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NEAR-TERM CLIMATE SCENARIOS AND WATER SCARCITY RISK IN THE SYR DARYA RIVER BASIN TO 2035: ANNUAL RUNOFF, SEASONAL DEFICIT AND UPSTREAM–DOWNSTREAM VULNERABILITY

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Abstract:
Planning in irrigated Central Asian basins needs near-term (decadal) estimates of how climate change will alter water supply and pressure on it, yet most projections focus on the mid- or late-century. This study assesses changes in the Syr Darya River Basin to 2035 under four CMIP6 Shared Socioeconomic Pathway (SSP) scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5). Low, median and high change signals for temperature, precipitation, potential evapotranspiration (PET) and snowfall were applied to the 2000–2024 climatology with a delta-change approach and propagated to annual runoff and water withdrawal through statistical models calibrated on historical data. By 2035, median mean annual temperature rises from 9.94 °C to 10.69–11.14 °C and

PET by 4–7%, while precipitation changes only by +1% to −2%; the climatic water balance therefore deteriorates from −726.36 mm to between −764.94 and −805.79 mm, and snowfall declines by 8–16%. Annual runoff reaches 37.85–36.48 km³, i.e. 0.25–3.87% below the 2000–2024 mean, while withdrawals rise slightly to 13.50–13.59 km³; the withdrawal-to-runoff ratio increases from 35.67% (SSP1-2.6) to 37.26% (SSP5-8.5). Seasonal signals are considerably stronger than annual ones: under SSP5-8.5 summer precipitation decreases by 7% and summer PET increases by 8.05%. The downstream zone and the summer irrigation season emerge as the most vulnerable area and period, indicating that near-term adaptation should prioritise seasonal storage management and downstream allocation over annual volume targets.

Keywords: Syr Darya; climate scenarios; SSP; CMIP6; delta change; runoff projection; water scarcity; seasonal deficit; Central Asia

1. Introduction

Rivers fed by snow and glaciers are particularly sensitive to warming, because higher temperatures shift precipitation from snow to rain, advance the melt season and raise evaporative demand [1–3]. In the Tien Shan and Pamir, which act as water towers for the arid lowlands of Central Asia, glacier retreat and a declining snowfall fraction have already been documented [4–6]. Projections for the region indicate that the timing of runoff is likely to change earlier and more strongly than its annual volume, with drier soils and reduced summer flow in snow-dominated catchments [7,8].

The Syr Darya River Basin is a transboundary system shared by Kyrgyzstan, Tajikistan, Uzbekistan and Kazakhstan. Its flow is generated mainly in the upstream mountains and regulated by a reservoir cascade, while the bulk of

consumptive use occurs in the irrigated mid- and downstream lowlands [9,10]. Recent modelling studies have evaluated future runoff of the upper Syr Darya sub-basins under climate scenarios [11] and quantified climate and human effects with ensemble and factorial approaches [12]. Decision-makers, however, also need near-term estimates on the horizon of national strategies, which in Uzbekistan extend to 2030–2035 [13], expressed not only as runoff but also as the resulting pressure on available water.

This paper addresses that need by (i) quantifying 2035 changes in the basin's meteorological drivers under four SSP scenarios, including their seasonal distribution; (ii) estimating the corresponding change in annual runoff and withdrawals; and (iii) assessing how scenario changes translate into water scarcity risk in the upstream, midstream and downstream zones.

2. Materials and Methods

2.1. Study area and baseline

The study area is the hydrologically active catchment of the Syr Darya (≈219 × 10^3 km^2), formed by the Naryn and Kara Darya rivers and regulated by the Toktogul, Andijan, Bahri Tojik, Chardara and other reservoirs [9,14]. Two reference states were used. The climatological baseline is the 2000–2024 mean of harmonised annual basin-scale series: mean temperature 9.94 °C, precipitation 317.65 mm, PET 1044.01 mm, climatic water balance −726.36 mm, snowfall 110.37 mm, runoff 37.95 km^3 and total withdrawal 13.35 km^3. The current state is represented by 2025, a relatively dry year with runoff of 33.25 km^3 (12.38% below the mean). Keeping both references is essential: comparison against the dry year alone would suggest a spurious improvement by 2035.

2.2. Scenario signals

Four CMIP6 scenarios spanning the ScenarioMIP range were used: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 [15,16]. For each scenario, low, median and high change signals to 2035 were defined for annual and seasonal temperature, precipitation, PET and snowfall (Table 1). The ranges were harmonised with regional climate reference regions for Central Asia [17] and with published near-term CMIP6 projections and downscaled products [18,19]. Medians are used as central estimates; low and high values are retained as scenario uncertainty, in line with the recommendation to use the ensemble central value and spread rather than a single model [20].

Table 1. Ranges of change signals adopted for the Syr Darya basin to 2035 (relative to 2000–2024)

Scenario	Temperature, °C	Precipitation, %	PET, %	Snowfall, %
SSP1-2.6	+0.55 to +0.95	−3 to +5	+2 to +6	−12 to −4
SSP2-4.5	+0.65 to +1.15	−5 to +5	+3 to +7	−15 to −5
SSP3-7.0	+0.75 to +1.35	−7 to +5	+4 to +9	−19 to −7
SSP5-8.5	+0.85 to +1.55	−9 to +5	+5 to +11	−23 to −9

2.3. Delta-change projection

Scenario values for 2035 were obtained by applying the change signal to the baseline climatology:

$$X_{2035,s} = \bar{X}_{2000–2024} \times (1 + \Delta_s / 100) \quad (1)$$

where $\bar{X}$ is the 2000–2024 mean and Δ_s the percentage change for scenario s. For temperature the change was added as an absolute increment in °C. The climatic water balance (P − PET) and the aridity ratio (P/PET) were derived from the projected components. The delta approach preserves the spatial and statistical

structure of the observed climatology while transferring the climate-change signal [19,21].

2.4. Runoff and withdrawal estimates

Projected meteorological variables were entered into a calibrated regularised regression model of annual basin runoff developed on the historical series. The historical runoff series had been completed with a bounded logistic regression on Toktogul reservoir inflow (calibration 2018–2025, RMSE = 1.125 km³, about 3% of mean runoff). Model outputs were checked against the historical minimum and maximum, the direction of the water balance change and published regional runoff-change ranges; values that were statistically acceptable but hydrologically implausible were rejected. The resulting 2035 runoff values are therefore literature-constrained, CMIP6-consistent central estimates rather than direct output of a process-based hydrological model.

Withdrawals were projected with a ridge regression on year and available runoff. Its explanatory power is low ($R^2 = 0.103$), because withdrawals depend on crop plans, irrigation scheduling and interstate allocation; withdrawal projections are therefore treated as an auxiliary estimate under continuation of current tendencies. Water pressure was expressed as the withdrawal-to-runoff ratio $WR = (W/Q) \times 100$, water availability as $WAI = 100 - WR$, and the conditional residual after withdrawal as $Q - W$.

3. Results

3.1. Meteorological drivers

Median annual temperature in 2035 reaches 10.69 °C under SSP1-2.6, 10.84 °C under SSP2-4.5, 10.99 °C under SSP3-7.0 and 11.14 °C under SSP5-8.5 (Table 2, Figure 1). Precipitation changes are small and of uncertain sign, from +1%

(320.82 mm) to −2% (311.29 mm). PET, in contrast, increases consistently by 4–7%, to 1085.77–1117.09 mm. As a result, the climatic water balance deteriorates in every scenario, by 38.58 mm under SSP1-2.6 and by 79.43 mm under SSP5-8.5, and the aridity ratio falls from 0.304 to 0.295–0.279. Snowfall declines by 8% (101.54 mm) to 16% (92.71 mm).

Table 2. Median 2035 values of the basin's annual meteorological indicators by scenario

Indicator	Baseline 2000–2024	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Mean annual temperature, °C	9.94	10.69	10.84	10.99	11.14
Annual precipitation, mm	317.65	320.82	317.65	314.47	311.29
PET, mm	1044.01	1085.77	1096.21	1106.65	1117.09
Climatic water balance, mm	−726.36	−764.94	−778.56	−792.18	−805.79
Aridity ratio P/PET	0.304	0.295	0.290	0.284	0.279
Snowfall, mm	110.37	101.54	99.33	96.02	92.71

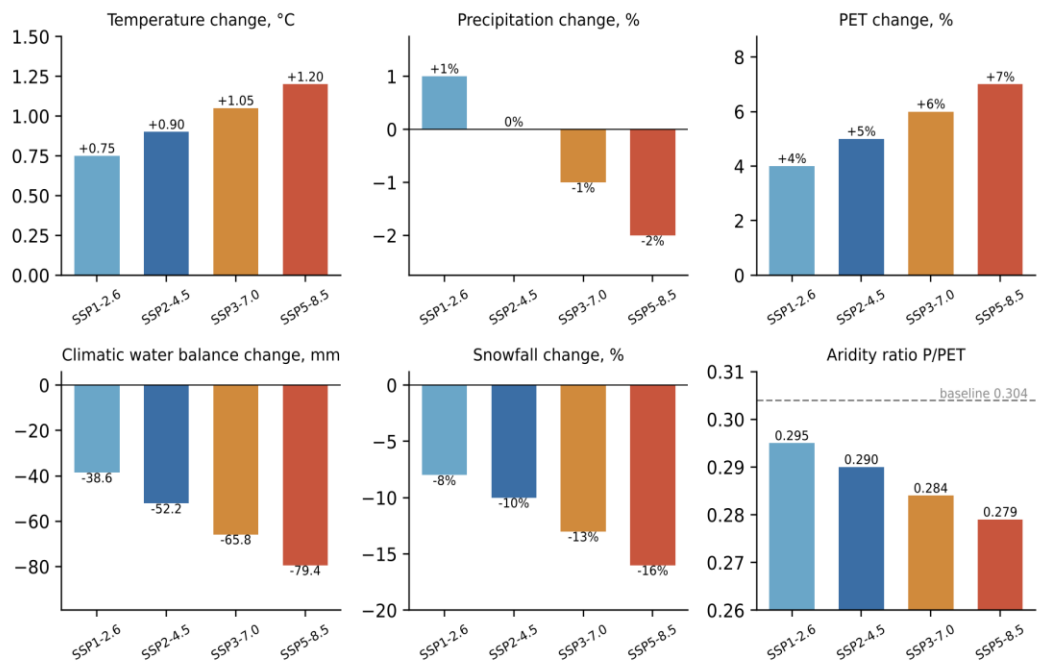


Figure 1. Median 2035 change in annual meteorological indicators relative to the 2000–2024 baseline under four SSP scenarios

Seasonally, warming is strongest in winter: +0.86 °C under SSP1-2.6 and +1.38 °C under SSP5-8.5, compared with +0.69 and +1.10 °C in summer. Winter warming favours rain over snow and earlier melt. The largest water deficit develops in summer: under SSP5-8.5 summer precipitation decreases by 7% (from 45.43 to 42.25 mm) while summer PET increases by 8.05% (from 507.79 to 548.67 mm), bringing the summer climatic water balance to −506.42 mm. In spring, precipitation decreases by 2% and PET increases by 7%, lowering the seasonal balance to −194.70 mm.

Uncertainty is larger for precipitation than for temperature. Under SSP5-8.5, the 2035 temperature range is 10.79–11.49 °C, whereas precipitation spans 289.06–

333.53 mm. Nevertheless, warming, rising PET, declining snowfall and a worsening water balance occur in all scenarios and at all bounds of the adopted ranges.

3.2. Annual runoff and withdrawals

Projected annual runoff for 2035 decreases monotonically with scenario forcing: 37.85 km³ (SSP1-2.6), 37.45 km³ (SSP2-4.5), 36.97 km³ (SSP3-7.0) and 36.48 km³ (SSP5-8.5), i.e. 0.25–3.87% below the 2000–2024 mean (Table 3). The spread between the lowest and highest forcing scenarios is 1.37 km³, or 3.62% of mean runoff. All values remain within the historical natural range. Relative to the dry year 2025, the same values are 9.71–13.84% higher; this reflects the low starting point rather than an improvement in water resources.

Withdrawals increase slightly, to 13.50–13.59 km³ (1.30–1.98% above 2025). Because runoff falls while withdrawals rise, WR increases from 35.67% under SSP1-2.6 to 37.26% under SSP5-8.5, WAI decreases from 64.33% to 62.74%, and the residual after withdrawal shrinks from 24.35 to 22.89 km³ (Figure 2).

Table 3. Annual runoff, withdrawals and water pressure indicators for the long-term mean, the 2025 baseline and 2035 scenarios

Indicator	Mean 2000–2024	2025	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Basin runoff Q, km³	37.95	33.25	37.85	37.45	36.97	36.48
Change vs long-term mean, %	–	−12.38	−0.25	−1.31	−2.59	−3.87
Change vs 2025, %	–	–	+13.84	+12.64	+11.18	+9.71
Total withdrawal W, km³	13.35	13.33	13.50	13.53	13.56	13.59
Withdrawal ratio WR, %	35.73	40.09	35.67	36.14	36.69	37.26
Water availability index, %	64.27	59.91	64.33	63.86	63.31	62.74
Residual after withdrawal, km³	24.60	19.92	24.35	23.92	23.40	22.89

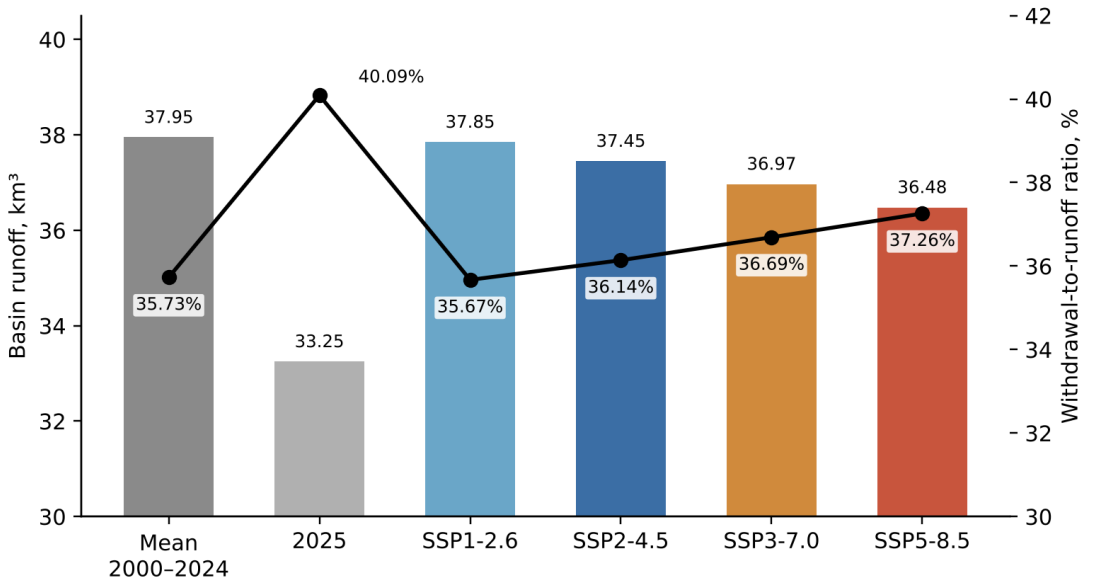


Figure 2. Projected 2035 basin runoff (bars) and withdrawal-to-runoff ratio (line) by scenario, compared with the 2000–2024 mean and the 2025 baseline

The historical model error (1.125 km³) exceeds the change projected under SSP1-2.6 (0.10 km³), so that scenario cannot be distinguished from no change. The decreases under SSP3-7.0 and SSP5-8.5, however, are consistent in direction with all meteorological drivers. Since the inter-scenario spread (1.37 km³) is of similar magnitude to the model error, the robust result is the common direction of change rather than the precise difference between individual scenarios.

3.3. Zonal and seasonal vulnerability

Because sub-basin withdrawal and runoff projections were not available, zonal vulnerability was assessed qualitatively by combining the annual results with the hydrological role of each zone (Table 4). Upstream areas remain the most water-secure in annual terms, but declining snowfall and earlier melt make their summer

contribution increasingly uncertain. In the midstream, reservoirs can partly compensate for seasonal shifts, but conflicting hydropower and irrigation objectives determine when water is released, and rising PET increases irrigation requirements per hectare. The downstream zone depends entirely on flow arriving from above; withdrawals accumulate along the river, so a basin-wide WR of 35–37% implies a considerably higher effective pressure at the lower end. Under SSP5-8.5 the combined effect of lower runoff, higher withdrawals and higher evaporative demand makes the downstream zone the most exposed.

Table 4. Qualitative sensitivity of Syr Darya basin zones to water scarcity under climate scenarios

Basin zone	Main water source	Main pressure factor	2025 status	2035 SSP2-4.5	2035 SSP5-8.5
Upstream	Snow, glaciers, mountain rivers	Reduced snowfall, earlier melt	relatively favourable	moderate risk	moderate-to-high risk
Midstream	Reservoir-regulated flow	Irrigation demand, rising PET	moderate pressure	moderate pressure	high pressure
Downstream	Inflow from upstream reaches	Cumulative withdrawal, evaporation, lower flow	high risk	high risk	very high risk

4. Discussion

The projections show a characteristic near-term pattern: modest change in annual runoff combined with a robust deterioration of the basin's climatic water balance and a pronounced seasonal signal. The 0.25–3.87% decline in annual flow appears small, but 1% of basin runoff is about 0.38 km³, and the 1.47 km³ loss under SSP5-

8.5 is a substantial volume for large irrigation schemes, reservoir refilling and downstream needs. More importantly, annual totals conceal the seasonal redistribution expected from winter warming and reduced snowfall: more water arriving in winter and early spring, less in late spring and summer, precisely when irrigation demand peaks. This agrees with process-based projections for the Naryn catchment, which found shifted discharge and drier summer soils under warming [8], and with regional evidence of a declining snowfall fraction [6].

The results also confirm that, on the near-term horizon, temperature and evaporative demand rather than precipitation drive the drying of the basin. Precipitation changes are small and of uncertain sign, whereas PET increases in every scenario. This implies that irrigation requirements will rise even in years with normal precipitation, which reinforces the pressure created by the slight upward tendency in withdrawals.

For water management, these findings shift attention from annual volumes to timing and location. Storing a larger share of winter and early-spring inflow for the summer season is constrained by hydropower demand in winter, flood-control requirements and interstate arrangements [10,22]. Reducing future scarcity therefore depends on improving the seasonal distribution of existing flow, protecting downstream allocations in dry summers and continuing efficiency measures that lower irrigation demand per hectare. A decision-support approach that links seasonal forecasts to allocation, as proposed recently for Central Asia [23], would directly address the vulnerabilities identified here.

Several limitations apply. The projections are annual and basin-wide; independent sub-basin, gauge-level or irrigation-scheme projections were not produced. Return flows, groundwater exchange, water quality and environmental flow requirements were not modelled, so the residual after withdrawal should not be interpreted as water actually available to all users or ecosystems. Future

reservoir operating rules, new infrastructure, changes in crop structure and irrigation efficiency were not scenario-dependent. The runoff projections are statistically derived and literature-constrained rather than produced by a physically based hydrological model, and the withdrawal model has low explanatory power. Coupling the scenario signals with a glacio-hydrological model at monthly resolution is the logical next step.

5. Conclusions

(1) By 2035, all four SSP scenarios project warming of the Syr Darya basin to 10.69–11.14 °C (median), a 4–7% increase in PET, an 8–16% decline in snowfall and a deterioration of the climatic water balance to between −764.94 and −805.79 mm, while precipitation changes only by +1% to −2%.
(2) Annual runoff is projected at 37.85–36.48 km³, 0.25–3.87% below the 2000–2024 mean; the decline is small but consistent in direction across scenarios, and values exceed those of the dry 2025 baseline.
(3) Slightly rising withdrawals (13.50–13.59 km³) combined with lower runoff raise the withdrawal-to-runoff ratio from 35.67% to 37.26% and reduce the residual after withdrawal from 24.35 to 22.89 km³.
(4) Seasonal deficits are much larger than annual changes: under SSP5-8.5 summer PET rises by 8.05% and summer precipitation falls by 7%, giving a summer water balance of −506.42 mm.
(5) The downstream zone and the summer irrigation season are the most vulnerable area and period; near-term adaptation should prioritise seasonal storage management and downstream allocation in dry summers.

Data Availability Statement: The scenario signals, baseline climatology and projected series are available from the author on reasonable request.



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References

1. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Masson-Delmotte, V., Zhai, P., Pirani, A., et al., Eds.; Cambridge University Press: Cambridge, UK, 2021. https://doi.org/10.1017/9781009157896
2. Barnett, T.P.; Adam, J.C.; Lettenmaier, D.P. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 2005, 438, 303–309. https://doi.org/10.1038/nature04141
3. Huss, M.; Hock, R. Global-scale hydrological response to future glacier mass loss. Nat. Clim. Change 2018, 8, 135–140. https://doi.org/10.1038/s41558-017-0049-x
4. Sorg, A.; Bolch, T.; Stoffel, M.; Solomina, O.; Beniston, M. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nat. Clim. Change 2012, 2, 725–731. https://doi.org/10.1038/nclimate1592
5. Immerzeel, W.W.; Lutz, A.F.; Andrade, M.; et al. Importance and vulnerability of the world's water towers. Nature 2020, 577, 364–369. https://doi.org/10.1038/s41586-019-1822-y
6. Li, Z.; Chen, Y.; Li, Y.; et al. Declining snowfall fraction in the alpine regions, Central Asia. Sci. Rep. 2020, 10, 3476. https://doi.org/10.1038/s41598-020-60303-z
7. Didovets, I.; Lobanova, A.; Krysanova, V.; et al. Central Asian rivers under climate change: Impacts assessment in eight representative catchments. J. Hydrol. Reg. Stud. 2021, 34, 100779. https://doi.org/10.1016/j.ejrh.2021.100779



8. Schaffhauser, T.; Lange, S.; Tuo, Y.; Disse, M. Shifted discharge and drier soils: Hydrological projections for a Central Asian catchment. J. Hydrol. Reg. Stud. 2023, 46, 101338. https://doi.org/10.1016/j.ejrh.2023.101338
9. Sorg, A.; Mosello, B.; Shalpykova, G.; Allan, A.; Hill Clarvis, M.; Stoffel, M. Coping with changing water resources: The case of the Syr Darya River Basin in Central Asia. Environ. Sci. Policy 2014, 43, 68–77. https://doi.org/10.1016/j.envsci.2013.11.003
10. Bernauer, T.; Siegfried, T. Climate change and international water conflict in Central Asia. J. Peace Res. 2012, 49, 227–239. https://doi.org/10.1177/0022343311425843
11. Kalashnikova, O.Yu.; Niyazov, J.; Nurbatsina, A.; Kodirov, S.; Radchenko, Y.; Kretova, Z. Kyrgyz transboundary rivers' runoff assessment: Syr-Darya and Amu-Darya River basins in climate change scenarios. Cent. Asian J. Water Res. 2023, 9, 59–88. https://doi.org/10.29258/CAJWR/2023-R1.v9-1/59-88.eng
12. Zhai, X.B.; Li, Y.P.; Wang, H.; Huang, G.H.; Li, Y. Assessment of the potential impacts of climate changes on Syr Darya watershed: A hybrid ensemble analysis method. J. Hydrol. Reg. Stud. 2023, 47, 101415. https://doi.org/10.1016/j.ejrh.2023.101415
13. Decree of the President of the Republic of Uzbekistan No. PF-158 of 11 September 2023 "On the Strategy 'Uzbekistan–2030'".
14. Scientific-Information Center of the Interstate Commission for Water Coordination of Central Asia (SIC ICWC). Water Management Infrastructure of the Syr Darya River Basin. Available online: http://www.cawater-info.net (accessed on 4 August 2026).
15. O'Neill, B.C.; Tebaldi, C.; van Vuuren, D.P.; et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci. Model Dev. 2016, 9, 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

16. Eyring, V.; Bony, S.; Meehl, G.A.; Senior, C.A.; Stevens, B.; Stouffer, R.J.; Taylor, K.E. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. 2016, 9, 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

17. Iturbide, M.; Gutiérrez, J.M.; Alves, L.M.; et al. An update of IPCC climate reference regions for subcontinental analysis of climate model data: Definition and aggregated datasets. Earth Syst. Sci. Data 2020, 12, 2959–2970. https://doi.org/10.5194/essd-12-2959-2020

18. Thrasher, B.; Wang, W.; Michaelis, A.; Melton, F.; Lee, T.; Nemani, R. NASA Global Daily Downscaled Projections, CMIP6. Sci. Data 2022, 9, 262. https://doi.org/10.1038/s41597-022-01393-4

19. Lange, S. Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). Geosci. Model Dev. 2019, 12, 3055–3070. https://doi.org/10.5194/gmd-12-3055-2019

20. Knutti, R.; Masson, D.; Gettelman, A. Climate model genealogy: Generation CMIP5 and how we got there. Geophys. Res. Lett. 2013, 40, 1194–1199. https://doi.org/10.1002/grl.50256

21. Maraun, D.; Wetterhall, F.; Ireson, A.M.; Chandler, R.E.; Kendon, E.J.; Widmann, M.; et al. Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user. Rev. Geophys. 2010, 48, RG3003. https://doi.org/10.1029/2009RG000314

22. Rakhmatullaev, S.; Huneau, F.; Le Coustumer, P.; Motelica-Heino, M.; Bakiev, M. Facts and perspectives of water reservoirs in Central Asia: A special focus on Uzbekistan. Water 2010, 2, 307–320. https://doi.org/10.3390/w2020307

23. Huang, J.; Bashiri, Z.; Disse, M. Climate-informed water allocation in Central Asia: Leveraging decision support system. Water 2026, 18, 161. https://doi.org/10.3390/w18020161