# **Analyzing Discharge Changes in the Tigris and Euphrates Rivers (1979-2022): The Role of Damming and Climate**

## **Abstract**

This study provides a comprehensive analysis of discharge changes in the Tigris and Euphrates River basins between 1979 and 2022, aiming to delineate the distinct roles of extensive damming, primarily by Turkey, and increasing climate change impacts.1 The investigation utilized daily discharge data from 12 near-dam and 12 far-from-dam sampling stations, alongside monthly Palmer Drought Severity Index (PDSI) datasets. The methodological approach employed time series analysis, correlation analysis, change point analysis, and comparisons of pre- and post-damming periods.1

The findings reveal significant reductions in average annual discharge, altered seasonal flow patterns, and a strong correlation between drought severity and river flow.1 Notably, the magnitude and timing of discharge changes differed between near-dam and far-from-dam stations, indicating distinct influences of damming and climate.1 Change point analysis indicates abrupt declines in discharge at near-dam stations, often coinciding with major dam operations, while far-from-dam stations showed a more gradual decline influenced by both damming and regional drought patterns.1

The study concludes that both damming and climate change have substantially impacted the hydrological regimes of the Tigris and Euphrates rivers. Damming exhibits a more immediate and pronounced effect in closer proximity to the infrastructure, while climate change exerts a broader influence across the basin, exacerbating water scarcity in downstream regions.1 The ability of this research to differentiate the roles of damming and drought through spatial analysis (comparing near-dam versus far-from-dam stations) represents a significant methodological advancement for understanding complex hydrological systems under multiple environmental pressures. This differentiation is particularly vital in politically sensitive transboundary basins where attributing water scarcity can be a source of contention.

## **1. Introduction**

### **Global Context of Dams and Flow Regulation**

Dams fundamentally alter the natural flow regime of rivers by acting as physical barriers that impound water, thereby creating reservoirs.1 This impoundment inherently disrupts the natural patterns of river flow, leading to what is known as flow regulation.1 The primary aim of this regulation is to meet various human demands, including water supply for domestic and industrial uses, irrigation for agriculture, the generation of hydroelectric power, and the mitigation of flood risks in certain areas.1 Dams typically reduce the peak flood discharge downstream by effectively storing a portion of the floodwaters within the reservoir.1 Conversely, during dry seasons, dams can increase the discharge downstream by releasing stored water, often leading to a more homogenized flow regime throughout the year.1 Furthermore, dams tend to flatten the natural variability of river discharge over time and can introduce unnatural short-term fluctuations driven by operational needs, particularly for hydroelectric dams.1

Globally, the number of large dams has escalated significantly, with over 50,000 large dams currently in operation, reflecting an average construction rate of two per day for half a century.5 Rivers in Mediterranean-climate and other semi-arid regions are particularly susceptible to heavy impoundment. This is primarily due to a greater demand for water to support irrigated agriculture and a temporal mismatch between natural runoff patterns and water demand.6 The dual nature of dam impacts—providing essential societal benefits like flood control and water supply while simultaneously disrupting natural hydrological and ecological processes—creates a complex management challenge. This is especially true in water-stressed regions where the demand for these benefits is highest, leading to a paradox where solutions to one problem can inadvertently create others by fundamentally changing the river's natural dynamics.

### **Climate Change and Hydrological Cycle**

Climate change has emerged as a significant global concern, with increasing scientific evidence indicating that the planet is warming largely due to human-generated greenhouse gases.7 This warming profoundly impacts the hydrological cycle, primarily through altered precipitation patterns, increased air temperatures, and enhanced evapotranspiration rates.7 These modifications can lead to more frequent and severe extreme weather events, including prolonged droughts and intense floods.7

Arid and semi-arid regions, characterized by inherently low and variable precipitation, are particularly vulnerable to the impacts of climate change, facing increased water scarcity and heightened risks of desertification.9 The projected increase in both drought frequency and flood intensity due to climate change presents a formidable challenge for water management. This creates a "double-edged sword" scenario, demanding simultaneous and often conflicting strategies for water conservation during dry periods and flood mitigation during wet extremes. Managing these opposing needs—for instance, retaining water in reservoirs for drought resilience versus releasing water to prevent flood risks—requires sophisticated planning and adaptive management strategies.

### **The Tigris and Euphrates River Basins (TEB): A Case Study in Water Stress**

The Tigris and Euphrates River basins (TEB), a region of immense historical and ecological significance in the Middle East, have sustained human civilizations for millennia.1 These transboundary rivers, originating in Turkey and flowing through Syria and Iraq to the Persian Gulf, are the lifeblood of an arid and semi-arid landscape, supporting extensive agriculture, providing essential water supplies, and sustaining diverse ecosystems.1

In recent decades, the basins have experienced increasing water stress due to large-scale damming projects, particularly within Turkey's Southeastern Anatolia Project (GAP), and the growing threat of climate change, manifested as prolonged and intensified droughts.1 Key structures such as the Atatürk Dam on the Euphrates and the Ilisu Dam on the Tigris have significantly altered the natural flow regimes of these rivers, leading to concerns about water availability and quality in downstream Syria and Iraq.1 Iraq, as the furthest downstream riparian state, has consistently reported significant reductions in its historical water supply from both rivers since the 1970s, coinciding with the intensification of Turkish dam construction.1 Reductions of 40% or greater for the Euphrates and anticipated decreases of up to 50% for the Tigris have been reported once all planned Turkish dams become fully operational.1 Some projections suggest that the Euphrates could face the dire risk of drying up within Iraqi territory by the year 2040, a consequence attributed to a combination of upstream damming and increasing climate change impacts.1

The Tigris and Euphrates basins exemplify a complex situation of water insecurity, where escalating anthropogenic pressures (large-scale damming, increased water demand) are interacting synergistically with intensifying climatic stressors (prolonged droughts, reduced snowmelt). This combination creates a rapid degradation of water resources and heightened geopolitical risks. The compounding and reinforcing nature of these multiple stressors—human-induced changes and natural climatic variability—is creating a crisis far greater than the sum of their individual parts, elevating the problem from a simple water shortage to a complex human security challenge with regional and international implications.

### **Research Objectives and Contribution**

This study provides a comprehensive spatial and temporal analysis of the changes in the discharge of the Tigris and Euphrates rivers over a 44-year period (1979-2022).1 Specifically, it investigates the roles of both upstream damming projects and climate-induced drought conditions in driving these alterations. This is achieved by employing a combination of hydrological and statistical methods on daily discharge data from 12 sampling stations in close proximity to major dams and 12 sampling stations located further downstream, along with monthly PDSI datasets.1 This research seeks to quantify the impacts of these factors on the rivers' flow regimes at different spatial scales, which is crucial for informed water resource management and for mitigating potential conflicts in this water-scarce and politically sensitive region.1 This paper builds upon existing literature by providing a detailed analysis of long-term discharge time series from spatially differentiated sampling points in conjunction with drought indices to offer insights into the complex interplay of anthropogenic and climatic influences on these vital transboundary rivers.1

## **2. Study Area**

### **Geographical and Climatic Overview**

The Tigris and Euphrates rivers originate in the eastern Anatolian highlands of Turkey, traversing southeastward through Syria and Iraq before their confluence at Al-Qurnah in Iraq, forming the Shatt al-Arab, which empties into the Persian Gulf.1 The elevation in the basin ranges from sea level up to 4000 meters in the mountainous northern and northeastern territories.1 The TEB exhibits significant climatic variations, transitioning from the mountainous headwaters in Turkey, which receive more rain and snow, to the arid and semi-arid plains of Syria and Iraq.1 Historically, annual snowmelt from these mountains brought spring floods, sustaining permanent and seasonal marshes in the lowlands.22 The rivers are the primary sources of freshwater in a region characterized by water scarcity, supporting extensive agricultural activities, diverse ecosystems including the critical Mesopotamian Marshes, and the water needs of a large population.1

### **Major Water Management Interventions**

Turkey's Southeastern Anatolia Project (GAP), with its extensive network of dams on both rivers, represents a major water management intervention in the upper reaches of the basin.1 The operation of these dams, coupled with the increasing frequency and intensity of droughts in the region, has significantly impacted the hydrological balance and downstream water availability in Syria and Iraq.1

The geographical asymmetry of the basin, with the headwaters located in an upstream country (Turkey) and critical downstream reliance in arid regions (Syria and Iraq), inherently creates hydropolitical tensions. This situation is significantly exacerbated by both large-scale dam development and intensifying climate change impacts.14 The fundamental geographical reality means that upstream actions have direct, often severe, downstream consequences. This pre-existing geopolitical sensitivity is amplified by the added stressors of dam construction and climate change, making water a tool for leverage and a source of conflict among riparian states.

## **3. Data**

### **Dams and Reservoirs**

The spatial distribution of significant dams in the TEB is presented in Fig. 2.1 Important dam characteristics, including year of construction, volume, and functions, are detailed in Table 1.1 These data were extracted from the Global Reservoir and Dam Database (GRanD), which collects information on reservoirs and dams with a storage capacity exceeding 0.1 km³.1

### **Daily Discharge Data**

This study utilized a gridded daily discharge dataset covering the period from 1979 to 2022.1 This dataset provides a modeled time series of river network discharges, generated with the help of the open-source hydrological model LISFLOOD.1 LISFLOOD is a distributed rainfall-runoff hydrological model widely used for water and climate studies, as well as flood and drought modeling and forecasting.1 Its application in large basins has proven effective in simulating maximum flows and extreme flood peaks.29 Daily streamflow measurements were collected from 24 key sampled stations located on the Tigris and Euphrates rivers. Twelve of these stations were strategically selected for their close proximity to major dams in TEB to assess the immediate impacts of dam operations. The remaining twelve stations were located at a significant distance downstream from these dams to capture the effects of other factors, such as climate variability and tributary inflows.1 The use of a sophisticated, gridded hydrological model like LISFLOOD, combined with spatially differentiated sampling, enhances the robustness and attribution capabilities of the study. This approach moves beyond simple observational trends to more causally-linked analyses of hydrological changes, allowing for a more confident understanding of the underlying causes of observed changes, rather than merely describing the changes themselves.

### **Monthly Palmer Drought Severity Index (PDSI)**

Monthly PDSI values for the geographical area encompassing TEB were obtained for the study period (1979-2022).1 The PDSI is a widely recognized and used index based on the soil-water balance equation that integrates temperature, precipitation, and potential evapotranspiration to provide a standardized measure of drought severity and duration.1 By using monthly PDSI, this study aims to capture the long-term drought conditions and their potential impact on the discharge of the rivers, and to compare its influence on the near-dam and far-from-dam stations.1 While classical drought indices like PDSI provide global-scale assessments and are valuable for historical analysis, some studies suggest they may lack the spatial-temporal resolution for accurate local monitoring or may not fully capture the multiscale nature of drought as effectively as newer indices like SPEI, particularly in regions with complex topography.13 However, PDSI remains a robust tool for long-term historical drought assessments.30 The deliberate selection of PDSI, despite the existence of newer indices, is justified for its historical depth and its ability to consistently capture long-term drought conditions over the study's 44-year period, providing a reliable measure for correlation analysis with river discharge.

## **4. Methodology**

### **Time Series Analysis (TSA)**

The daily discharge data for both the Tigris and Euphrates rivers at the 24 sampling stations were subjected to time series analysis to identify long-term trends and patterns.1 TSA methods were used to detect the trend of discharge in the sampled stations, capturing relationships between a time series and its lagged values and analyzing interdependencies among different time series.1 TSA could also identify regime shifts in time series data.1 The Breaks For Additive Season and Trend (BFAST) model was employed, which integrates the decomposition of time series into trend, season, and residual components.1 BFAST is particularly effective for detecting changes within time series data by iteratively fitting piecewise linear models to the trend component.1 The Mann–Kendall test, a non-parametric statistical test, was implemented on the monthly discharge series to detect statistically significant trends.1 This test is widely used in hydrological studies for trend detection in precipitation and streamflow data.12 These techniques were used to visualize and quantify shifts in the average flow and seasonal discharge patterns over the 44-year study period for both near-dam and far-from-dam locations, helping to understand the overall trajectory of river discharge and identifying periods of significant change at different distances from damming infrastructure.1

### **Correlation Analysis**

To assess the relationship between climate variability and river discharge at different locations, correlation analysis was performed between the monthly discharge data from the 24 stations and the corresponding monthly PDSI values.1 Pearson's correlation coefficient was calculated to quantify the strength and direction of the linear association between drought conditions and river flow for both near-dam and far-from-dam stations.1 This analysis helps to determine the extent to which drought events influence the discharge of TEB rivers at varying distances from major dams.1 The application of correlation analysis in conjunction with spatial differentiation (near-dam versus far-from-dam) allows for a more precise attribution of drought influence. This reveals how the presence of damming infrastructure might alter the sensitivity of downstream flows to climatic signals. By comparing correlations at these distinct locations, the study can infer whether dams act as buffers against drought or, conversely, amplify its effects on downstream discharge, moving beyond simple correlation identification to understanding how human infrastructure mediates this relationship.

### **Change Point Analysis**

Change point analysis was employed to detect statistically significant points in time where the mean discharge of the rivers experienced abrupt shifts at both sets of sampling stations.1 These identified change points were then compared with the operational timelines of major dam construction projects in the upper catchments, such as the Atatürk Dam (operational in the early 1990s) and the Ilisu Dam (began filling in 2019).1 By comparing the timing and magnitude of change points at near-dam and far-from-dam stations, this method helps to identify the spatial extent and immediate versus delayed impacts of dam construction on river flow.1 The temporal alignment of statistically significant abrupt discharge declines with the operational dates of major dams provides compelling causal evidence for the direct hydrological impact of damming. This effectively distinguishes these immediate anthropogenic effects from more gradual, climate-induced changes, allowing for a strong inferential leap from correlation to causation for damming impacts.

### **Comparison of Pre- and Post-Damming Periods**

To quantify the impact of damming on the rivers' flow regimes at different spatial scales, the average discharge and seasonal flow patterns were compared between distinct periods: before the operation of major dams and after their significant operational phases.1 This comparison was conducted separately for the 12 near-dam stations to assess the differential impacts of damming on discharge depending on the distance from the dams.1

### **Differential Analysis of Near-Dam and Far-From-Dam Stations**

Finally, a comparative analysis was conducted between the discharge patterns observed at the near-dam stations and the far-from-dam stations for the same time periods.1 This involved comparing the magnitude of discharge reduction, changes in seasonal flow variability, and the strength of correlation with the PDSI between the two groups of stations.1 This differential analysis aimed to isolate the localized impacts of damming from the broader regional influences of climate change.1 These methodologies collectively provide a robust framework for analyzing the complex interactions between damming, climate change, and the discharge of the Tigris and Euphrates rivers over the study period, while also accounting for the spatial variability of these impacts through the use of near-dam and far-from-dam sampling stations.1 The multi-faceted differential analysis, combining time series, correlation, and change point methods across spatially distinct stations, provides a robust framework for disentangling complex anthropogenic and climatic influences, establishing a model for future transboundary river basin studies. This comprehensive approach allows for a more rigorous attribution of impacts in a complex, multi-stressor system.

## **5. Results**

### **Annual Discharge and Drought Changes**

Annual changes in discharge and drought (PDSI) for both near-dam and far-from-dam stations during 1979 to 2022 are illustrated in Fig. 3 and Fig. 4, respectively.1 PDSI values were categorized into eight classes, ranging from extremely drought to extremely wet, with values between -1 and 1 excluded from categorization.1 A comparison of average discharge values at near-dam stations before and after dam constructions (Fig. 5-a) revealed a considerable reduction in discharge across all stations during the latter period.1 Furthermore, the variation of near-dam station discharges within the two periods showed an increment in average discharge fluctuation (m³/s) for most stations (Fig. 5-b).1 The observed increase in discharge fluctuation at near-dam stations post-construction, despite an overall reduction in average flow, suggests a shift from natural hydrological variability to an operationally-driven, less predictable flow regime. This altered variability poses new challenges for downstream water users and ecosystems that rely on stable flow patterns, as dams' releases for hydropower or irrigation can introduce rapid, artificial changes in discharge.1

### **Monthly Discharge Trending (1979 to 2022)**

To assess flow trending, the Mann–Kendall test was initially applied to the monthly discharge series at sampled near-dam points.1 Fig. 6 presents the monthly trends of near-dam stations from 1979 to 2022. Eight of the 12 near-dam stations exhibited a significant monthly flow trend, with the majority showing a decreasing trend, except for the Bassel Al Assad Dam station.1 Fig. 7 illustrates the trend and seasonality components for these time series.1

For the period 1979 to the year of dam construction, only two stations, Lower Kaleköy and Ilisu, demonstrated a decreasing monthly flow trend (Fig. 8).1 Fig. 9 displays the trend and seasonality components for those time series.1 Subsequently, for the period from the year of dam construction to 2022, five stations confirmed a decreasing monthly flow trend (Fig. 10).1 Fig. 11 illustrates the trend and seasonality components for these monthly discharge time series.1

The monthly trends of sampled far-dam stations during 1979 to 2022 are shown in Fig. 12. Ten of these stations verified a decreasing monthly flow trend during this period, while only two stations showed no trend.1 Fig. 13 illustrates the trend and seasonality components of those time series.1 The observation that more far-dam stations showed a significant monthly trend compared to near-dam stations during the same period (1979-2022) suggests a more uniform impact of effective factors on discharge trends in sampled far-dam stations.1 The widespread prevalence of decreasing discharge trends in far-from-dam stations, despite being less immediately impacted by dam operations, underscores the pervasive and basin-wide influence of climate change and cumulative upstream abstractions, indicating a systemic decline in water availability across the entire basin. This points to broader, non-localized stressors, such as regional climate change (e.g., reduced precipitation, increased evapotranspiration) and the integrated effect of all upstream water withdrawals and impoundments, rather than just the direct impact of the nearest dam.

### **PDSI Changes of Near-Dam and Far-From-Dam Stations**

Average PDSI changes consistently showed lower (more negative) PDSI values after dam construction across all near-dam stations (Fig. 14-a), indicating an increase in drought severity downstream of the dams.1 Average values of PDSI for far-dam stations during 1979 to 2022 are shown in Fig. 14-b.1 The average PDSI for near-dam stations during 1979-2022 was -1.3, with values of -0.50 before dam construction and -2.10 after dam construction. For far-dam stations, the average PDSI was -0.82.1 These PDSI changes directly imply a worsening of drought conditions, particularly in downstream stations of the dams.1 The observed increase in drought severity (more negative PDSI values) at near-dam stations post-construction suggests a potential feedback loop where reduced surface water availability due to damming exacerbates localized drought impacts. This intensifies water stress beyond climatic signals alone, as dams, by altering natural flow and potentially increasing evaporative losses from reservoirs, contribute to a perceived or actual intensification of hydrological drought conditions in their immediate downstream vicinity.

### **Relationship between Annual Discharge and PDSI**

To quantify the correlation between drought and monthly discharge, scatter plots are presented separately for near-dam stations during two periods: before and after dam constructions (Fig. 15).1 R² values for these periods were calculated for all stations and are presented as histograms in Fig. 16 for comparative purposes.1 Generally, the correlation between PDSI and discharge in the period after dam construction was higher than before.1 The Sırımtaş station in the northwest of TEB was the only exception, showing less sensitivity of discharge to climatic and drought conditions, resulting in similar correlations across both periods.1 Stations sensitive to drought exhibited a greater correlation between discharge and drought after dam constructions.1

The scatter plots and correlation between monthly drought and discharge for far-dam stations during 1979 to 2022 are provided in Fig. 17.1 Overall, the correlation between PDSI and monthly discharge for stations 1, 10, 11, and 12 (located in the northwest of TEB) was higher than for stations 2 and 3 (located in the southeast of TEB).1 This difference is primarily attributed to stations 2 and 3 having a much higher average discharge (exceeding 100 m³/s compared to 20 m³/s), rendering them less affected by meteorological drought.1 Consequently, the correlation between discharge and drought is higher at stations with a lower average discharge, due to the more pronounced impact of drought on discharge in these areas.1

Fig. 18 illustrates the correlation between 12 values of average annual discharge and PDSI for near-dam stations (before and after dam construction) and far-dam stations (1979 to 2022).1 This cumulative analysis reveals that the regression between river flow and PDSI in near-dam stations is noticeably higher than in far-dam stations (R² values of near and far-dam stations during 1979 to 2022 were 0.56 and 0.52, respectively).1 Furthermore, for near-dam stations, the correlation after dam construction was greater than before dam construction.1 The increased correlation between discharge and PDSI at near-dam stations post-construction, coupled with the observed increase in drought severity, suggests that dams transform the hydrological response, making downstream flows more acutely dependent on regional climatic conditions and upstream management decisions. This thereby amplifies climate vulnerability, as dams not merely reduce water quantity but fundamentally alter the system's sensitivity to climatic variability.

## **6. Discussion**

The analysis of discharge and PDSI time series from 1979 to 2022, considering the differentiated sampling locations, reveals significant changes in the flow regimes of both the Tigris and Euphrates rivers, with distinct influences from damming and drought observed at near-dam and far-from-dam stations.

### **Discharge Reduction and Damming Impacts**

A substantial decrease in the average discharge was observed for both rivers across all sampling stations.1 However, the magnitude of reduction was significantly higher at the 12 stations located near major dams, particularly after the dams became operational (Fig. 5-a).1 Far-from-dam stations also showed a reduction in discharge, but the decline was more gradual and less pronounced compared to the near-dam stations (Fig. 4).1 A primary finding is the substantial reduction in average river flow observed at monitoring stations located downstream of dams following their construction and operation.1 This aligns with expectations, as dams inherently alter natural flow regimes by impounding water, regulating releases, and potentially increasing evaporative losses from reservoirs.1 The observed decrease in flow is a direct consequence of these activities, leading to reduced water availability downstream.1 The case of the Ilisu dam downstream station, showing lower flow even before impoundment, is noteworthy and could be attributed to significant disruption of the natural river course during the prolonged construction phase, highlighting that even pre-operation activities can impact flow.1 The immediate and pronounced discharge reduction observed near dams, even during their construction phases, demonstrates that the physical presence and operational logic of large-scale water infrastructure override natural hydrological processes, establishing a new, human-controlled flow regime with significant and often detrimental downstream implications. This dominance of human activity has cascading effects on downstream ecosystems, water availability, and inter-state relations.

### **Varying Impact of Drought and Climate Change**

The analysis of drought conditions, as indicated by the PDSI, reveals a concerning trend: drought intensity has increased at all studied near-dam stations in the period after dam construction compared to the period before (Fig. 19).1 This suggests either a regional shift towards drier conditions coinciding with the operational period of the dams or a potential feedback mechanism where reduced surface water availability due to damming exacerbates localized drought impacts.1 The amplified reduction in river flow observed at near-dam stations during drought periods, compared to stations further away, strongly supports the notion that dams compound the effects of drought on downstream water availability.1

Correlation analysis indicated a strong positive relationship between river discharge and PDSI values at both near-dam and far-from-dam stations.1 However, the strength of this correlation was generally higher at the far-dam stations with a lower average discharge and at near-dam stations after dam construction (Fig. 18).1 This suggests a greater influence of regional drought conditions on these locations due to climatic and damming factors, respectively.1 Near-dam stations showed a discharge pattern more immediately responsive to dam operation schedules, and with damming, the impact of climate on discharge in those stations could increase and intensify.1 The Middle East is recognized as a climate change hotspot, with projections indicating significant declines in snow-water availability (ranging from 10-60% to 55-87%) and shifts in the timing of flows (18-39 days earlier).12 Precipitation is expected to decrease by 15-25%, leading to projected reductions in river flows of 29-73%.17 The observed increase in drought severity and the amplified correlation between discharge and PDSI at near-dam sites post-dam construction points to a critical "dam-drought synergy." This suggests that dams, while intended to enhance water security, paradoxically increase the vulnerability of downstream areas to climatic variability by concentrating water resources and altering natural buffering capacities of the river system. This amplification of vulnerability is a critical, perhaps counter-intuitive, consequence that directly impacts the long-term water security of downstream populations, especially when combined with regional climate change projections.

### **Alteration of Flow Patterns and Seasonality**

The average slope of the monthly discharge trends for near-dam points in the period after dam impoundment is greater (more decreasing) than in the other two periods, indicating a more pronounced decreasing trend in discharge downstream of those stations (Fig. 20).1 Damming projects caused a more immediate and pronounced alteration of flow patterns at the near-dam stations.1 Peak flows were significantly reduced, and their timing sometimes shifted shortly after dam operation commenced.1 Predicting and trending the seasonality of flow downstream of these dams becomes more challenging.1 Far-from-dam stations also experienced changes in seasonality, but these changes appeared to be a combination of the integrated effects of tributary flows and broader regional climate patterns.1 The observed shift from naturally variable to operationally-driven flow regimes downstream of dams disrupts the ecological cues vital for many aquatic and riparian species (e.g., migration, spawning, germination).1 This leads to broader ecosystem degradation beyond just water quantity, as the fundamental functioning and health of the riverine ecosystem are affected.

### **Spatial Differences in Discharge Changes**

Change point analysis identified earlier and more significant declines in the mean discharge at the near-dam stations, with change points often coinciding with the operational years of major dams.1 Far-from-dam stations also showed change points, but these were sometimes delayed, and the magnitude of the initial drop was less severe, suggesting a lagged and potentially buffered response to upstream damming, influenced by the cumulative effects of the basin.1 The estimated percentage reduction in average annual discharge during the post-damming periods was considerably higher for the near-dam stations compared to the far-from-dam stations (Fig. 20).1

The pairwise correlation analysis of annual discharges of near-dam and far-dam stations further illuminates the altered hydrological landscape (Fig. 21).1 Comparing the pairwise correlation between stations near and far from dams over the entire study period (1979-2022) shows similar general behavior for both sets of stations (Fig. 21-a and Fig. 21-b), indicating that broader regional drought patterns affect both sets of stations.1 However, the more pronounced reduction in flow and the increased drought intensity specifically at the near-dam stations in the post-construction period underscore the additional, localized impact of dam operations superimposed on the regional climatic signal.1 The pairwise correlation among stations near dams increased after dams were constructed (Fig. 21-c and Fig. 22), suggesting relatively uniform responses to climatic forcing, while the correlations became more varied in the before-construction period (Fig. 21-d).1 This suggests that after damming, the flow dynamics at these stations are no longer solely dictated by localized or sub-regional climatic variations but are increasingly influenced by the regulated releases from the upstream dams, which themselves may be managed based on regional water availability dictated by climate.1 The increasing homogenization of flow responses (higher pairwise correlation) among near-dam stations post-construction suggests that dams act as dominant "control points," effectively overriding localized hydrological variability and making downstream water availability a function of upstream management decisions and basin-wide climate, rather than natural sub-basin dynamics. This shift from distributed natural control to centralized anthropogenic control has profound implications for water governance and the resilience of the system.

### **Socio-economic and Environmental Consequences**

The reduced water flow, particularly the decrease in seasonal flooding, has had a devastating impact on the vital Iraqi marshes located in the lower reaches of the river basins, leading to their significant destruction and the disruption of unique ecosystems and livelihoods.1 These drying marshes and wetlands significantly convert them to active dust sources, allowing wind to easily lift exposed soil particles and leading to increased dust storm events.1 Iraq experienced over 200 dusty days in 2022, more than double the annual average recorded in the 1980s and 1990s.36 Dust storms are not only a public health hazard, causing spikes in asthma, bronchitis, and eye infections, but also an economic burden, disrupting air traffic and agricultural production.36

Groundwater depletion is also a major concern in the Tigris-Euphrates Basin, with alarming rates of decrease in total water storage and significant groundwater losses observed.22 This depletion has led to inelastic compaction and land subsidence, particularly near Baghdad.39 Water quality degradation, particularly increasing salinity, is a severe problem, rendering water unsuitable for drinking and irrigation downstream.40 The cascading environmental impacts—from damming and drought to marsh destruction, increased dust storms, groundwater depletion, and salinity—create a vicious cycle of land degradation and human vulnerability. This fundamentally transforms the region's ecology and threatens the habitability and agricultural productivity of downstream areas.

## **7. Conclusion**

This study, utilizing daily discharge data from near-dam and far-from-dam stations, as well as monthly PDSI datasets for the 1979 to 2022 period, provides a spatially differentiated analysis of the roles of damming and climate (drought) in discharge changes within the Tigris and Euphrates rivers. The findings reveal that damming has a more immediate and substantial impact on river discharge in close proximity to the dams, leading to significant reductions in flow and alterations in seasonal patterns. Climate change, as indicated by the PDSI, plays a more pervasive role across the basin. The combination of these factors has resulted in a widespread decline in the water resources of the Tigris and Euphrates rivers, exacerbating water scarcity in downstream regions.

The study provides valuable insights into the complex interplay between large-scale dam construction and regional drought variability on river flow dynamics in the Tigris and Euphrates rivers. The findings clearly demonstrate that both anthropogenic alterations (damming) and natural climate phenomena (drought) exert significant, and often synergistic, influences on river discharge, particularly in arid and semi-arid environments. The differentiated impacts observed at near-dam and far-from-dam stations underscore the complex interplay of anthropogenic and climatic influences on these vital transboundary rivers.

In conclusion, this study provides compelling evidence that both dam construction and drought are significant drivers of reduced river flow in the study area. Their combined impact is particularly severe at locations downstream of dams, especially during periods of drought. The findings highlight the vulnerability of river systems in arid and semi-arid regions to combined anthropogenic and climatic pressures. Effective water resource management in such areas must therefore consider not only the direct impacts of infrastructure like dams but also the amplified risks posed by increasing climate variability and drought, particularly in regulating downstream flows to maintain ecological health and meet water demands.

Future research should focus on developing more sophisticated hydrological models that can explicitly simulate the spatial variability of damming and climate change impacts, as well as on exploring water management strategies that can mitigate the adverse consequences for both near-dam and downstream communities and ecosystems. Collaborative efforts among the riparian countries are essential to address these challenges and ensure the sustainable management of the TEB in the face of increasing water stress. Further research could explore the specific operational rules of the dams and their influence on downstream flow variability under different drought scenarios.

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