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Declining Transboundary Inflows Drive Rising Water Stress in Azerbaijan: A 24-Year WSI Decomposition Corroborated by GRACE Storage Trends

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Abstract: Azerbaijan faces escalating water stress driven by climate variability, socio-economic pressures, and pronounced transboundary dependence. This study presents a transparent, reproducible framework that decomposes the Water Stress Index (WSI = $TAWW/TRWR \times 100$) into its hydrological (internal runoff, transboundary inflows, groundwater) and sectoral (agricultural, domestic, industrial) components, and integrates it with hydro-climatic drivers (P , ET_a) and GRACE/GRACE-FO total water storage (TWS). Applied to Azerbaijan for 2000–2023, the framework yields mean TRWR of $21.8 \text{ km}^3 \text{ year}^{-1}$, mean TAWW of $11.7 \text{ km}^3 \text{ year}^{-1}$, and mean WSI of 56% (range 35–88%); the high-stress threshold (40%) was exceeded in 20 of 24 years, peaking at 88% in 2020. TRWR declined at $-524 \text{ Mm}^3 \text{ year}^{-1}$ ($p < 0.001$), driven almost entirely by falling transboundary inflows, while TAWW rose at $+89 \text{ Mm}^3 \text{ year}^{-1}$ and WSI at $+1.8$ percentage points year^{-1} . GRACE mascons show a basin-scale TWS decline of -1.1 to $-1.5 \text{ cm year}^{-1}$ over 2002–2025 ($p < 0.001$). A key new result is a national water-balance closure test: a climate-only budget ($\Delta S = P - ET_a - Q$) is essentially flat ($+0.10 \text{ cm year}^{-1}$) and negatively correlated with GRACE ($r = -0.61$), whereas a full budget that includes the documented anthropogenic groundwater over-abstraction (which grew 4.3-fold between 2000 and 2020) matches GRACE with $r = +0.96$, $RMSE = 2.5 \text{ cm}$, and trend agreement within $0.07 \text{ cm year}^{-1}$. This provides an independent, budget-based attribution of the observed storage decline to unsustainable groundwater extraction rather than climatic variability. Sensitivity analysis reveals a supply-side dominance: a 20% reduction in Q , raises WSI by ≈ 10 percentage points, versus ≈ 7 for an equivalent demand reduction.

Keywords: water stress index; transboundary water resources; climate variability; Azerbaijan; GRACE; groundwater

1. Introduction

Azerbaijan, located in the South Caucasus, faces acute and escalating water stress driven by climate variability, expanding agricultural demand, and pronounced dependence on transboundary water resources.



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Transboundary inflows from the Kura, Aras, and Samur rivers contribute most of the country's renewable freshwater supply—about two-thirds to four-fifths in most years [1–4], with the remainder originating from internal runoff and groundwater recharge. This heavy reliance on external flows exposes national water security to upstream management decisions, climate anomalies in neighboring catchments, and limited institutional frameworks for coordinated data sharing and governance ([5–8]. Domestic pressures compound this vulnerability: agricultural withdrawals account for 60–70% of total water use [4], often relying on inefficient irrigation infrastructure with high distribution losses [3,9], while climate projections signal declining precipitation, reduced snowpack, and rising evapotranspiration across the South Caucasus region [10–14]. The Water Stress Index (WSI) defined as the ratio of total annual water withdrawals (TAWW) to total renewable water resources (TRWR), provides a widely used metric for quantifying demand relative to supply [15–18]. However, most regional assessments report aggregate WSI values without explicitly decomposing the underlying components (TRWR into internal runoff, transboundary inflows, and groundwater; TAWW into sectoral withdrawals) or documenting the data sources, processing steps, and uncertainties that underpin these estimates [19–21]. This implicit treatment obscures the mechanisms driving water stress and limits the ability to identify leverage points for adaptive management in regions where transboundary dependence and climate variability are dominant controls. For Azerbaijan, a data-scarce country with strong external dependence, this knowledge gap constrains evidence-based policy formulation and transboundary cooperation [22–24].

The dominant mechanistic explanation for water stress in transboundary-dependent regions rests on two interacting processes: (1) external supply variability, in which fluctuations in upstream precipitation, snowmelt, and land use alter transboundary inflows independent of domestic conditions, and (2) internal demand rigidity, in which sectoral withdrawals (especially agriculture) remain relatively inelastic despite declining supply, amplifying stress during dry periods [7,8,25]. In regions where transboundary inflows constitute the major source of renewable water, even modest reductions in upstream flow—due to climate anomalies, reservoir operations, or expanding upstream extractions—can disproportionately elevate national water stress [5,6]. Conversely, improvements in domestic water-use efficiency (e.g., modernizing irrigation systems, reducing distribution losses) may have limited impact if external supply continues to decline [3,26]. This asymmetry between external forcing and internal adaptation capacity defines the core vulnerability of transboundary-dependent water systems. Conventional WSI assessments, by aggregating TRWR and TAWW, fail to distinguish between these mechanisms, thereby underestimating the structural vulnerability and misidentifying intervention priorities [19–21]. Explicit decomposition of WSI components—integrated with long-term trends in hydro-climatic drivers (precipitation, evapotranspiration) and storage dynamics (GRACE-derived Total Water Storage, TWS)—is required to test whether observed stress arises primarily from declining external supply, increasing domestic demand, or both.

Azerbaijan provides a practical test case for this framework. The country's water resources are highly variable, with interannual fluctuations in TRWR ranging from 13.9 km³ (2020) to 30.0 km³ (2003) over 2000–2023, driven primarily by climate anomalies in upstream catchments of the Kura–Aras basin [4,27,28]. Internal runoff (generated within Azerbaijan's borders from precipitation and snowmelt) is comparatively stable across years, contributing on average about one-fifth of annual renewable surface water, while transboundary inflows account for the remainder [1,2]. Long-term renewable groundwater recharge is reported by national hydrogeological assessments at approximately 4.4 km³ year^{−1} but is not fully captured by conventional monitoring networks [29]. Agricultural water use dominates total withdrawals, with irrigation concentrated in the Kura–Aras lowlands, where evapotranspiration rates often exceed precipitation by a factor of three, necessitating surface water diversion [4,12,13]. Domestic and industrial demand have grown with urbanization and economic development, but efficiency improvements in these sectors have been limited by infrastructure deficits and weak regulatory enforcement [3,9]. Recent climate trends indicate declining spring precipitation, earlier snowmelt timing, and rising summer temperatures, all of which reduce summer baseflows and elevate irrigation demand during the peak growing season [27,30,31]. GRACE/GRACE-FO satellite observations (2002–2025) reveal persistent negative trends in Total Water Storage (TWS) for the Kura–Aras basin, consistent with groundwater depletion or reduced soil moisture, though the relative contributions of climate-driven recharge reductions versus anthropogenic extraction remain uncertain [32]. These converging pressures—external supply variability, internal demand growth, and climate non-stationarity—position Azerbaijan as a critical example of transboundary water stress under climate change.

This study addresses the knowledge gap by presenting a transparent and reproducible framework for decomposing WSI components and applying it systematically to Azerbaijan for the period 2000–2023. The framework integrates explicit derivation of TRWR (internal runoff, transboundary inflows, groundwater) and TAWW (agricultural, domestic, industrial withdrawals) with long-term trends in precipitation, actual evapotranspiration (ET_a), and GRACE-derived TWS. All data sources, processing steps, and uncertainties are documented, enabling reproducibility and extension to other transboundary-dependent, data-scarce regions. The

central question is not whether transboundary inflows matter for Azerbaijan's water stress—given that they account for 70–80% of renewable surface water, their relevance is structurally constrained—but rather: by what margin does supply-side variability exceed demand-side variability as a driver of WSI, and what does that asymmetry imply for the relative effectiveness of adaptation strategies? Three falsifiable predictions follow from this framing: (1) interannual variability in WSI will be dominated by fluctuations in transboundary inflows (Kura and Aras rivers), with internal runoff contributing a comparatively stable residual; (2) sensitivity analysis will show that plausible reductions in transboundary inflows (e.g., 10–20%) elevate WSI by a greater margin than equivalent percentage reductions in domestic withdrawals would lower it—an asymmetry that constrains the adaptive potential of irrigation efficiency improvements alone; and (3) GRACE-derived TWS trends will reflect basin-scale storage changes of a magnitude and trend consistent with groundwater extraction or climate-driven recharge reduction, but not attributable to either mechanism in isolation from gravimetry alone. By embedding explicit decomposition, sensitivity analysis, and storage dynamics into WSI assessment, this framework provides a systematic approach for understanding and managing water stress in transboundary-dependent regions under climate change and variability, with direct applicability to policy formulation, adaptive planning, and regional cooperation.

2. Study Area

Azerbaijan covers approximately 86,600 km² in the South Caucasus, with a population of ~10.23 million (2023). The country is bordered by Russia (north), Georgia (northwest), Armenia (west), Iran (south), and the Caspian Sea (east) (Figure 1). Topographically, Azerbaijan combines the Greater Caucasus mountains (north), the Lesser Caucasus (west), the Kura–Aras lowlands (central), and the Lankaran coastal plain (southeast). Climate ranges from humid subtropical (Lankaran) to semi-arid continental (central lowlands), with mean annual precipitation varying from <300 mm in the central plains to >1600 mm in the southern mountains.

The hydrological system is dominated by the Kura–Aras river basin, the largest in the South Caucasus [29,33]. The Kura River originates in northeastern Turkey, flows through Georgia, and enters Azerbaijan from the northwest; the Aras River originates in eastern Turkey, flows along the Armenia–Iran border, and joins the Kura within Azerbaijan before discharging to the Caspian Sea. Approximately 70% of Azerbaijan's renewable freshwater resources originate as transboundary inflows from these rivers [1,2,4,13]. Internal runoff is generated mainly in the Greater and Lesser Caucasus ranges, while groundwater resources are concentrated in alluvial aquifers of the Kura–Aras lowlands [29].

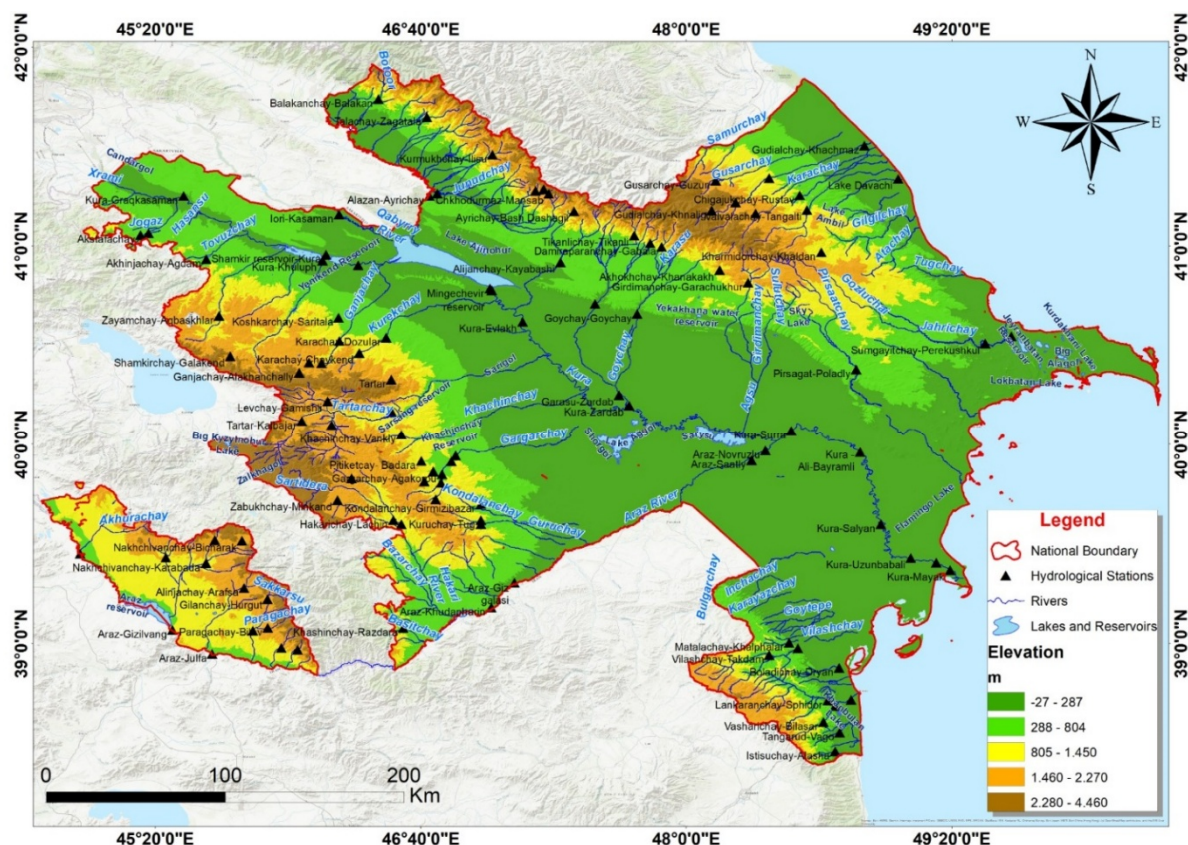


Figure 1. Study area with main river systems showing transboundary water inflows.

3. Materials and Methods

3.1. Data Sources, Variables, and Uncertainties

This study integrates multiple hydro-climatic and socio-economic datasets for Azerbaijan covering the period 2000–2023, with satellite-derived Total Water Storage (TWS) extending to 2025 (GRACE/GRACE-FO). All data sources, processing steps, and estimated uncertainties are documented in Table 1 to ensure reproducibility and facilitate extension to other transboundary-dependent regions. National water balance components (surface water resources, groundwater, sectoral withdrawals) were obtained from the State Committee on Statistics of the Republic of Azerbaijan and the Ministry of Ecology and Natural Resources. Long-term precipitation and evapotranspiration data were compiled from national meteorological networks, satellite remote sensing products (CHIRPS, MODIS MOD16), and reanalysis datasets (ERA5). Transboundary inflow data for the Kura, Aras, and Samur rivers were obtained from border gauging stations operated by the Azerbaijan State Water Resources Agency. GRACE/GRACE-FO mass concentration (mascon) TWS anomalies were retrieved from the Jet Propulsion Laboratory (JPL) and Center for Space Research at University of Texas (CSR) for the Kura–Aras basin. Population data were obtained from the State Committee on Statistics.

3.2. Derivation of Total Renewable Water Resources (TRWR)

Total Renewable Water Resources represent the long-term average annual volume of freshwater available for human use and ecological functions, excluding non-renewable fossil groundwater. Following standard water-balance conventions [1–3], TRWR is decomposed into three components:

$$\text{TRWR} = \text{SWR} + \text{GWR} - \text{O} \quad (1)$$

where SWR is Surface Water Resources (million $\text{m}^3 \text{ year}^{-1}$), GWR is renewable groundwater recharge (million $\text{m}^3 \text{ year}^{-1}$), and O is the overlap between surface water and groundwater (baseflow contribution already counted in SWR, million $\text{m}^3 \text{ year}^{-1}$). For most assessments, O is assumed to equal GWR (i.e., all renewable groundwater eventually discharges to surface water as baseflow), simplifying Equation (1) to “TRWR” $\approx$ “SWR”. Surface Water Resources are further decomposed into internal and transboundary components:

$$\text{SWR} = \text{IR} + \text{Q}_{\text{in}} \quad (2)$$

where IR is Internal Runoff (generated within national borders from precipitation and snowmelt, million $\text{m}^3 \text{ year}^{-1}$) and Q_{in} is Transboundary Inflow (water entering from upstream riparian states, million $\text{m}^3 \text{ year}^{-1}$). For Azerbaijan, official statistics report TRWR as the sum of IR, Q_{in} , and GWR (treated separately to capture deep aquifer recharge not fully reflected in river baseflow):

$$\text{TRWR} = \text{IR} + \text{Q}_{\text{in}} + \text{GWR} \quad (3)$$

Internal runoff is estimated from river discharge records for catchments originating entirely within Azerbaijan (smaller tributaries draining the Greater and Lesser Caucasus). Transboundary inflows are measured at border gauging stations on the Kura, Aras, and Samur rivers. GWR is estimated from long-term hydrogeological assessments and water-balance models [29]; Ministry of Ecology), typically reported as an annual average recharge value ($\sim 6 \text{ km}^3 \text{ year}^{-1}$ for Azerbaijan).

3.3. Derivation of Total Annual Water Withdrawals (TAWW)

Total Annual Water Withdrawals quantify the volume of freshwater extracted from surface and groundwater sources for human use. Following [1] and [2,3] World Water Development Reports conventions, TAWW is decomposed into three sectoral components:

$$\text{TAWW} = \text{W}_{\text{agri}} + \text{W}_{\text{dom}} + \text{W}_{\text{ind}} \quad (4)$$

where W_{agri} , W_{dom} , and W_{ind} are agricultural (irrigation + livestock), domestic (municipal + household), and industrial (energy + mining + manufacturing) withdrawals, respectively (million $\text{m}^3 \text{ year}^{-1}$).

Table 1. Data sources, variables, temporal and spatial coverage, processing steps, role in the WSI framework, and uncertainty estimates.

Variable	Symbol	Unit	Temporal Coverage	Spatial Coverage	Source	Processing	Role in WSI	Main Uncertainty
Total Renewable Water Resources	TRWR	million m ³ year ⁻¹	2000–2023	National	State Committee on Statistics; Ministry of Ecology	Annual aggregation	Denominator	±10–15% (gauging, ungauged tributaries)
Internal Runoff	IR	million m ³ year ⁻¹	2000–2023	National	River discharge records; State Hydrology Institute	Basin-scale aggregation	TRWR component	±12% (incomplete gauge networks)
Transboundary Inflow	Q _{in}	million m ³ year ⁻¹	2000–2023	Kura, Aras, Samur	Border gauging stations (State Water Resources Agency)	Direct measurement at entry points	TRWR component	±8–10% (gauge uncertainty, ice periods)
Groundwater Resources	GWR	million m ³ year ⁻¹	Long-term average	National	Hydrogeological assessments [29], Ministry of Ecology	Long-term recharge estimate	TRWR component	±20% (recharge models, limited monitoring)
Total Annual Water Withdrawals	TAWW	million m ³ year ⁻¹	2000–2023	National	State Committee on Statistics	Sectoral aggregation	Numerator	±10% (metering gaps in agriculture, industry)
surface-water extraction	TAWW _{sw}	million m ³ year ⁻¹	2000–2023	National	State Committee on Statistics	Direct metering/district records	TAWW sub-component	±10%
groundwater extraction	TAWW _{gw}	million m ³ year ⁻¹	2000–2023	National	State Committee on Statistics	Well-level metering; national survey	TAWW sub-component	±15% (incomplete well metering)
Agricultural Withdrawals	W _{agri}	million m ³ year ⁻¹	2000–2023	National	State Committee; irrigation district records	Irrigation + livestock	TAWW component	±15% (non-metered use, return flow)
Domestic Withdrawals	W _{dom}	million m ³ year ⁻¹	2000–2023	Urban and rural	State Committee; municipal water utilities	Metered supply + per-capita estimates	TAWW component	±10% (rural non-metered supply)
Industrial Withdrawals	W _{ind}	million m ³ year ⁻¹	2000–2023	National	State Committee; industrial surveys	Energy, mining, manufacturing	TAWW component	±20% (self-supplied use underreported)
SDG 6.4.2 Water Stress Level	SDG-WSI	%	2016–2023	National	State Committee on Statistics	Official SDG indicator: withdrawals/available resources after EFR	External validation	Reporting-round uncertainty
Precipitation	P	mm year ⁻¹	2000–2023	National	Meteorological network; CHIRPS; ERA5	Spatial averaging; gap-filling	Hydro-climatic driver	±10% (gauge density, orographic effects)
Actual Evapotranspiration	ET _a	mm year ⁻¹	2000–2023	National	MODIS MOD16; reanalysis	Spatial averaging	Hydro-climatic driver	±15% (model uncertainty, soil moisture)
Total Water Storage Anomaly	TWS	cm	2002–2025	Kura–Aras basin	GRACE/GRACE-FO mascon (JPL, CSR)	Mascon solutions; 2004–2009 baseline	Storage dynamics	±2–3 cm (leakage error, signal attenuation)
Population	Pop	million	2000–2023	National	State Committee on Statistics	Annual census and projections	Falkenmark Indicator	<1%

Agricultural withdrawals (W_{agri}) are estimated from irrigated area, crop water requirements, and irrigation efficiency. Data sources include the State Committee on Statistics (irrigated area by district and crop type), regional irrigation district records (metered and non-metered supply), and standard irrigation norms (mm per hectare per crop). Where direct metering is incomplete, estimates are derived from irrigated areas, crop types, and standard irrigation norms. Livestock water use is estimated from animal counts and per-capita water requirements. Domestic withdrawals (W_{dom}) are obtained from municipal water utilities and the State Committee on Statistics, aggregating metered urban supply (~70% metering coverage in major cities) and per-capita norms for rural areas. Industrial withdrawals (W_{ind}) are reported by the State Committee on Statistics from industrial surveys covering energy production (thermoelectric cooling, hydropower reservoir evaporation), mining, and manufacturing. Self-supplied industrial withdrawals (e.g., factories with private wells) may be underreported.

This sectoral decomposition follows standard international accounting conventions [1–3,16], ensuring comparability with global and regional assessments.

3.4. Water Stress Index Computation and Classification

The Water Stress Index expresses total annual water withdrawals as a percentage of total renewable water resources:

$$WSI = \frac{TAWW}{TRWR} \times 100 \quad (5)$$

WSI values are interpreted using widely adopted thresholds [2,3,15,16]:

- Low stress: $WSI < 10\%$ (minimal pressure)
- Moderate stress: $10\% \leq WSI < 20\%$ (emerging demand pressures)
- Medium-high stress: $20\% \leq WSI < 40\%$ (significant pressure, management required)
- High stress: $40\% \leq WSI < 80\%$ (severe pressure, structural risk)
- Extreme stress: $WSI \geq 80\%$ (critical pressure, scarcity)

As a complementary per-capita indicator, the Falkenmark Water Stress Indicator is computed as [17]:

$$FWS = \frac{TRWR}{Pop} \quad (6)$$

with thresholds of $1700 \text{ m}^3 \text{ capita}^{-1} \text{ year}^{-1}$ (stress), $1000 \text{ m}^3 \text{ capita}^{-1} \text{ year}^{-1}$ (scarcity), and $500 \text{ m}^3 \text{ capita}^{-1} \text{ year}^{-1}$ (absolute scarcity) [17,21].

3.5. Comparison with Alternative WSI Accounting Assumptions

To assess how accounting assumptions alter stress classification, WSI is computed under three configurations:

- (1) Standard WSI (Equation (5)), using full TRWR including transboundary inflows.
- (2) Internal-only WSI, excluding transboundary inflows from the denominator:

$$WSI_{internal} = \frac{TAWW}{IR + GWR} \times 100 \quad (7)$$

- (3) Sensitivity WSI, simulating reductions in transboundary inflows:

$$WSI_{sens}(\alpha) = \frac{TAWW}{IR + (1 - \alpha) Q_{in} + GWR} \times 100 \quad (8)$$

where $\alpha \in \{0.10, 0.20, 0.30\}$ represents plausible reductions of 10%, 20%, and 30% in transboundary inflows, reflecting upstream climate or management changes.

3.6. Hydro-Climatic Driver Analysis

Annual precipitation (P) and actual evapotranspiration (ET_a) over 2000–2023 are characterized using national meteorological networks, satellite remote sensing products, and reanalysis (CHIRPS, ERA5, MODIS MOD16; see Table 1). Linear trends are estimated by ordinary least-squares regression, and the Pearson correlation coefficient between P and ET_a is computed to assess whether evapotranspiration is primarily water-limited or energy-limited at the national scale.

3.7. GRACE/GRACE-FO Total Water Storage Analysis

Monthly GRACE (2002–2017) and GRACE-FO (2018–2025) mass concentration (mascon) Total Water Storage anomalies are analyzed for the Kura–Aras basin using two independent processing centers: the Jet Propulsion Laboratory (JPL) and the Center for Space Research at University of Texas (CSR). Mascon solutions provide spatially regularized TWS estimates with reduced leakage error compared to spherical harmonic representations [34,35]. Anomalies are computed relative to the 2004–2009 baseline (standard GRACE reference period). Because monthly TWS contains a strong seasonal cycle that can bias short-window linear fits, long-term trends are estimated jointly with annual and semi-annual harmonics:

$$\text{TWS}(t) = \beta_0 + \beta_1 t + \sum_{k=1}^2 [a_k \cos(2\pi k t) + b_k \sin(2\pi k t)] + \varepsilon \quad (9)$$

where β_1 is the long-term trend (cm year^{-1}), t is time (years), and the harmonic terms remove the annual ($k = 1$) and semi-annual ($k = 2$) cycles. Trends are computed separately for JPL and CSR mascon solutions. To account for serial correlation in the monthly residuals, the standard error of β_1 is inflated by the autocorrelation correction $\sqrt{(1 + r_1)/(1 - r_1)}$, where r_1 is the lag-1 autocorrelation of the residuals [36], yielding 95% confidence intervals robust to non-independent observations.

3.8. Statistical Analysis

Trends in annual series are reported with two complementary estimators: (i) ordinary least-squares (OLS) regression, reporting slope, p -value, and R^2 ; and (ii) the non-parametric Mann–Kendall test [37,38] with Sen's slope estimator [39], which is robust to non-normality and outliers and appropriate for short hydrological time series. Bootstrap 95% confidence intervals for Sen's slope are computed from 5000 resamples. Lag-1 autocorrelation (r_1) is reported as a diagnostic for serial dependence; where r_1 is non-negligible, results are cross-checked using the variance-corrected modifications of [40,41]. Pearson and Spearman correlation coefficients are reported jointly for bivariate relationships, with 95% confidence intervals derived from the Fisher z -transformation. Uncertainty in the reported WSI is propagated using a Monte Carlo procedure (10^5 realizations) that draws TAWW and TRWR from Gaussian distributions centered on their 2000–2023 means with standard deviations equal to the reported data uncertainties (Table 1); the resulting distribution of WSI is summarized by its median, 95% credible interval, and exceedance probabilities for the high (40%) and extreme (80%) stress thresholds. Sensitivity scenarios in Section 3.5 are deterministic and complement the Monte Carlo analysis. All tests use $\alpha = 0.05$. Computations were performed in Python (NumPy, SciPy, pymannkendall); the analysis script is available from the authors on request.

4. Results

4.1. Water Balance and Sectoral Withdrawals (2000–2023)

Over 2000–2023, the official national water balance (Table 4 of [4]; reproduced here as Table 2) shows mean Total Renewable Water Resources of $21.78 \text{ km}^3 \text{ year}^{-1}$, ranging from 13.92 km^3 (2020) to 30.04 km^3 (2003), and mean Total Annual Water Withdrawals of $11.65 \text{ km}^3 \text{ year}^{-1}$. TRWR declined significantly over the study period (OLS: $-524 \text{ million m}^3 \text{ year}^{-1}$, $p < 0.001$, $R^2 = 0.64$; Mann–Kendall: Sen's slope = $-518 \text{ million m}^3 \text{ year}^{-1}$, 95% CI $[-654, -301]$, $\tau = -0.62$, $p < 0.001$), while TAWW rose (OLS: $+89 \text{ million m}^3 \text{ year}^{-1}$, $p < 0.001$, $R^2 = 0.61$; Sen's slope = $+97 \text{ million m}^3 \text{ year}^{-1}$, 95% CI $[+37, +131]$, $\tau = +0.61$, $p < 0.001$). Lag-1 autocorrelations are non-negligible for both series ($r_1 = 0.76$ for TRWR, 0.80 for TAWW); variance-corrected modifications [40,41] preserve significance at $p < 0.001$. Across six benchmark years in the official record (2000, 2005, 2010, 2015, 2020, 2023), transboundary inflows (Q_{in}) from the Kura, Aras, and Samur rivers contributed on average 76.9% of renewable surface water (range 67.6–81.8%), while internal runoff (IR) contributed 23.1% (range 18.2–32.4%). Long-term renewable groundwater recharge is reported at approximately $4.4 \text{ km}^3 \text{ year}^{-1}$ [29]. Sectoral withdrawals are dominated by irrigated agriculture, with the agricultural share (irrigation and livestock) rising from 90% of total extraction in 2000 (9891 Mm^3) to 91% in 2023 ($10,911 \text{ Mm}^3$) according to the national statistical register (State Committee on Statistics), and representing approximately 74–85% of total consumption after accounting for recirculated and returned flows; industry and energy contributed 5–8%, municipal and household supply the remainder. Conveyance losses in the distribution network averaged $3530 \text{ Mm}^3 \text{ year}^{-1}$ over 2000–2023 (range $3034\text{--}4280 \text{ Mm}^3 \text{ year}^{-1}$; State Committee on Statistics), equivalent to 28–32% of the volume abstracted from natural sources and constituting the single largest non-consumptive loss in the national water system. Groundwater extraction

more than quadrupled over the study period, rising from 547 Mm³ in 2000 to 2081 Mm³ in 2023 (+281%), while surface-water extraction remained broadly stable (10,443 Mm³ in 2000; 9875 Mm³ in 2023; Table S1).

Table 2. Annual water balance for Azerbaijan, 2000–2023 (million m³ year^{−1}), with computed Water Stress Index. Data source: State Committee on Statistics of the Republic of Azerbaijan, reproduced from [4].

Year	TAWW	TRWR	WSI (%)	Stress Class
2000	10,990	23,407	47	High
2001	9923	22,744	44	High
2002	9919	27,401	36	Medium–high
2003	10,518	30,036	35	Medium–high
2004	11,175	27,970	40	High
2005	11,800	23,915	49	High
2006	12,144	28,763	42	High
2007	12,085	25,763	47	High
2008	11,530	21,337	54	High
2009	11,140	22,074	50	High
2010	10,970	28,735	38	Medium–high
2011	11,296	25,893	44	High
2012	11,975	20,623	58	High
2013	11,994	19,091	63	High
2014	11,592	17,932	65	High
2015	11,689	18,367	64	High
2016	11,878	19,830	60	High
2017	12,120	16,986	71	High
2018	12,167	19,584	62	High
2019	12,590	16,225	78	High
2020	12,203	13,915	88	Extreme
2021	12,968	17,266	75	High
2022	13,028	17,042	76	High
2023	11,956	17,819	67	High
Mean	11,652	21,780	56	High

4.2. WSI Trends and Classification

The Water Stress Index (Equation (5)) averaged 56% over 2000–2023 (Table 2), placing Azerbaijan in the high-stress category (40–80%; [15]). Annual values ranged from 35% (2003, abundant transboundary inflows) to 88% (2020, lowest TRWR on record). The high-stress threshold (40%) was exceeded in 20 of 24 years, and the extreme-stress threshold (80%) was exceeded in 2020 (Figure 2). WSI increased significantly over the study period (OLS: +1.82 percentage points year^{−1}, $p < 0.001$, $R^2 = 0.76$; Mann–Kendall: Sen’s slope = +1.83 pp year^{−1}, 95% CI [+1.18, +2.19], $\tau = +0.67$, $p < 0.001$). The lag-1 autocorrelation in WSI is high ($r_1 = 0.84$), reflecting persistence in the underlying TAWW/TRWR signals; variance-corrected Mann–Kendall tests retain $p < 0.001$. A Monte Carlo propagation (10^5 realizations) of the reported component uncertainties ($\pm 10\%$ for TAWW, $\pm 12.5\%$ for TRWR) yields a 95% credible interval of [39, 75]% on the long-term mean WSI; under this propagation, the probability of mean WSI exceeding the high-stress threshold (40%) is 97%, while the probability of exceeding the extreme-stress threshold (80%) is 1%.

4.3. Decomposition of Renewable Surface Water and Sensitivity to Alternative Accounting Assumptions

Disaggregating renewable surface water into internal and transboundary components for the six benchmark years available in the official record (Table 3) reveals that transboundary inflows dominate national supply but are far more variable than internal runoff. The coefficient of variation across these years is 31% for Q_{in} versus 12% for IR, and the lowest renewable freshwater year (2020) corresponds to a near-halving of Q_{in} relative to the long-term mean (Figure 3).

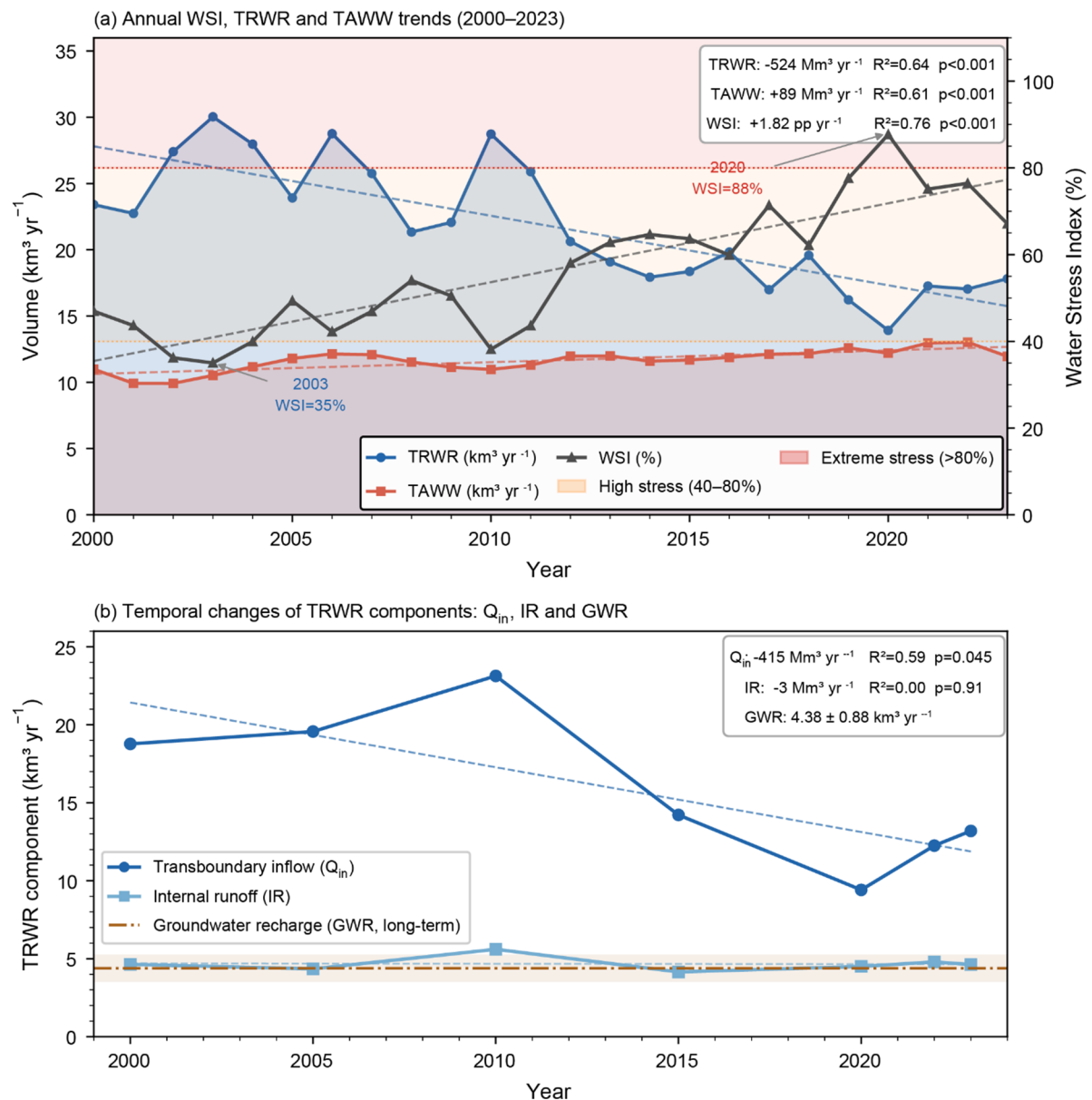


Figure 2. Annual water resources and stress in Azerbaijan, 2000–2023. (a) TRWR (blue), TAWW (red) and WSI (black, right axis) with OLS trend fits (dashed); shaded bands mark the high-stress (40–80%) and extreme-stress (>80%) zones. (b) Temporal changes of the three TRWR components—transboundary inflow Q_{in} , internal runoff IR, and long-term groundwater recharge GWR ($\approx 4.38 \text{ km}^3 \text{ year}^{-1}$; $\pm 20\%$ band, [29])—showing that the TRWR decline in (a) is driven by Q_{in} , while IR and GWR are effectively steady. Trend statistics are given in the inset boxes.

Table 3. Decomposition of renewable surface water in Azerbaijan for benchmark years (million $\text{m}^3 \text{ year}^{-1}$). Source: State Committee on Statistics.

Year	Precipitation	ET_a	Internal Runoff (IR)	Transboundary Inflow (Q_{in})	RFR (IR + Q_{in})	Q_{in} Share (%)
2000	38,369	33,735	4634	18,773	23,407	80.2
2005	35,252	30,904	4348	19,566	23,915	81.8
2010	43,282	37,679	5603	23,132	28,735	80.5
2015	40,927	36,777	4150	14,217	18,367	77.4
2020	37,671	33,168	4503	9412	13,915	67.6
2022	32,129	27,239	4792	12,250	17,042	71.9
2023	40,130	35,503	4627	13,192	17,819	74.0
Mean	38,251	33,572	4665	15,792	20,457	76

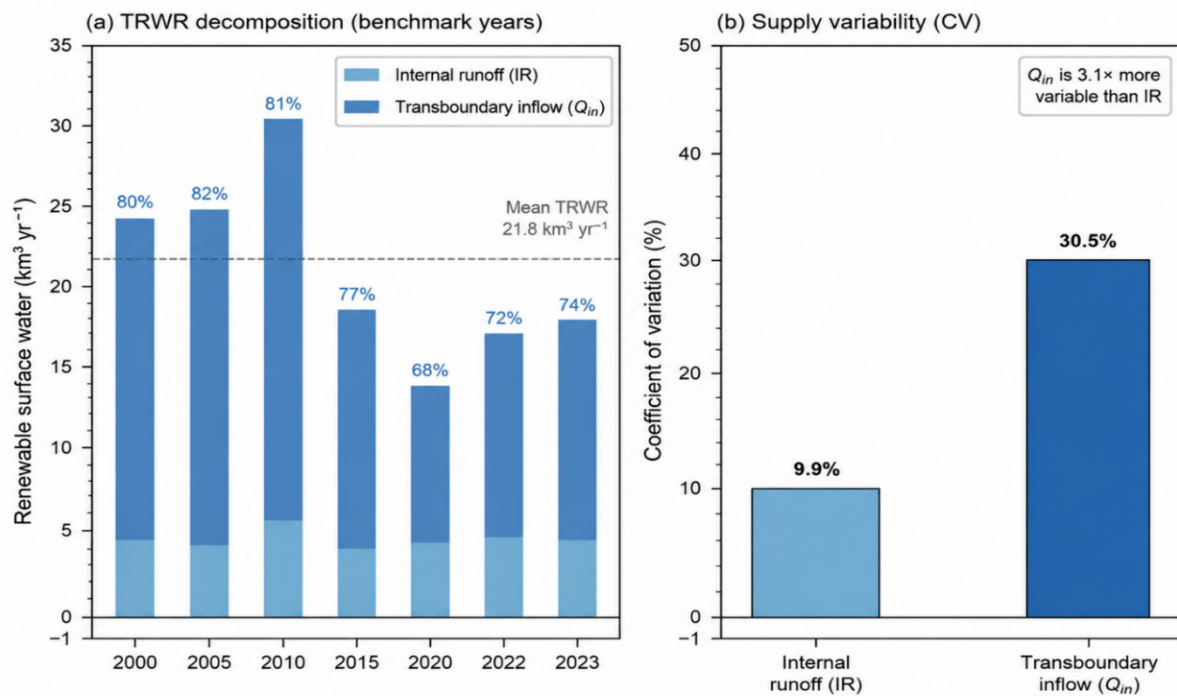


Figure 3. Decomposition of renewable surface water resources in Azerbaijan into internal runoff (IR) and transboundary inflow (Q_{in}) components. **(a)** Stacked bar chart for seven benchmark years (2000, 2005, 2010, 2015, 2020, 2022 and 2023); the Q_{in} percentage share of total renewable freshwater resources is labelled above each bar; the dashed horizontal line indicates the 24-year mean TRWR ($21.8 \text{ km}^3 \text{ year}^{-1}$). **(b)** Coefficient of variation (%) of IR and Q_{in} across the seven benchmark years, showing that transboundary inflows are 2.6 times more variable than internal runoff ($\text{CV} = 31\%$ vs. 12%).

Recomputing WSI under alternative configurations (Section 3.5) reveals how accounting assumptions alter stress classification (Table 4). The internal-only WSI (Equation (7)) uses the long-term internal renewable water reported by national hydrogeological assessments ($\text{IR} \approx 4.64 \text{ km}^3 \text{ year}^{-1}$ from Table 3; $\text{GWR} \approx 4.38 \text{ km}^3 \text{ year}^{-1}$ from [29]). Sensitivity scenarios (Equation (8)) reduce the transboundary component of mean TRWR by 10%, 20%, and 30%, holding internal runoff and groundwater constant.

Table 4. WSI under standard, internal-only, and transboundary-sensitivity configurations (2000–2023 means).

Configuration	Equation	WSI (%)	Stress Class
Standard (full TRWR)	(5)	56	High
Internal-only (IR + GWR, no Q_{in})	(7)	129	Extreme
Sensitivity, $Q_{in} - 10\%$	(8)	60	High
Sensitivity, $Q_{in} - 20\%$	(8)	65	High
Sensitivity, $Q_{in} - 30\%$	(8)	70	High

Excluding transboundary inflows from the denominator (Equation (7)) shifts WSI from 56% to 129%, reclassifying Azerbaijan from “high” to “extreme” stress and quantifying its dependence on external supply. Reductions in Q_{in} of 10–30% (Equation (8)) elevate WSI by 4–14 percentage points, narrowing the buffer between observed stress and the extreme-stress threshold (80%).

4.4. Sectoral Contribution and Demand-Side Sensitivity

Year-specific sectoral consumption data from the national statistical register (State Committee on Statistics) indicate that agriculture, hunting, and forestry consistently accounted for approximately 72–86% of total annual water consumption over 2000–2023. Based on the 2000–2023 mean TAWW of $11.65 \text{ km}^3 \text{ year}^{-1}$ and a representative agricultural share of 78% (mean of the annual series), sectoral mean withdrawals are: $W_{agri} \approx 9.1 \text{ km}^3 \text{ year}^{-1}$ (78%), $W_{ind} \approx 1.7 \text{ km}^3 \text{ year}^{-1}$ (15%), and $W_{dom} \approx 0.8 \text{ km}^3 \text{ year}^{-1}$ (7%). These values replace the coarser range estimates previously reported in the literature (60–70% for agriculture; [4]) with year-specific accounting. A 20% reduction in W_{agri} (e.g., through modernized irrigation infrastructure, which already produces substantial conveyance losses—see Section 4.1) would reduce TAWW by approximately $1.82 \text{ km}^3 \text{ year}^{-1}$ and lower WSI

from 56% to about 47% (a 9 percentage-point reduction). An equivalent 20% reduction in Q_{in} elevates WSI by about 10 percentage points (Section 4.3). The asymmetry between supply-side and demand-side sensitivities indicates that external supply variability exerts stronger leverage on national water stress than domestic demand adjustments of comparable magnitude, though the revised agricultural share implies that irrigation efficiency improvements carry greater potential stress-reduction benefit than previously estimated. The official SDG 6.4.2 water stress level for Azerbaijan, reported by the State Committee on Statistics, was 52.5–57.5% over 2016–2023, compared to the WSI values of 60–88% calculated here for the same period. This systematic difference of approximately 10–20 percentage points reflects definitional differences: SDG 6.4.2 subtracts an environmental flow requirement (EFR) from the denominator, whereas the WSI computed here uses full TRWR. The two series are directionally consistent and confirm high-stress conditions throughout the period; the SDG 6.4.2 values constitute an independent external validation of the stress classification reported in Section 4.2 (Figure 4).

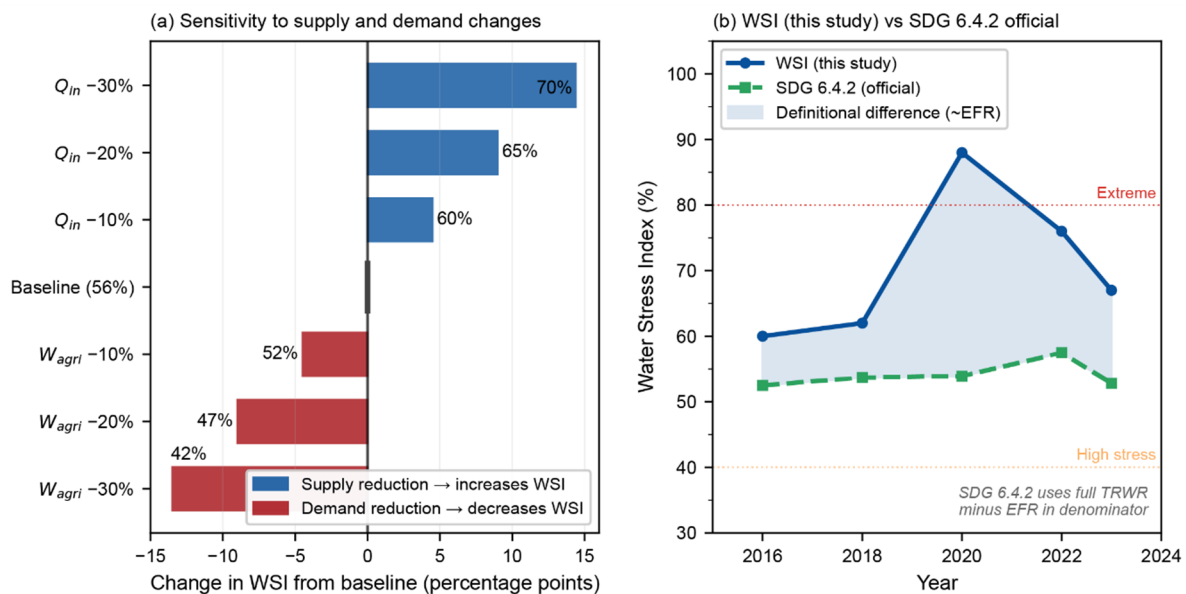


Figure 4. Sensitivity analysis and external validation of the Water Stress Index. **(a)** Divergence plot showing sensitivity of WSI to symmetric percentage reductions (10%, 20%, 30%) in transboundary inflow (Q_{in}) and agricultural withdrawals (W_{agri}) relative to the baseline WSI of 56% (vertical line at $x = 0$). Bars represent changes from baseline (percentage points), with labeled values showing final WSI under each scenario: supply reductions increase WSI to 60%, 65%, and 70%, while demand reductions decrease WSI to 52%, 47%, and 42%. The asymmetry demonstrates that supply-side vulnerabilities dominate Azerbaijan’s water stress dynamics. **(b)** Comparison of WSI computed in this study using full TRWR as denominator (filled circles) versus the official SDG 6.4.2 water stress level (squares) for Azerbaijan over 2016–2023. The shaded area between the two series reflects the definitional difference arising from the subtraction of environmental flow requirements (EFR) in the SDG 6.4.2 denominator. Data source for SDG 6.4.2: State Committee on Statistics of the Republic of Azerbaijan.

4.5. Groundwater Extraction and Its Implications for Storage

The national statistical register documents a sustained increase in groundwater extraction over 2000–2023, from 547 $\text{Mm}^3 \text{ year}^{-1}$ in 2000 to a peak of 2395 $\text{Mm}^3 \text{ year}^{-1}$ in 2020 and 2081 $\text{Mm}^3 \text{ year}^{-1}$ in 2023 (State Committee on Statistics, Table S1). Groundwater’s share of total extraction rose from approximately 5% in 2000 to 17–20% by 2016–2020, representing a 4.3-fold increase over the study period. This trend is directionally consistent with the negative GRACE/GRACE-FO TWS trend reported in Section 4.7: accelerating groundwater extraction constitutes an anthropogenic mechanism that would contribute to basin-scale storage decline independently of any climate-driven reduction in recharge. The long-term hydrogeological recharge estimate of $\sim 4.4 \text{ km}^3 \text{ year}^{-1}$ [29] exceeds the peak extraction of 2.4 $\text{km}^3 \text{ year}^{-1}$ recorded in 2020, suggesting that groundwater depletion is not structural under current extraction rates; however, the upward extraction trend warrants monitoring. The attribution between climate-driven recharge variability and anthropogenic extraction cannot be partitioned from GRACE alone, but is quantitatively resolved by the water-balance closure test presented in Section 4.7 and discussed in Section 5.3 (Figure 5).

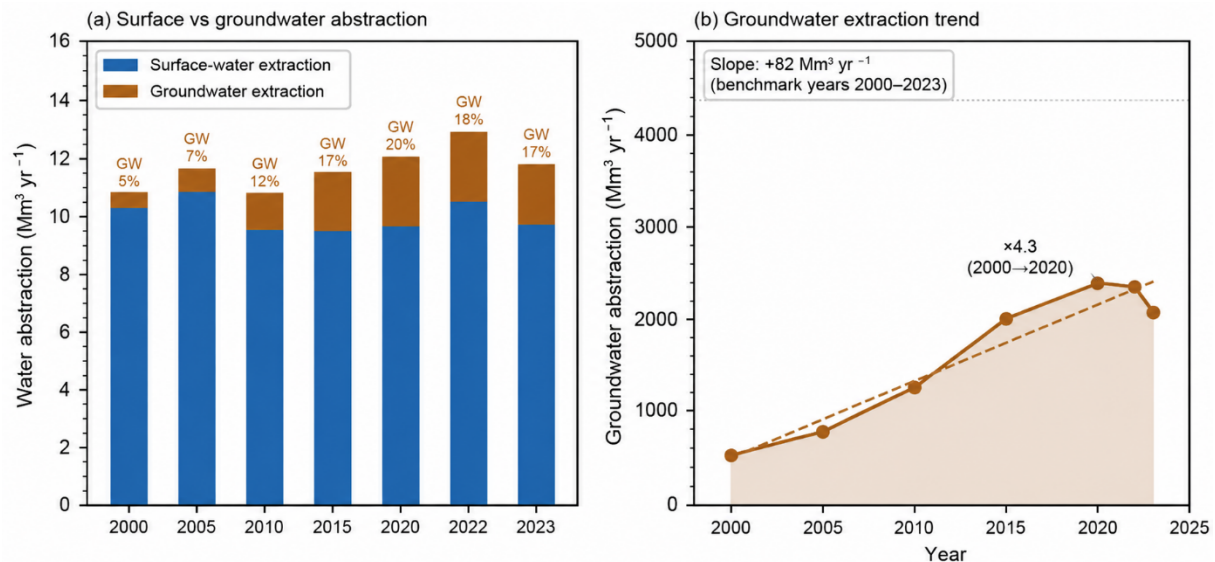


Figure 5. Surface-water and groundwater extraction in Azerbaijan for benchmark years (2000–2023). **(a)** Stacked bar chart of surface-water (blue) and groundwater (brown) extraction ($\text{km}^3 \text{ year}^{-1}$), with the groundwater percentage share of total extraction labelled above each bar. **(b)** Groundwater extraction time series ($\text{Mm}^3 \text{ year}^{-1}$) with OLS trend line (dashed). The horizontal dotted line indicates the long-term renewable groundwater recharge estimate ($\sim 4380 \text{ Mm}^3 \text{ year}^{-1}$ [29]). The 4.3-fold increase in groundwater extraction between 2000 and the 2020 peak is annotated. Data source: State Committee on Statistics of the Republic of Azerbaijan.

4.6. Hydro-Climatic Drivers

Annual precipitation averaged 462 mm year^{-1} ($39,984 \text{ million m}^3 \text{ year}^{-1}$) over 2000–2023, with a declining tendency (OLS: $-3.75 \text{ mm year}^{-1}$, $p = 0.05$, $R^2 = 0.16$; Mann–Kendall Sen’s slope: $-4.51 \text{ mm year}^{-1}$, 95% CI $[-7.75, +0.00]$, $\tau = -0.29$, $p = 0.05$) that lies at the conventional significance threshold and should be treated as marginal. Actual evapotranspiration averaged 406 mm year^{-1} ($35,164 \text{ million m}^3 \text{ year}^{-1}$), with a comparable but more clearly significant declining trend (OLS: $-3.65 \text{ mm year}^{-1}$, $p = 0.04$, $R^2 = 0.17$; Sen’s slope = $-4.34 \text{ mm year}^{-1}$, 95% CI $[-7.48, +0.00]$, $\tau = -0.32$, $p = 0.03$). Annual P and ET_a were strongly correlated (Pearson $r = 0.997$, 95% CI $[0.994, 0.999]$, $p < 0.001$; Spearman $\rho = 0.992$, $p = p < 0.001$; $n = 24$), consistent with a water-limited evapotranspiration regime at the national scale: in drier years, soil moisture constraints reduce ET_a in close proportion to reduced inputs, with negligible decoupling between supply and atmospheric demand (Figure 6). This very high correlation is physically expected under the climatic conditions of Azerbaijan, where the dryness ratio ($\text{PET}/P \approx 1.5$) places the system firmly in the water-limited domain of the Budyko framework; at the national scale and annual timestep, spatial and temporal averaging suppress the sub-annual and sub-basin variability that would otherwise reduce the correlation. A partial methodological contribution cannot be excluded, since ET_a estimates derived from ERA5 land-surface reanalysis use precipitation as a boundary forcing, which may inflate the apparent covariance. However, the Spearman $\rho = 0.992$ based on ranks is equally high, and the MODIS MOD16 ET_a product—the second source used here—derives from satellite-observed NDVI and net radiation rather than precipitation directly, providing an independent line of evidence that the relationship is physically real rather than an artefact of shared forcing.

4.7. GRACE/GRACE-FO Total Water Storage

Mascon-derived TWS anomalies for Azerbaijan (2002–2025) were fit jointly with annual and semi-annual harmonics (Equation (9)) to isolate the long-term trend from the seasonal cycle. After harmonic removal, the JPL solution ($n = 243$) yields a trend of $-1.52 \text{ cm year}^{-1}$ (autocorrelation-adjusted 95% CI $[-1.72, -1.31]$; full-model $R^2 = 0.91$), and the CSR solution ($n = 244$) yields $-1.13 \text{ cm year}^{-1}$ (95% CI $[-1.26, -1.00]$; $R^2 = 0.84$); both are highly significant ($p < 0.001$) and remain so under non-parametric Mann–Kendall tests applied to the deseasonalized series. The two processing solutions agree on the sign and order of magnitude of the trend; the difference ($\sim 0.4 \text{ cm year}^{-1}$) provides an indication of processing-related uncertainty and exceeds the formal 95% confidence interval of either estimate, indicating that processing choice is the dominant uncertainty for the basin-scale trend. The negative TWS trend is consistent with reduced recharge, groundwater depletion, or long-term basin-scale drying; the relative contributions cannot be partitioned from GRACE alone and would require coupled hydrological–extraction modelling (Figure 7).

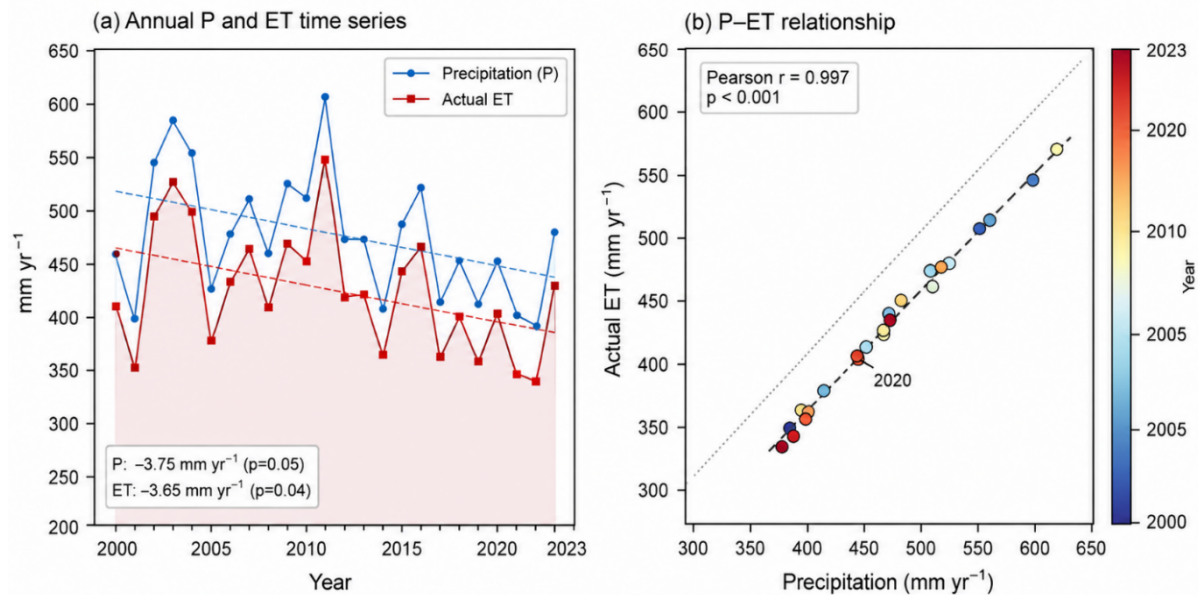


Figure 6. Annual precipitation (P, mm year⁻¹) and actual evapotranspiration (ET_a, mm year⁻¹) for Azerbaijan, 2000–2023. (a) Time series with OLS trend lines (dashed). (b) Scatter plot of annual P versus ET_a, with the fitted regression line (dashed grey) and the 1:1 reference line (dotted). The Pearson correlation coefficient ($r = 0.997$, $p < 0.001$) is shown in the inset, consistent with a water-limited evapotranspiration regime at the national scale. The anomalously dry year 2020 is labelled.

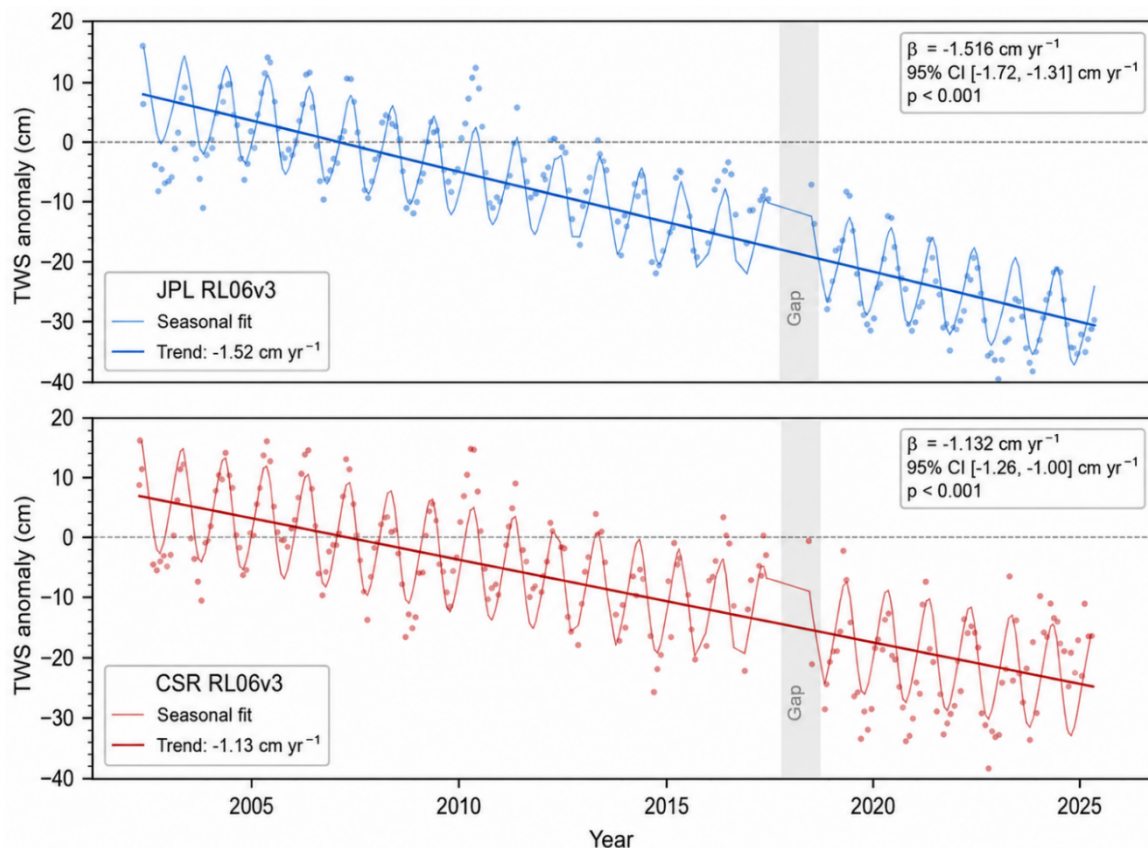


Figure 7. Monthly GRACE/GRACE-FO total water storage (TWS) anomalies (cm, relative to 2004–2009 baseline) for the Kura–Aras basin, 2002–2025. Upper panel: JPL RL06v3 mascon solution (n = 243 months). Lower panel: CSR RL06v3 mascon solution (n = 244 months). In each panel, grey dots show monthly observations; the solid line shows the harmonic fit (annual and semi-annual cycles plus linear trend, Equation (9)); the thick line is the linear trend component; and the shaded band is the autocorrelation-adjusted 95% confidence interval on the trend slope. The GRACE/GRACE-FO inter-mission data gap (2017–2018) is indicated by a grey shaded bar. Trend statistics (β_1 , 95% CI, p -value) are reported in the inset box.

To test this attribution quantitatively, we constructed an independent, national-scale annual water-balance TWSA from $\Delta S = P - ET_a - Q$, where P is precipitation, ET_a is actual evapotranspiration, and Q is annual runoff (approximated by internal runoff IR , $\approx 4.6 \text{ km}^3 \text{ year}^{-1}$). We evaluate two variants: a climate-only balance (ΔS_{clim}) and a full balance ($\Delta S_{\text{full}} = \Delta S_{\text{clim}} - \Delta \text{ext}$) in which the incremental groundwater over-abstraction relative to the year-2000 baseline (Δext ; from Table 3 and Figure 5) is treated as an additional storage sink. Both series were cumulated and re-centred on the 2004–2009 GRACE baseline. Over the 22-year overlap 2003–2023, the climate-only water balance is essentially flat (trend $+0.10 \text{ cm year}^{-1}$) and negatively correlated with GRACE ($r = -0.61$, $\text{RMSE} = 12.5 \text{ cm}$), demonstrating that natural climatic forcing alone cannot generate the observed multi-decadal storage decline. When the documented anthropogenic groundwater term is included, the water-balance TWSA closely reproduces the GRACE signal—Pearson $r = +0.96$ ($p < 0.001$), $\text{RMSE} = 2.5 \text{ cm}$, and a slope of $-1.19 \text{ cm year}^{-1}$ that agrees with the GRACE trend ($-1.26 \text{ cm year}^{-1}$) within $0.07 \text{ cm year}^{-1}$ (Figure 8). Because this convergence requires the anthropogenic Δext term to close the budget, it provides an independent, budget-based line of evidence—beyond satellite gravimetry—that the observed decline in basin-scale total water storage over the Kura–Aras basin is dominated by unsustainable groundwater abstraction rather than by climatic variability.

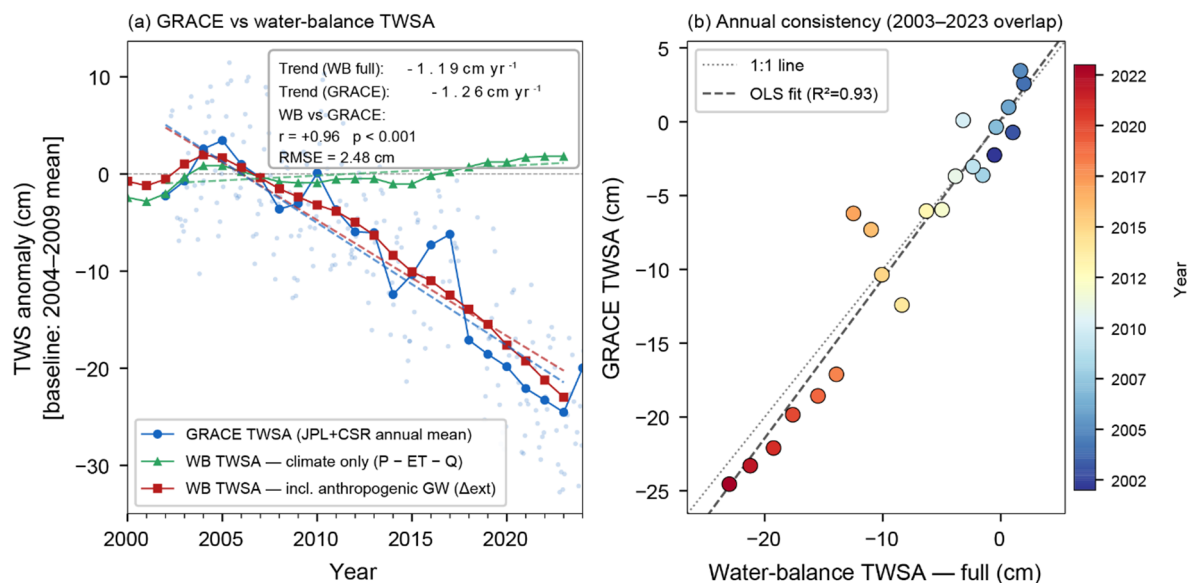


Figure 8. Consistency between GRACE TWSA and an independent water-balance-derived TWSA for Azerbaijan, 2000–2023. **(a)** Cumulative TWS anomaly (cm; baseline: 2004–2009 mean) from GRACE (JPL + CSR annual mean, blue circles; light blue dots = original monthly values), a climate-only water balance $\Delta S = P - ET_a - Q$ with $Q \approx$ internal runoff (green triangles), and a full water balance that additionally subtracts the incremental groundwater over-abstraction Δext relative to the 2000 baseline (red squares); dashed lines are OLS fits over the 22-year overlap. **(b)** Annual scatter of full-balance TWSA against GRACE TWSA ($n = 22$, coloured by year); the dashed line is the OLS fit ($R^2 = 0.93$) and the dotted line is the 1:1 reference. The climate-only budget is essentially flat ($+0.10 \text{ cm year}^{-1}$) and cannot reproduce GRACE ($r = -0.61$, $\text{RMSE} = 12.5 \text{ cm}$), whereas the full budget matches GRACE closely ($r = +0.96$, $p < 0.001$; $\text{RMSE} = 2.5 \text{ cm}$; trend -1.19 vs. GRACE $-1.26 \text{ cm year}^{-1}$, agreement within $0.07 \text{ cm year}^{-1}$), providing an independent budget-based attribution of the observed TWS decline to anthropogenic groundwater over-abstraction rather than to climatic variability.

4.8. Per-Capita Water Availability

Using the 2000–2023 mean TRWR ($21.78 \text{ km}^3 \text{ year}^{-1}$) and a population of 10.23 million (2023), per-capita renewable freshwater (Equation (6)) is approximately $2130 \text{ m}^3 \text{ capita}^{-1} \text{ year}^{-1}$, above the Falkenmark stress threshold ($1700 \text{ m}^3 \text{ capita}^{-1} \text{ year}^{-1}$) but well below the no-stress level expected for water-secure countries. Excluding transboundary inflows, internal per-capita availability ($IR + \text{GWR} \approx 9.0 \text{ km}^3 \text{ year}^{-1}$) is approximately $880 \text{ m}^3 \text{ capita}^{-1} \text{ year}^{-1}$, which falls in the “scarcity” category ($<1000 \text{ m}^3 \text{ capita}^{-1} \text{ year}^{-1}$). This contrast quantifies the extent to which Azerbaijan’s apparent per-capita water security depends on continued upstream inflows.

5. Discussion

5.1. Mechanisms Driving Water Stress in Azerbaijan

The results indicate that water stress in Azerbaijan is driven primarily by reductions in the renewable freshwater supply (TRWR $-524 \text{ million m}^3 \text{ year}^{-1}$, $p < 0.001$), within which transboundary inflows are the dominant and most variable component (Table 3; CV = 31% for Q_{in} versus 12% for IR over the six benchmark years). Internal runoff has remained comparatively stable, and total withdrawals have grown only modestly in aggregate ($+89 \text{ million m}^3 \text{ year}^{-1}$). This pattern is consistent with the hypothesis articulated in Section 1: in transboundary-dependent regions, external supply variability dominates the WSI signal. The very strong correlation between annual P and ET_a ($r = 0.997$) indicates a tightly water-limited evapotranspiration regime at the national scale, in which dry years amplify stress through both reduced supply (lower upstream and internal runoff) and concurrent reductions in available soil moisture supporting rainfed agriculture.

Within TAWW, the composition of demand has shifted over the study period in a manner not captured by the aggregate trend alone. Agricultural water consumption grew from approximately 5172 Mm^3 in 2000 to 7236 Mm^3 in 2023 ($+40\%$), while the irrigated area remained broadly stable at 1423–1439 thousand hectares (State Committee on Statistics). Note that this figure refers to consumptive use (the volume evapotranspired or incorporated into products, not returned to the system), which is distinct from agricultural withdrawals ($W_{agri} \approx 9.1 \text{ km}^3 \text{ year}^{-1}$), the gross extraction term used in the WSI numerator (Equation (4)); total water extraction from natural sources rose more moderately, from $11,110 \text{ Mm}^3$ in 2000 to $12,806 \text{ Mm}^3$ in 2023 ($+15\%$), with the difference reflecting conveyance losses and return flows (Table S1). The combination of stable irrigated area and growing agricultural water use implies either declining on-farm irrigation efficiency, a shift toward more water-intensive crops, or increasing evapotranspiration demand as temperatures rise, mechanisms that are not mutually exclusive and warrant further disaggregation at the sub-basin level. Concurrently, groundwater extraction increased 4.3-fold (Figure 5), providing an additional demand-side mechanism acting on storage. These demand-side changes occur alongside the dominant supply-side forcing from transboundary inflows, reinforcing the dual-pressure character of Azerbaijan's water stress.

5.2. Transboundary Dependence as a Risk Multiplier

The sensitivity analysis (Equation (8); Table 4) quantifies how upstream flow variability translates into national stress. A 20% reduction in Q_{in} elevates WSI by about 10 percentage points ($56\% \rightarrow 65\%$), while an equivalent 20% reduction in W_{agri} reduces WSI by about 7 percentage points ($56\% \rightarrow 47\%$). This asymmetry indicates that adaptation strategies focused exclusively on domestic efficiency gains cannot fully compensate for upstream supply reductions of comparable magnitude. Climate projections for the South Caucasus [10,11] suggest declining precipitation and earlier snowmelt in upstream catchments, conditions that would amplify the supply-side risk identified here.

5.3. Attribution of the Basin-scale Storage Decline: Water-balance Closure vs. GRACE

The GRACE-observed decline in basin-scale total water storage (-1.1 to $-1.5 \text{ cm year}^{-1}$) admits, in principle, several competing explanations—reduced climatic recharge, soil-moisture drawdown, groundwater over-abstraction, or long-term drying—none of which can be separated from satellite gravimetry alone. Closing an independent national water balance ($P - ET_a - Q$) and comparing it directly with the GRACE signal provides the missing constraint. A climate-only budget, in which Q is set equal to internal runoff (IR, $\approx 4.6 \text{ km}^3 \text{ year}^{-1}$), is essentially flat over 2003–2023 (trend $+0.10 \text{ cm year}^{-1}$) and is only weakly and negatively related to GRACE ($r = -0.61$, RMSE = 12.5 cm); at the national annual scale, in other words, precipitation and actual evapotranspiration co-vary sufficiently closely (Figure 6; $r = 0.997$) that natural climatic forcing cannot generate the multi-decadal storage loss actually observed. When the documented anthropogenic groundwater over-abstraction—which grew 4.3-fold between 2000 and 2020—is added as an incremental sink (Δ_{ext}), the water-balance TWSA converges tightly with GRACE: Pearson $r = +0.96$ ($p < 0.001$), RMSE = 2.5 cm , and a trend of $-1.19 \text{ cm year}^{-1}$ that agrees with GRACE ($-1.26 \text{ cm year}^{-1}$) within $0.07 \text{ cm year}^{-1}$ (Figure 8). The convergence is not a fit or a calibration— Δ_{ext} is measured independently in the State Committee on Statistics abstraction records ([42], Table 3)—so its ability to close the budget provides an independent budget-based attribution of the observed storage decline to unsustainable groundwater extraction, rather than to climatic variability. This strengthens the interpretation offered above (Sections 5.1 and 5.2): supply-side pressure from declining Q_{in} is the dominant driver of aggregate stress (WSI), and the storage side of the same system is being drawn down anthropogenically, not climatically. The two

lines of evidence—the WSI trend and the GRACE-derived TWS trend, now attributed via water-balance closure—converge on the same policy conclusion (Section 6).

5.4. Added Value and Limits of the Framework

The primary contribution of this study is not the development of a new methodological framework but rather the transparent and reproducible application of standard WSI decomposition [1–3,16] to a transboundary-dependent, data-scarce region. The added value rests on four elements: (i) explicit decomposition of TRWR and TAWW with documented data sources and uncertainties (Table 1; Equations (1)–(4)); (ii) integration with hydro-climatic drivers and GRACE-derived storage dynamics over a 24-year window; (iii) sensitivity analysis to alternative accounting assumptions (Equations (7) and (8); Table 4); and (iv) systematic application to Azerbaijan, where prior assessments have lacked this level of transparency. Several limits should be acknowledged. First, the WSI computation relies on national statistics that aggregate sub-basin variability; sub-national analysis is precluded by available data. Second, the sensitivity scenarios in Section 4.3 are deterministic, not probabilistic. Third, the long-term groundwater recharge value ($\sim 4.4 \text{ km}^3 \text{ year}^{-1}$) is a published estimate [29] rather than a directly monitored flux, and its uncertainty ($\sim \pm 20\%$) propagates into the internal-only WSI. Fourth, the official national accounts present some internal inconsistencies between long-term resource summaries (e.g., total renewable water reported variably as 21–35 km^3 depending on the data layer); the analysis here uses the annual 2000–2023 time series consistently and treats the long-term summaries as complementary references.

5.5. Uncertainty and Future Work

Quantitative uncertainty in WSI propagates from TAWW ($\sim \pm 10\%$) and TRWR ($\sim \pm 10\text{--}15\%$). Monte Carlo propagation (Section 4.2) yields a 95% credible interval of [39, 75]% on the long-term mean WSI, with a 97% posterior probability of exceeding the high-stress threshold and a 1% probability of exceeding the extreme-stress threshold. The largest single source of uncertainty is the long-term GWR estimate ($\sim \pm 20\%$), reflecting limited national groundwater monitoring; this uncertainty dominates the internal-only WSI configuration (Equation (7)) and is not included in the WSI Monte Carlo because GWR enters only the alternative configurations. Trend estimates are robust: all reported slopes are statistically significant under both parametric (OLS) and non-parametric (Mann–Kendall with Sen’s slope) tests, with non-overlapping 95% confidence intervals; the only marginal case is annual precipitation ($p \approx 0.05$), and high lag-1 autocorrelations in TAWW, TRWR, and WSI ($r_1 = 0.76\text{--}0.84$) do not alter significance under variance-corrected modifications [40,41]. The GRACE/GRACE-FO TWS decline is large and statistically robust (-1.1 to $-1.5 \text{ cm year}^{-1}$; 95% CIs exclude zero and $-0.5 \text{ cm year}^{-1}$). At the national-annual scale, the water-balance closure with the independent abstraction record (Section 5.3, Figure 8) resolves the attribution in favour of anthropogenic groundwater over-abstraction; however, sub-basin partitioning between climate-driven recharge variability and anthropogenic extraction at higher spatial resolution still requires coupled hydrological–extraction modelling.

Several directions would extend the scope of this analysis. Subnational assessment of the Kura, Aras, and Samur sub-basins would capture spatial heterogeneity that national aggregates obscure, subject to availability of sub-basin discharge and extraction records. Coupling the WSI framework with downscaled CMIP6 climate projections could yield stress trajectories under alternative socioeconomic pathways, though the reliability of such projections in the South Caucasus is constrained by substantial model spread in precipitation. Incorporating Environmental Flow Requirements (EFR) into the TRWR denominator, consistent with the SDG 6.4.2 protocol, would increase computed stress values and render the series more directly comparable with official reporting; the magnitude of that adjustment depends on the EFR method applied (e.g., Tennant, Variable Monthly Flow, or desktop Q90 approaches). Joint inversion of GRACE TWS with hydrological model output and groundwater well records would help disaggregate climate-driven recharge variability from extraction-driven storage change, a partition that gravimetry alone cannot provide. The mechanism underlying stable irrigated area combined with rising agricultural withdrawals also warrants closer examination: contributing factors may include shifts in crop mix, changes in conveyance and on-farm efficiency, or temperature-driven increases in reference evapotranspiration, but these have not been tested quantitatively in this context.

5.6. Implications for Integrated Water Management and Transboundary Cooperation

Three management implications follow from the results. First, agricultural efficiency gains (modernizing irrigation, reducing distribution losses) are necessary but insufficient: a 20% reduction in W_{agri} alone reduces WSI by only about 7 percentage points, while a comparable reduction in transboundary inflows raises WSI by about 10 percentage points [3,9]. Second, transboundary cooperation with upstream riparian states (Georgia, Armenia,

Turkey, Iran) is essential to manage supply-side risk, given that transboundary inflows account for ~70–80% of renewable surface water in most years (Table 3; [1,2]. Coordinated data sharing in the Kura–Aras basin is constrained by limited institutional frameworks for systematic exchange, differences in monitoring protocols, and sensitivities around upstream extraction reporting; bilateral agreements exist, but real-time data exchange and joint forecasting remain underdeveloped [5–8]. Third, integration of GRACE-derived TWS and ground-based monitoring would improve detection of climate- and extraction-driven storage changes, supporting adaptive management [32]. Beyond the WSI-based leverage argument, the water-balance closure with GRACE (Section 5.3, Figure 8) provides an operational monitoring tool: policy measures directed at reducing groundwater over-abstraction should manifest, within a few years, as an attenuation of the negative slope of both the national water-balance TWSA and the GRACE TWSA, providing an independent success criterion.

6. Conclusions

This study applied a transparent and reproducible framework for decomposing the Water Stress Index into its hydrological and sectoral components, integrated with hydro-climatic drivers and GRACE-derived storage dynamics, to Azerbaijan over 2000–2023. Four findings emerge:

- Mean annual WSI was 56% (range 35–88%), placing Azerbaijan in the high-stress category in 20 of 24 years and reaching extreme stress (88%) in 2020. WSI rose at +1.8 percentage points year^{−1} ($p < 0.001$), driven by declining TRWR (−524 million m³ year^{−1}) and rising TAWW (+89 million m³ year^{−1}).
- Across benchmark years, transboundary inflows accounted for 68–82% of renewable surface water and were 2.6 times more variable (CV = 31%) than internal runoff (CV = 12%).
- Sensitivity analysis indicates that external supply variability exerts stronger leverage on national stress than domestic demand adjustments of comparable magnitude: a 20% reduction in Q_{in} raises WSI by about 10 percentage points, while a 20% reduction in W_{agri} lowers it by about 7 percentage points.
- GRACE/GRACE-FO mascon solutions show a long-term TWS decline of −1.1 to −1.5 cm year^{−1} over 2002–2025 ($p < 0.001$), consistent with reduced recharge, groundwater depletion, or basin-scale drying. Closing an independent national water balance ($\Delta S = P - ET_a - Q$, with the documented anthropogenic groundwater over-abstraction included as a sink) reproduces the GRACE-observed basin-scale storage decline with $r = +0.96$ and trend agreement within 0.07 cm year^{−1}, whereas a climate-only budget cannot (Figure 8). This budget-closure test attributes the observed TWS loss primarily to unsustainable groundwater extraction rather than to climatic variability and provides an independent monitoring criterion for the success of adaptation measures.
- Adaptive management in Azerbaijan requires a dual strategy combining domestic efficiency gains with strengthened transboundary cooperation and shared monitoring in the Kura–Aras basin.

Supplementary Materials

The additional data and information can be downloaded at: <https://media.sciltp.com/articles/others/2608141534143086/HWR-25120140-SI.pdf>.

Author Contributions

R.I. conceived and designed the study, compiled national datasets, and drafted the initial manuscript. B.J. performed the water-balance analysis and provided substantive revisions. Á.S. conducted the climate analysis, performed statistical analysis and contributed to manuscript revisions. All authors contributed to the preparation of tables and figures and approved the final manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Earth Observation datasets used in this review are publicly available. GRACE and GRACE Follow-On (GRACE-FO) terrestrial water storage data were obtained from the NASA Jet Propulsion Laboratory (JPL) GRACE/GRACE-FO Mascon dataset (RL06.3Mv04), available through [43]. Earth Observation datasets, including Landsat, MODIS, Sentinel, and GRACE products, were accessed through the NASA Earthdata portal (<https://earthdata.nasa.gov/>) and processed using Google Earth Engine (GEE) (<https://earthengine.google.com/>). The Google Earth Engine platform and publicly available datasets are described by [44].

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with improving the grammar, language, and readability of the manuscript. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the published article.

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