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SUPPLY-DRIVEN WATER STRESS IN THE SYR DARYA RIVER BASIN: RUNOFF VARIABILITY, RESERVOIR REGULATION AND WITHDRAWAL PRESSURE, 2000–2025

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Abstract:
Water stress in transboundary irrigated basins is usually discussed in terms of growing demand, yet the share of available flow that is withdrawn can rise sharply even when withdrawals stay constant. This study quantifies that mechanism for the Syr Darya River Basin, Central Asia, using a harmonised annual dataset for 2000–2025 that combines basin runoff, Toktogul reservoir inflow and outflow, total withdrawals and climatic drivers. Trends were tested with the Mann–Kendall test and Sen's slope; relationships were assessed with Pearson and Spearman coefficients; pressure was expressed by the withdrawal-to-runoff ratio (WR) and a complementary water availability index (WAI). Mean basin runoff was 37.95 $km^3\ yr^{-1}$ (range 27.64–50.29 km^3), with no significant monotonic trend (Kendall $\tau = -0.080$, $p = 0.591$). Total withdrawals were remarkably stable (mean



13.35 km³, range 12.00–14.10 km³), so WR was governed by supply: it fell to 27.08% in the wet year 2009 and rose to 47.40% in the drought year 2007. In the baseline year 2025, runoff was 12.38% below the long-term mean while withdrawals were virtually unchanged (−0.18%), lifting WR to 40.09% and lowering WAI to 59.91%; the Toktogul reservoir released 1.64 km³ more than it received. The results show that interannual supply variability, rather than demand growth, currently controls basin-scale water stress, and that drought-year allocation rules are a more immediate lever than long-term demand reduction alone.

Keywords: Syr Darya; water stress; withdrawal-to-runoff ratio; Toktogul reservoir; runoff variability; transboundary basin; Central Asia.

1. Introduction

The Syr Darya is one of the two principal rivers of the Aral Sea Basin. Its flow is generated mostly in the Tien Shan and Alay ranges of Kyrgyzstan and Tajikistan, while the largest consumptive uses are located in the irrigated lowlands of Uzbekistan and Kazakhstan [1,2]. A cascade of reservoirs, led by the Toktogul reservoir on the Naryn River (total capacity about 19.5 km³, active capacity about 14 km³), redistributes this flow between seasons and years and between hydropower and irrigation interests [3,4]. This spatial separation of supply and demand makes the basin a classic example of upstream–downstream interdependence in a transboundary system [5,6].

Previous studies have shown that much of the change observed in the middle and lower Syr Darya is attributable to human activity, chiefly irrigation withdrawals and reservoir operation, superimposed on climatic variability [7–9]. Global analyses have likewise demonstrated that water stress in transboundary basins is

shaped by upstream use as much as by local demand [10,11]. Most basin-scale assessments, however, express pressure either in absolute withdrawal volumes or in long-term averages. Such metrics can mask a simple but important mechanism: when withdrawals are institutionally fixed, the fraction of available water that is withdrawn moves inversely with runoff, so that stress peaks in dry years even without any growth in demand.

The objectives of this study were therefore (i) to characterise interannual variability and trends in Syr Darya basin runoff and Toktogul inflow over 2000–2024; (ii) to quantify how much of the variation in withdrawal pressure is explained by supply rather than demand; and (iii) to evaluate 2025 as a baseline year for subsequent scenario work, explicitly separating climatic anomalies from changes in use.

2. Materials and Methods

2.1. Study area

The analysis covers the hydrologically active catchment of the Syr Darya, approximately 219 × 10^3 km², which contributes directly to flow in the main stem [3]. The river is formed by the confluence of the Naryn (length ≈ 807 km, catchment 59.1 × 10^3 km², mean flow ≈ 14.5 km³ yr^{-1}) and the Kara Darya (≈ 177 km, 30.1 × 10^3 km², ≈ 3.9 km³ yr^{-1}) in the Fergana Valley and flows some 2212 km to the Aral Sea [3]. For interpretation the basin was divided into an upstream flow-generation zone, a midstream regulation and irrigation zone (Fergana Valley, Tashkent oasis, Mirzachul) and a downstream transit and delta zone (Turkistan and Kyzylorda regions).

2.2. Data

The dataset consists of annual series for 2000–2025: Toktogul reservoir inflow and outflow, total basin runoff, total water withdrawal, and climatic drivers (mean air temperature, precipitation, potential evapotranspiration (PET), climatic water balance and snowfall). Hydrological values were taken from official and documented water-management sources, including the yearbooks of the Scientific-Information Center of the Interstate Commission for Water Coordination [12], and climatic series were harmonised at basin scale using the methodological basis of ERA5-Land and CRU TS [13,14]. Each annual value carries a provenance flag (observed, documented, calculated or reconstructed), and reconstructed values were kept distinct from documented ones throughout the analysis [15].

Gaps in the basin runoff series, mainly in 2000–2016, were filled using a bounded logistic regression on Toktogul inflow, constrained to the historical natural-flow range of 23.6–51.1 km³. The model was calibrated on official calendar-year data for 2018–2025; 2017 was excluded because of a reporting-period inconsistency. Gaps in total withdrawal were filled with a ridge regression on year and available runoff. Model skill statistics are reported with the results so that the reader can judge their influence.

2.3. Indicators

Withdrawal pressure was expressed as the withdrawal-to-runoff ratio:

$$WR = (W / Q) \times 100 \quad (1)$$

where W is total annual withdrawal (km³) and Q is total annual basin runoff (km³). The complementary water availability index is:

$$WAI = 100 - WR \quad (2)$$

WAI is a relative indicator of the share of runoff conditionally remaining in the river system after withdrawal; it is not a measure of environmental flow and does not account for return flows or water quality. The conditional annual balance of the Toktogul reservoir was computed as:

$$B_T = I_T - O_T \quad (3)$$

where I_T and O_T are annual inflow and outflow (km³). Because evaporation and seepage are not included, B_T describes the inflow–release relationship rather than the true change in storage.

2.4. Statistical analysis

Trend direction and magnitude were estimated by ordinary least squares and Sen's slope, and significance by the Mann–Kendall test with the Hamed–Rao variance correction where lag-1 autocorrelation was present [16–19]. Pettitt's test was used to detect change points [20]. Associations between runoff and its drivers were evaluated with Pearson's r and Spearman's ρ. Statistical significance was assessed at $\alpha = 0.05$. All computations were performed in Python.

3. Results

3.1. Runoff and Toktogul inflow, 2000–2024

Mean annual basin runoff was 37.95 km³, ranging from 27.64 km³ in 2007 to 50.29 km³ in 2009; the 22.64 km³ difference between these years equals about 60% of the mean. The linear trend (−0.068 km³ yr⁻¹) was not significant (Kendall $\tau = -0.080$, $p = 0.591$), and the means of 2000–2012 and 2013–2024 differed by only 0.24 km³ (38.06 vs. 37.83 km³). Toktogul inflow averaged 13.37 km³ (9.91 km³ in 2007, 19.20 km³ in 2009) and also showed no significant trend (−0.021 km³ yr⁻¹; 13.41 vs. 13.32 km³ in the two sub-periods).

Behind the flat long-term mean lies a sequence of sharp swings: runoff stayed at 39.72–42.90 km³ in 2014–2017, fell to 32.24 and 32.09 km³ in 2020 and 2021, recovered to 39.73 km³ in 2022, dropped to 35.28 km³ in 2023, rose to 41.99 km³ in 2024 and fell again to 33.25 km³ in 2025. The 8.74 km³ drop between 2024 and 2025 alone is almost a quarter of the mean annual flow.

Toktogul inflow and basin runoff varied almost in parallel (Table 1). Runoff was very strongly associated with precipitation ($r = 0.984$), climatic water balance ($r = 0.950$) and Toktogul inflow ($r = 0.946$; $\rho = 0.988$), and moderately and inversely associated with PET ($r = -0.397$, $p = 0.049$). Because part of the runoff series was reconstructed from Toktogul inflow, these coefficients partly reflect the reconstruction method and should be read as indicators of hydroclimatic consistency rather than as proof of causation.

Table 1. Statistical relationships, trends and model performance for the Syr Darya hydrological series (2000–2024)

Relationship / model	Statistic	Value	p-value	Interpretation
Precipitation vs basin runoff	Pearson r	0.984	<0.001	very strong, positive
Climatic water balance vs runoff	Pearson r	0.950	<0.001	very strong, positive
Toktogul inflow vs runoff	Pearson r	0.946	<0.001	very strong, positive
Toktogul inflow vs runoff	Spearman ρ	0.988	<0.001	very strong, monotonic
PET vs runoff	Pearson r	−0.397	0.049	moderate, inverse
Basin runoff trend	Kendall τ	−0.080	0.591	no significant trend

Relationship / model	Statistic	Value	p-value	Interpretation
Withdrawal ratio trend	Kendall τ	0.093	0.528	no significant trend
Runoff reconstruction model	RMSE	1.125 km³	–	≈3 % of mean runoff
Withdrawal ridge regression	R^2	0.103	–	low explanatory power

3.2. Reservoir regulation

Average Toktogul outflow (13.71 km³) slightly exceeded average inflow (13.37 km³), giving a mean conditional balance of −0.34 km³. The reservoir buffered extreme years in both directions: in 2007 releases exceeded inflow by 4.23 km³, drawing down storage accumulated earlier, whereas in 2009 inflow exceeded releases by 6.79 km³. In 2025, inflow was 12.33 km³ and outflow 13.97 km³, a balance of −1.64 km³. A single negative year is consistent with the reservoir's regulating role, but a run of such years would progressively reduce the carry-over storage available for subsequent droughts.

3.3. Withdrawals and withdrawal pressure

Total withdrawals averaged 13.35 km³ yr^{-1} and varied within a narrow band of 12.00–14.10 km³. The mean WR was 35.73%, with no significant trend (τ = 0.093, p = 0.528). The ridge model used to complete the withdrawal series had low explanatory power (R^2 = 0.103), which is itself informative: withdrawals are set by crop plans, irrigation schedules and interstate allocation decisions rather than by the volume of water available in a given year.

The consequence is shown in Table 2 and Figure 1. In 2007, withdrawals of 13.10 km³ consumed 47.40% of runoff; in 2009, a larger withdrawal of 13.62 km³

represented only 27.08%. Between the favourable year 2015 and the dry year 2020, withdrawals actually fell by 1.03 km³, yet WR rose from 32.69% to 38.49% because runoff fell faster. Across the selected years, WR therefore tracks runoff, not withdrawal volume.

Table 2. Runoff, withdrawals and withdrawal pressure in contrasting years of the study period

Indicator	2007	2009	2010	2015	2020	2025
Toktogul inflow, km³	9.91	19.20	13.78	14.01	11.68	12.33
Basin runoff Q, km³	27.64	50.29	40.27	41.11	32.24	33.25
Total withdrawal W, km³	13.10	13.62	13.40	13.44	12.41	13.33
Withdrawal ratio WR, %	47.40	27.08	33.27	32.69	38.49	40.09
Water availability index WAI, %	52.60	72.92	66.73	67.31	61.51	59.91
Hydrological character	extreme dry	extreme wet	wet	wet	dry	relatively dry

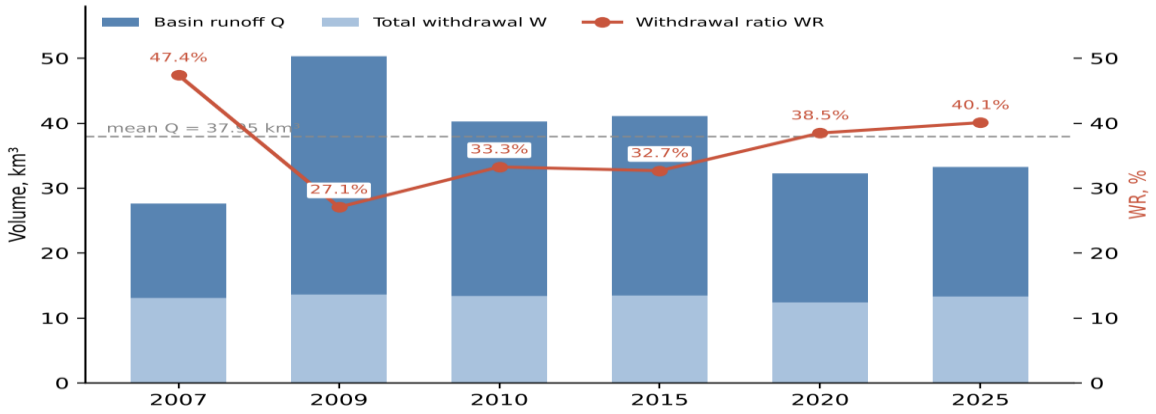

Figure 1. Basin runoff (bars) and withdrawal-to-runoff ratio (line) in contrasting years. Withdrawals remain within 12.4–13.6 km³, so the ratio is driven by runoff.

3.4. The 2025 baseline year

In 2025 the basin was warmer and drier than the long-term mean: mean temperature was 0.44 °C higher, precipitation 8.18% lower, PET 1.44% higher, and the climatic water balance 41.05 mm more negative (Table 3). Snowfall was 15.56% below normal and the maximum snow water equivalent 6.85% below normal, limiting the seasonal snowpack that sustains spring and early-summer flow. Toktogul inflow was 7.76% and basin runoff 12.38% below the mean. With a standardised precipitation index of −0.72 and runoff above the 2007, 2020 and 2021 minima, 2025 is classified as a relatively dry rather than an extreme drought year.

Total withdrawal, however, was 13.33 km³, only 0.18% below the mean. As a result WR rose by 4.36 percentage points to 40.09% (+12.21% in relative terms), the largest positive deviation of all indicators, while WAI fell to 59.91% and the conditional residual after withdrawal was 19.92 km³ (Figure 2).

Table 3. Hydroclimatic and water-use indicators of the 2025 baseline year compared with the 2000–2024 mean

Indicator	Unit	Mean 2000–2024	2025	Abs. change	Change, %	Assessment
Mean annual temperature	°C	9.94	10.39	+0.44	+4.46	above normal
Annual precipitation	mm	317.65	291.65	−26.00	−8.18	below normal
Potential evapotranspiration	mm	1044.01	1059.06	+15.06	+1.44	above normal
Climatic water balance	mm	−726.36	−767.41	−41.05	−5.65	deficit increased
Snowfall	mm	110.37	93.20	−17.17	−15.56	below normal
Toktogul inflow	km³	13.37	12.33	−1.04	−7.76	below normal
Toktogul outflow	km³	13.71	13.97	+0.26	+1.91	slightly above
Toktogul conditional balance	km³	−0.34	−1.64	−1.30	–	storage drawn down

Indicator	Unit	Mean 2000–2024	2025	Abs. change	Change, %	Assessment
Basin runoff	km³	37.95	33.25	−4.70	−12.38	relatively dry
Total withdrawal	km³	13.35	13.33	−0.02	−0.18	nearly unchanged
Withdrawal ratio	%	35.73	40.09	+4.36 pp	+12.21	pressure increased
Water availability index	%	64.27	59.91	−4.36 pp	−6.79	availability reduced

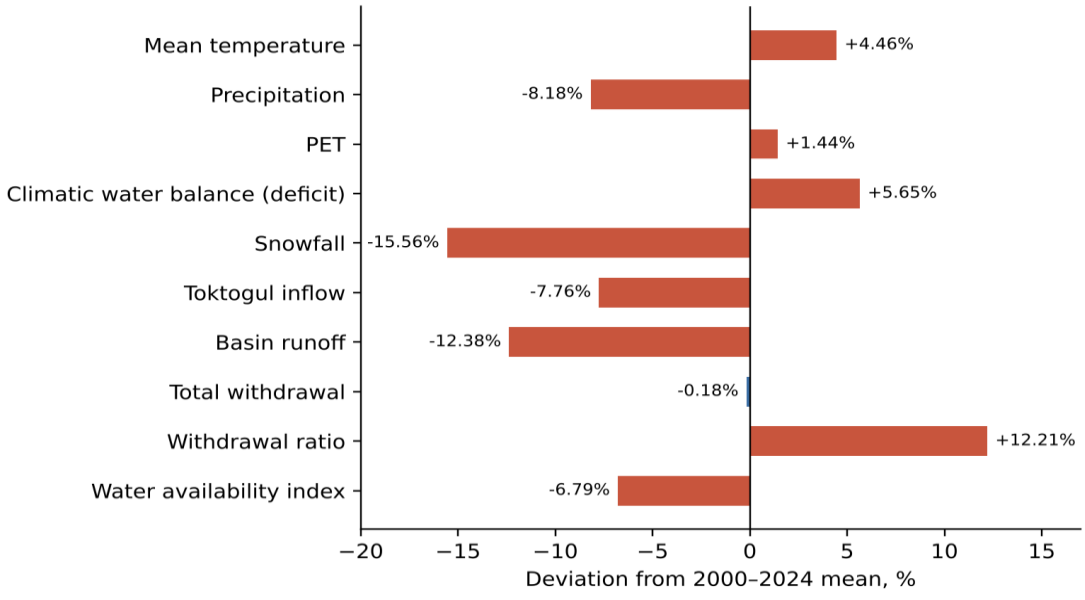

Figure 2. Deviation of 2025 indicators from the 2000–2024 mean (%). Red bars denote changes that increase water stress; for the climatic water balance the bar shows the relative increase in deficit.



4. Discussion

The central finding is that basin-scale water stress in the Syr Darya is currently supply-driven. Withdrawals have been held within a narrow range for 25 years, while runoff has varied by a factor of almost two. Because the denominator of the withdrawal ratio moves and the numerator does not, stress is concentrated in dry years. This agrees with earlier attributions of mid- and lower-basin flow changes primarily to irrigation and reservoir management [7–9] and with global evidence that upstream use amplifies downstream stress in transboundary basins [11].

This mechanism has a practical implication. Long-term efficiency programmes, such as canal lining and expansion of water-saving irrigation targeted in national strategies [21,22], reduce the average numerator, but they do not by themselves make withdrawals responsive to the denominator. In years like 2007, 2020–2021 and 2025, the decisive variables are how quickly allocation plans are adjusted to forecast inflow and how much carry-over storage remains in Toktogul. Pre-agreed drought-year allocation rules, linked to an early estimate of Toktogul inflow, would therefore address the dominant source of stress more directly.

The absence of a significant runoff trend should not be read as evidence of stability. Over the same period, air temperature and PET in the basin increased significantly, and the climatic water balance remained strongly negative in every year. These changes build a background against which a given precipitation deficit produces a larger runoff deficit, as observed in 2020–2021 and 2025. Sequences of dry years are particularly problematic because they combine high WR with successive reservoir draw-down.

The study has limitations. Part of the runoff and withdrawal series was reconstructed; the runoff model error (RMSE = 1.125 km³, about 3% of the mean) is acceptable for basin-scale annual analysis but larger than some year-to-year differences. The strong correlations reported in Table 1 are partly inflated by the

reconstruction design. WR and WAI are relative indicators that ignore return flows, groundwater exchange, water quality and environmental flow requirements, and the annual time step hides the seasonal mismatch between winter hydropower releases and summer irrigation demand. Extending the analysis to monthly data and to sub-basin withdrawals would allow the downstream concentration of stress to be quantified directly.

5. Conclusions

(1) Syr Darya basin runoff averaged 37.95 km^3 yr^{-1} in 2000–2024 with no significant trend but with very high interannual variability (27.64–50.29 km^3).
(2) Total withdrawals were nearly constant (12.00–14.10 km^3), so the withdrawal-to-runoff ratio varied between 27.08% and 47.40% almost entirely in response to runoff.
(3) The Toktogul reservoir buffered extreme years (balance −4.23 km^3 in 2007, +6.79 km^3 in 2009); in 2025 it released 1.64 km^3 more than it received.
(4) In 2025, runoff was 12.38% below normal while withdrawals were unchanged, raising the ratio to 40.09% and lowering water availability to 59.91%. The year is a relatively dry, high-pressure baseline for future scenario assessments.
(5) Making allocations responsive to forecast inflow during dry years is likely to reduce basin-scale stress more immediately than measures that only lower average demand.

Data Availability Statement: The harmonised annual series used in this study are available from the author on reasonable request. Hydrological source data are published by SIC ICWC.



Conflicts of Interest: The author declares no conflict of interest.

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