations on the main corridor of the Tigris River are Baghdad and Kut, located below the Samarra barrage. This barrage was constructed in 1955. Therefore, the period 1931–1955 is considered to give the correlation between the monthly flow of these stations (Fig. SM2). The regulation of the Diyola River (an eastern tributary that joins the Tigris below the Baghdad gauge) did not influence the river flow at the Kut during the selected period (1931–1955) because both constructed dams (Derbendi Khan in 1962 and Hamrin in 1980) were commissioned after 1955. Likewise, the correlation between monthly river flows at the Baghdad gauge station and its adjacent upstream station, Baiji, was calculated using the data from 1931 to 1955 (Fig. SM3). In addition to the Samarra barrage, the Mosul dam on the main corridor of the Tigris River (1983) and two other dams, Dokan and Dibbas, were built on the Lesser Zab in 1962 and 1965. Therefore, the flow at Baiji (1931–1955) was not influenced by any of these dams. The influence of these three dams can be seen at the Baiji station after 1962. Thus, the monthly flow from 1931 to 1962 was used to evaluate the correlation between the Mosul and Baiji gauges in natural conditions (Fig. SM4). Since the flow at the Mosul dam has been regulated since 1982 (the commissioning year for the Mosul dam), the monthly correlation between river flow at the Mosul and Cizre gauges was calculated using the observations from 1969 to 1982 (Fig. SM5). The lack of data at the Cizre gauge before 1969 was the reason for evaluating the monthly and annual flow correlation between Cizre and Mosul from 1969 instead of 1931.

5.2. Justification of pre-impact period selection

The period (1982–1995) was selected as pre-impact (referring to the impact of water regulation and irrigation in Turkey). It is a period after the commissioning of the Mosul dam (the latest major constructed dam on the main corridor of the Tigris in Iraqi territory, Table SM1) and before the start of significant regulation in Turkey, e.g., the construction of the Dicle (1996), Batman (1999) Dams and the relevant irrigation network. The pre-impact flows were directly extracted from the provided flow data by Saleh (2010). This period reflects the impact of river regulation in Iraq on the Tigris flow. The impact of the Mosul, Dokan and Dibbis dams can be seen in the Baiji, Baghdad, and Kut gauge flow regimes. For Baghdad and Kut, the estimated impact is aggregated with the impact of the Samarra barrage. Finally, the evaluated impact at the Kut gauge includes the impact of the Derbendi Khan and Hamrin dams on the Diyola River.

5.3. The impact of river regulation on the Tigris flow regime

Here we evaluate the possible impact of Turkish water regulation on the Tigris flow regime in Iraqi territory. The main regulation inside Iraq consists of the Samarra Barrage (1955) and the Mosul dam (1982). In contrast, river regulation started in Turkish territory in 1997.

The impact of the Samarra Barrage and Mosul dam can be seen in the Baghdad and Kut gauges river flow regimes. Due to massive regulation before 1982, the impact of the regulation of the Tigris River below the Samarra dam was classified as severe, with RI values of 0.36 and 0.34 at the Baghdad and Kut gauges (Table SM5). This part of the river experienced hydrological drought conditions for more than 90% of the years (1956–1996), according to the MDSI value. During this period, 37.5 (42.5%) and 32.5 (27.5%) of the years for Baghdad (Kut) were categorized as having mild and moderate hydrological droughts. The flow regime in the rest of the river was generally low, and hydrological drought was observed at around 55%. By implementing the Irrigation scenarios (S1-S3), the flow regime impact extends to the whole Iraqi territory, with a considerable decrease in RI values along the river. The number of years with extreme hydrological drought significantly increases through the different scenarios. Cizre and Mosul will experience extreme conditions in 37.5–87.5% of the year; this means a considerable reduction in the Mosul dam's inflow (135–326 m^3/sec), with a large part of the hydropower capacity remaining useless. Renewable hydropower could be replaced with fossil fuel power to compensate for this flow reduction in the Mosul dam.

For the operation of the water shortage below the Samarra dam, It is the choice of Iraq to decide whether this depletion of flow influences diverted flow by Samarra or reduces the flow rate downstream, influencing Baghdad, Kut gauges, and the Arvandroud estuary at the end of the basin. Of the different water beneficiaries, only the Arvandroud estuary is placed in a mercy position, and the main socio-economic impacts of this massive river regulation will be reflected in this area, as has previously been seen with the impact of Euphrate flow regulation (Torabi Haghighi et al., 2020). The lowest impact and hydrological drought were observed at the Baiji gauge, where the Great and Lesser Zab rivers join the Tigris. It is worth mentioning that the contribution of the Great and Lesser Zab and Diyola rivers is about 29%, 15%, and 14% of the Tigres river flow, which is 28% more than the contribution of the Tigris basin in Turkish territory at the Cizre gauge (Fig. SM1).

5.4. Data uncertainty

Although the exchange of hydrologic data is required for cooperation in transboundary river basins, upstream riparians are not interested in sharing data due to competition over water resources. Particularly in developing countries, the transparency of data sharing has been disrupted (Rougé et al., 2018; Akbari et al., 2022). Likewise, the limited access to existing hydrological data on the Tigris River is one of the main challenges in addressing the hydro-political conflict across the basin (Kavvas et al., 2011; Rougé et al., 2018; Torabi Haghighi et al., 2020). However, All available long-term streamflow data up to 2005 in the Tigris and Euphrates River Basins in Iraq were provided by the US Department of the Interior (US Geological Survey) (Saleh, 2010). To our knowledge, this valuable database, *Stream gage descriptions and streamflow statistics for sites in the Tigris River and Euphrates River basins, Iraq*, is a unique online flow data source inside Iraqi territory. To assess the possible hydrological changes caused by the implementation of irrigation scenarios, we deducted Turkey's monthly agricultural water consumption from the monthly flow in different gauges along the Tigris river. Although this data includes several uncertainties, the approach can be applied to estimate flow in data-scarce transboundary river basins.

5.5. Modifying the available streamflow drought index

The Standardized Drought Index (SDI) is a commonly used tool for assessing hydrological drought, and its calculation involves using flow characteristics, such as mean and standard deviation, of the entire flow time series. This study suggests modifying the streamflow drought index (SDI) as a novel approach for assessing hydrological droughts. In MSDI, we recommend the mean and standard deviation of the flow time series before significant flow change (or natural flow, for Tigris we used reconstructed natural flow). For this purpose the average and standard deviation of flow data before the change (or natural flow) will be used. Analysis of the hydrological drought in different gauges over the Tigris River shows the advantage of using MSDI over SDI to detect hydrological droughts (Fig. 5 I and II, Table SM7). For example, due to considerable flow diversion at the Samarra barrage, significant flow reduction can be seen between natural conditions (Fig. 3d1 or e1) and the flow regime before Turkish water resource development (S0, Fig. 3d2 or e2) at the Baghdad, or Kut, gauge. Therefore, we expect the hydrological drought index to detect drought in most of the years. For these two stations, SDI and MSDI report 60% (52%) and 90% (92.5%), respectively, for Baghdad (Kut) (Table SM8). Alternatively, at Cizre station, after implementation, in the first irrigation scenario, SDI and MSDI report 57.5% and 92.5% droughts (Table SM8). Hydrological droughts usually occur due to stream flow reduction; therefore, if the whole applied flow time series for calculating hydrological droughts belonged to the period after the reduced flow, the drought index does not report any significant droughts for the whole period (like in the mentioned example in Baghdad and Kut). It must be pointed out that here we did not separate the hydrological drought from the water management impact. Our findings show that the dominant hydrological drought results from upstream water development and management. Scenario S0 represents the conditions before Turkey's river modification, the dominant hydrological drought was observed below Samarra, primarily due to intensive water diversion to Tharthar Lake. Subsequently, in Scenarios 1–3, we deducted the estimated water consumption in Turkey from the S0 scenario and evaluated the resulting hydrological drought. Therefore, the hydrological drought presented and evaluated in this study results from water management impact.

6. Conclusions

Once, the Tigris River (with its twin sister, the Euphrates) was the greatest river in the western Asia and made Mesopotamia a cradle of civilization thousands of years ago. Upstream anthropogenic activity has choked the Tigris River, the connecting lifeline across Iraq, and caused the country to be plagued by poverty caused by droughts and desertification. In this work, we have provided a flow regime alteration analysis for the main corridor of the Tigris River at Cizre, Mosul, Baiji, Baghdad, and Kut before and after the operation of three planned irrigation scenarios in Turkey. Before extensive river regulation in the Turkish Territory (before 1997), only the area below the Samarra barrage faced hydrological drought and severe flow regime alteration according to the river impact method. Commissioning new dams (including the Ilisu dam) and implementing the irrigation scenarios (S1, S2, and S3) in Turkey has led to the extension of sever hydrological conditions to the whole corridor of the Tigris River in Iraqi territory (which was previously only found below the Samarra barrage in the pre-impact period). Overall, about 26% of Tigris flow passed the Cizre gauge on the border with Iraq through the main channel of the Tigris, and the rest of the flow mainly joined the Tigris through other tributaries inside of the Iraqi territory. After the fully expected regulation in Turkey, some parts of Mosul's hydropower and reservoir capacity will be useless. The hydrological drought upstream of the Samarra dams will dominate, and considerable socio-economic impacts will emerge. The flow reduction will have the greatest influence below the Samarra barrage, particularly in the Arvandroud estuary, where the river is discharged to the Persian Gulf.

Author's statement

All authors have read and agreed to the published version of the manuscript.

CRediT authorship contribution statement

Ali Torabi Haghighi: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Mahdi Akbari:** Methodology, Formal analysis, Data curation, Software, Writing – review & editing. **Roohollah Noori:** Investigation, Conceptualization, Writing – original draft, Writing – review & editing. **Ali Danandeh Mehr:** Data curation, Writing – review & editing, Formal analysis, Data curation. **Ali Reza Gohari:** Conceptualization, Methodology, Writing – review & editing. **Mehmet Emin Sönmez:** Writing – review & editing, Formal analysis, Data curation. **Nizar Abou Zaki:** Investigation, Methodology. **Nese Yilmaz:** Writing – review & editing, Formal analysis, Data curation. **Bjørn Kløve:** Conceptualization, Methodology, Supervision, Writing – review & editing.

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.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101454.

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