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Staged Dam Regulation Flattens and Delays Snowmelt Runoff in the Topalang River, Uzbekistan: Hydrologic Alteration and Environmental Flows

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Abstract

The Topalang, a snow-fed Amu Darya tributary in Uzbekistan, has been regulated since 1986 by a reservoir enlarged in stages. We compared natural discharge (1930–1985) with operator records of release, storage and reconstructed inflow (1990–2024) to separate the reservoir's effect from changes in the water reaching it. As storage reached about a fifth of annual flow, the ratio of release to inflow fell to 0.80 in April–July and rose to 1.90 in August–October. Seasonal ecochange attributable to the reservoir grew three- to fivefold, and release now lies outside the natural range every year in March and from October to December. August–October inflow fell about a quarter below the natural mean and was lower in warmer and in drier years, while reanalysis precipitation showed no significant decline. The reservoir masks that decline downstream while flattening the spring flood, and winter release fell below the Tennant-based benchmark of 10.5 m^3/s (20% of natural mean flow) on about 55 days a year. Both pressures call for release rules and an inflow gauge.

Keywords: flow regulation; hydrologic alteration; Range of Variability Approach; ecodeficit; environmental flows; snowmelt river; reservoir operation; Amu Darya; Central Asia; Uzbekistan

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1. Introduction

The Amu Darya is the largest source of freshwater in Central Asia, and so much of its water is withdrawn for irrigation that almost none now reaches the delta or the Aral Sea [1]. Most of its flow is generated in the mountain headwaters, and none of the

sites assessed downstream of Kerki met its environmental-flow requirements [1]. The headwater tributaries are also where new storage is being built. In Uzbekistan the number of hydropower plants rose from 36 in 2017 to 100 by 2025 and installed capacity from 1.6 to 2.4 GW, and plans for almost 3000 further small and micro plants were under review in 2026 [2].

Snow-fed rivers feel both pressures in the same months. Storage holds back the spring flood and releases it later in the year, while warmer springs melt snow earlier and can leave less water for late summer [3]. A gauge below a dam records the sum of the two. Without a separate account of the water reaching the reservoir, it cannot say which of them caused a change. The distinction matters for management, because a change produced by operation can be adjusted through release rules, whereas one produced by climate has to be planned around.

Dams are the most widespread direct alteration of river flow. More than half of the world's 292 large river systems are affected by dams, and the loss of seasonal flooding that regulation brings may be especially harmful in dry and cold biomes [4]. Globally, flow regulation is the dominant pressure in about a quarter (23.5%) of river reaches with impaired connectivity. Its effect falls mainly on lateral and temporal connectivity, through lower peaks and delayed releases that shift the timing of flow events [5]. Grill et al. [5] measure this pressure with the degree of regulation, the share of mean annual flow that upstream reservoirs can store. A small reservoir on a modest river can therefore alter the flow regime more than its absolute size suggests.

Studies of regulated rivers in the United States give a sense of scale. Across 21 dams of different purposes, the annual 1-day maximum fell by 55%, on average, after impoundment, from 21% at a single-purpose hydropower dam to 79% [6]. Mean flows in the same sample tended to fall in April and May and to rise in August and September, and the authors stress that changes in timing can be as dramatic as changes in magnitude. Below very large reservoirs, 1-day maxima were on average 71% lower than on comparable unregulated reaches, but 30-day maxima only 25% lower [7]. Graf also named the central difficulty of such work: separating dam effects from simultaneous changes in climate and land use is "a fluvial Gordian knot" [7] (p. 343).

The ecological case for caring about timing rests on the natural flow regime concept. Magnitude, frequency, duration, timing and rate of change of flow together structure river ecosystems [8]. Snowmelt rivers have among the most predictable flood timing of any stream type, a regularity to which riverine organisms are adapted [9]. Two practical tools follow from this view. The Indicators of Hydrologic Alteration summarise a regime in a set of ecologically relevant statistics [10], and the Range of Variability Approach compares a regulated regime with the natural range of each statistic [11]. Both need a pre-impact reference, ideally of 20 years or more of natural record.

Snowmelt rivers are also those most exposed to warming. Higher temperatures bring melt forward and reduce flow in summer and autumn, at least where precipitation does not change, whereas changes in volume depend mainly on precipitation [3]. In Central Asia, warming has been strongest in winter and in September, lengthening the melt season, and ablation-season runoff has recently been falling in some rivers [12]. The regional response is not uniform. Catchments with a large glacier share have mostly shown rising runoff, whereas basins with little or no glacier ice show large variations [13]. Rivers in Kyrgyzstan, fed by snow, glaciers and rising precipitation, have carried more water since the 1990s, 4% to 16% above their long-term mean in 2000–2020 [14]. The Amu Darya basin, to which the Topalang belongs, is among the five most important mountain water towers of Asia and the most vulnerable of them [15].

Evidence on how Central Asian rivers have actually changed since 1991 is thin. The observation network contracted sharply after the collapse of the Soviet Union, gauges went without maintenance or recalibration, and internationally archived runoff series largely end in 1992 [13]. At the basin scale, flow of the Amu Darya at Kerki has declined since the 1970s, but the gauge integrates withdrawals and reservoir operations across the upper basin, and the authors did not separate these from climate [16]. The same problem affects smaller catchments. A recent study of the Surkhandarya headwaters reported falling discharge since 2000 and attributed it to glacier loss and warming, without discussing the Tupalang reservoir within the catchment it described [17]. How hydropower and irrigation reservoirs reshape seasonal flow in the region has been examined mainly through model scenarios for the large transboundary schemes [18], not through observed records at individual dams.

This study addresses that gap for one river where the necessary records exist. The Topalang has a natural discharge record from 1928, a reservoir built in stages since 1986, and release and storage recorded at the same dam, from which inflow can be reconstructed. That combination allows the regulation signal and the inflow signal to be separated directly and both to be judged against a long natural reference. We ask how far each stage of storage altered the seasonal regime below the dam, how the water reaching the dam changed and how closely that change follows temperature and snow cover, and what the two signals together imply for the river's environmental flows.

2. Materials and Methods

2.1. Study Area

The Topalang River (Figure 1) rises at about 3800 m on the southern slope of the Hisar Range and joins the Karatag to form the Surkhandarya, a right-bank tributary of the Amu Darya [19,20]. Throughout, Topalang refers to the river and Tupalang to the dam, reservoir and hydropower station, following local usage. According to the operator's records, the river is 124 km long and drains 3080 km^2 at its confluence. The catchment above the dam and the Zarchob gauge is smaller: published sources give a water-collecting area of 2200 km^2 [19,20], the figure also listed for the Zarchob gauge in the gauging-station records. More than 40% of it lies between 2000 and 3000 m, and only about 5% lies below 1000 m [21]. The river is fed mainly by seasonal snow; perennial snow and glaciers contribute little [21], and published estimates attribute about 65% of annual runoff to snowmelt, 26% to groundwater, 6% to ice and 3% to rain [19]. Flow rises from late February, peaks in May and June and recedes through September [21]. According to the reservoir administration, there are no water intakes, pumping stations or hydropower plants on the river above the reservoir.

Construction of the Tupalang dam began in 1982 and the reservoir entered service in 1986, according to the operator's technical passport. The dam is a 185 m earth and rockfill structure with a crest 410 m long. Its storage was licensed at 380 × 10^6 m^3 by a ministerial order of 2 December 2016 and at 500 × 10^6 m^3 in 2023. Of the 500 × 10^6 m^3, 470 × 10^6 m^3 is useful volume and 30 × 10^6 m^3 is dead storage, and the full reservoir covers 8.85 km^2. A 30 MW hydropower plant began operating in 2006 and the station reached 175 MW in 2023 [22]. Through the Hazarbog canal the reservoir supplies about 117,000 ha of irrigated land in seven districts, against a design command of 202,000 ha.

2.2. Data

Table 1 lists the series used. Monthly discharge at the Topalang–Zarchob gauge for 1928–2014 was obtained from the Uzbek Hydrometeorological Service (Uzhydromet). The reservoir operator supplied monthly inflow for 1991–2024, ten-day inflow, release and storage for 2009–2025, daily release for 1990–2024, the annual maximum storage and annual release for 1986–2024, and the elevation–volume table of the reservoir. Monthly

air temperature at the Baysun station (1220 m; 38.200° N, 67.183° E) was taken from the Pogoda i Klimat climate archive [23]. Daily snow-covered area of the catchment above the dam (2200 km^2) for 2000–2025 was derived from MODIS imagery with the MODSNOW tool [24]. No gauge stands above the reservoir, so inflow is not measured directly. The operator reconstructs it from the measured release and the change in storage, which is read from water level through the elevation–volume table. According to the reservoir administration, the calculation also allows for evaporation from the reservoir surface and for seepage, and the elevation–volume table was updated as the dam was raised and is re-checked at fixed intervals, formerly every five years and now every two. The dates of the individual revisions were not available to us. Inflow is thus the only series in Table 1 that is computed from other records. In the ten-day records we received, storage change and net inflow agree only approximately ($r = 0.74$, $n = 575$), probably because ten-day values are rounded and storage is read once in each period. Over 2009–2024 the residual of the ten-day water balance averaged 7.8 m^3/s in absolute terms, 4.6 m^3/s in Phase 2 and 10.7 m^3/s in Phase 3, but only 0.4 m^3/s in the mean ($n = 539$). In August–October of Phase 3 the recorded inflow exceeded the balance by 2.0 m^3/s on average, so the reconstructed inflow, if anything, understates the late-season decline reported below.

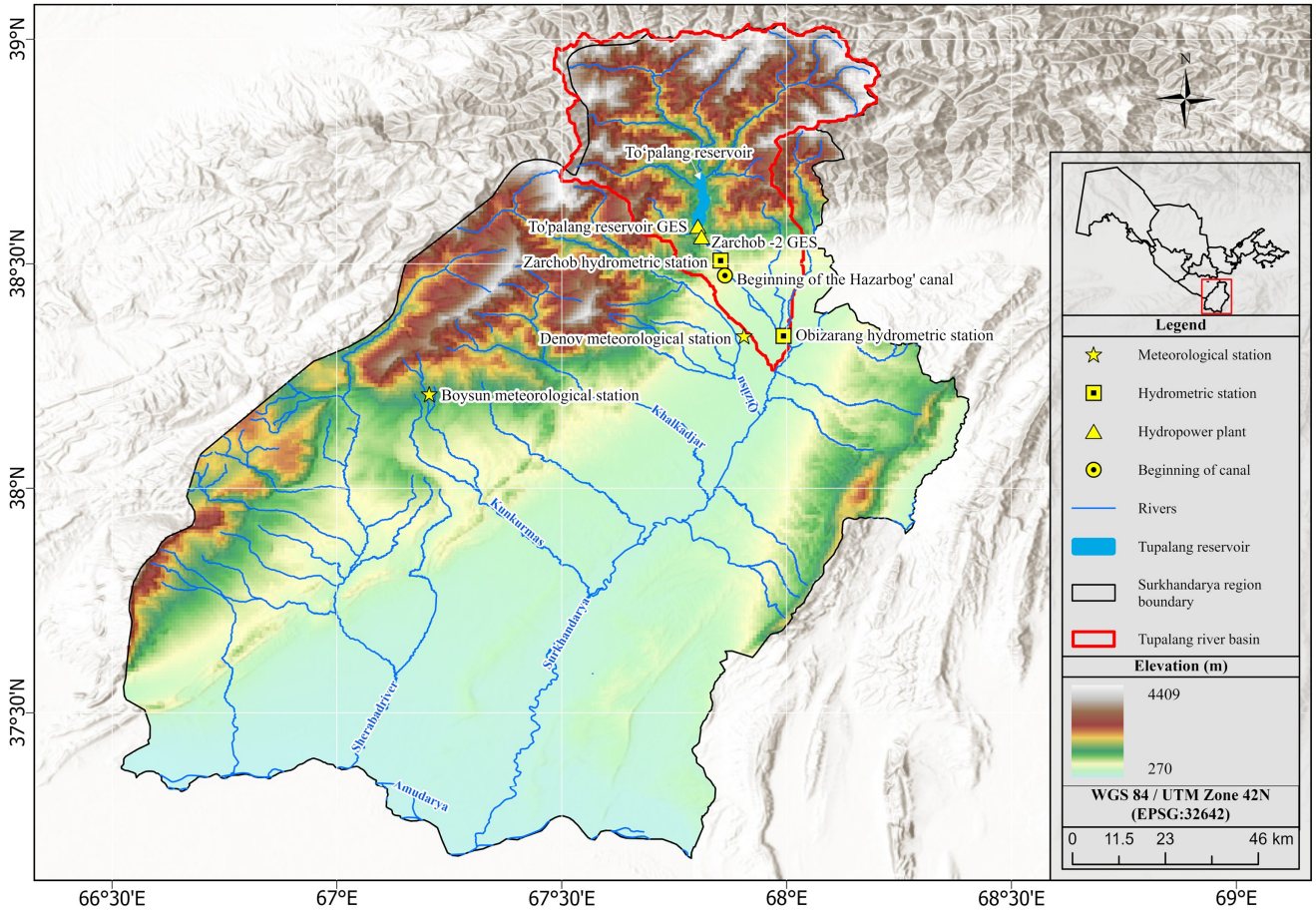

Figure 1. The Topalang River basin to its confluence (3080 km^2) within Surkhandarya Region, Uzbekistan, showing the Tupalang reservoir hydropower plant at the dam, the Zarchob-2 hydropower plant, the Zarchob and Obizarang gauging stations, the head of the Hazarbog canal and the Baysun and Denov meteorological stations. Inset: location within Uzbekistan. The reservoir is shown in blue. On the map, GES denotes a hydropower plant, and To'palang and Boysun are the Uzbek spellings of Tupalang and Baysun.

Table 1. Data used in the study.

Series	Period	Time Step	Source (Type)
Natural discharge, Topalang–Zarchob gauge	1930–1985	Monthly	Uzhydromet (measured)
Discharge below the dam, Topalang–Zarchob gauge	1986–2014	Monthly	Uzhydromet (measured)
Reservoir inflow, reconstructed from release and storage change	1991–2024	Monthly; 10-day from 2009	Reservoir operator (derived)
Reservoir release	1990–2024	Daily	Reservoir operator (measured)
Reservoir storage	2009–2025	10-day	Reservoir operator (measured)
Annual maximum storage	1986–2024	Annual	Reservoir operator (measured)
Elevation–volume table	824–974 m	–	Reservoir operator (survey)
Air temperature, Baysun station	1933–2025	Monthly	Pogoda i Klimat archive (measured)
Snow-covered area above the dam (2200 km^2)	2000–2025	Daily	MODIS, processed with MODSNOW (satellite)
Precipitation and air temperature, MERRA-2 reanalysis	1981–2025	Monthly	NASA POWER (reanalysis)

Excluded and corrected observations are listed in Table S1. Inflow is computed by the operator from release, storage change, evaporation and seepage; the reanalysis series is the mean of four grid cells over the upper catchment.

The Zarchob gauge, opened in November 1927, lies about 1 km below the dam at 38.577° N, 67.798° E. Since the reservoir was built, it has measured only the water released from it. Its record agrees with that role. Over 1991–2005 its monthly values correlate at 0.988 with release and at 0.936 with inflow; over 2006–2014 the figures are 0.978 and 0.965 (Figure 2). Two values for 2011 had been entered with a misplaced decimal point, 6.72 and 5.21 m^3/s in place of 67.2 and 52.1 m^3/s for April and August, and were corrected. The gauge also registers the winter shutdowns of the outlet. In the six months up to 2014 in which the operator recorded zero release on at least 90% of days, all of them in Phase 2, Zarchob still measured 1.1 to 5.5 m^3/s, so a closed outlet did not leave the channel dry. A local study places the gauge 0.2 km above Zarchob village [25]. Its record before 1986 is therefore natural flow, and its record from 1986 is a measure of regulated flow kept independently of the operator. Over 1991–1997, when storage never exceeded 77 × 10^6 m^3 and the reservoir passed most water through, Zarchob ran on average 4.1% above the reservoir's inflow record: 4.9% in April–July, 3.6% in August–October and nil in November–March. With little storage in those years and no tributary over the kilometre between dam and gauge, the difference mainly reflects the two gauging programmes. For the years before 2009, for which no ten-day storage records were available to us, this agreement is the check on the reconstructed inflow. The Zarchob record available to us ends in 2014, so no comparison of this kind can be made for Phase 3. The Obizarang gauge (Figure 1) could not serve as a further check. Its annual flow fell steadily relative to Zarchob long before the dam was built, from 0.84 of the Zarchob flow in 1930–1939 to 0.51 in 1976–1985, so its record is not homogeneous with the natural Zarchob series.

Several data problems were handled by exclusion rather than repair. The operator's records for May and June 2011 duplicate those of 2010 day for day, whereas the Uzhydromet record for the two years differs; May 2011 inflow and May–June 2011 release were removed. Daily release for December 2024 repeats that of June 2024 value for value, while the operator's ten-day record gives 17 to 30 m^3/s for that month, so it was removed as well. Daily release

is missing for 2004 and for July to November 2024, so release-based annual indicators stop in 2023 and omit 2004. Release is recorded as exactly zero on some days in every phase, mainly in January–February and September–December. In operating practice the gates are closed when there is no demand downstream, so that water is stored for winter generation, and we read these values as closures. Because the records themselves do not say so, all results that depend on release were also recomputed with days of 0.5 m^3/s or less treated as missing, requiring at least 10 valid days for a monthly mean. The 2025 annual inflow appears with three different values in the material received, and 2025 was left out of annual inflow analyses. The Baysun temperature record shows a fall of about 2 °C in summer temperature between the early 1950s and the early 1960s, with no counterpart in spring. We attribute it to a change in station siting or practice, and temperature analyses therefore begin in 1961. The precipitation series supplied to us, from the Denov station, was not analysed because of long gaps and implausible annual totals, and reanalysis precipitation was used instead. Table S1 lists every excluded and corrected observation.

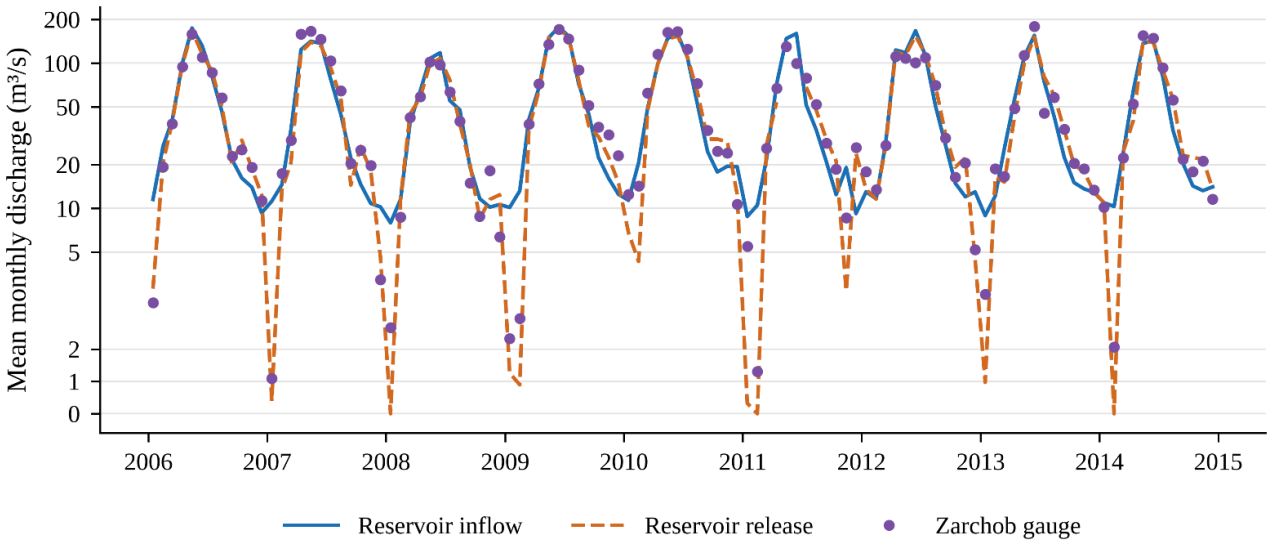

Figure 2. Mean monthly discharge at the Zarchob gauge, about 1 km below the dam, compared with the operator's reconstructed reservoir inflow and release, 2006–2014. The vertical axis is logarithmic above 5 m^3/s and linear below. Zarchob values for April and August 2011 are shown after correction of a misplaced decimal point.

2.3. Regulation Phases and Degree of Regulation

We divide the regulated period into three phases using the operator's licensing dates and the observed annual maximum storage. Phase 1 (1986–2005) covers construction-era impoundment, with annual maximum storage of 10 to 100 × 10^6 m^3. Phase 2 (2006–2016) begins with the first hydropower units, and storage rose to 229 × 10^6 m^3. Phase 3 (2017–2024) begins after storage was licensed at 380 × 10^6 m^3 and includes the raising to 500 × 10^6 m^3 in 2023; annual maximum storage ranged from 253 × 10^6 m^3 in 2021 to 417 × 10^6 m^3 in 2024, the year after the higher licence. In 2019 storage rose above the licensed 380 × 10^6 m^3, to 400 × 10^6 m^3 in the annual record and 433 × 10^6 m^3 in the ten-day record. The dam had already been raised in steps and could hold that volume before the higher licence of 2023; DOR uses the annual record. Because daily release starts in 1990, release-based results for Phase 1 refer to 1990–2005.

To express regulation on a continuous scale we adapt the degree of regulation (DOR) of Grill et al. [5], the ratio of reservoir storage capacity to the mean annual natural flow volume. Because the licensed capacity changed only twice, we use the observed annual

maximum storage instead, and the natural volume is the 1930–1985 mean discharge at Zarchob, 52.6 m^3/s, or 1660×10^6 m^3 per year. Observed maximum storage also depends on the inflow of each year, so DOR in this form mixes capacity with water availability, a confounding that we test directly. The records available to us give a licensed capacity only from December 2016. As a check, we therefore also computed DOR for 2017–2024 from the licensed capacities of 380 and 500×10^6 m^3 (22.9% and 30.1%), keeping the observed maximum for earlier years, when the dam was being raised in steps.

2.4. Trend and Change-Point Tests

Monotonic trends were tested with the Mann–Kendall test [26] and their magnitude estimated with the Sen slope and its 95% confidence interval [27]. Where the lag-1 autocorrelation of the Sen-detrended series was significant at the 10% level, the test was applied after trend-free pre-whitening [28]; the Sen slope was always computed on the original series. A single change point was located with the Pettitt test [29]. Tests were run on annual and seasonal discharge (April–July, August–October and November–March), on spring (March–May) and summer (June–August) temperature, and on the April–June and February–April snow-covered area.

2.5. Separating the Reservoir Signal from the Inflow Signal

Because release and storage are recorded at the same structure, and inflow is reconstructed from them for the same years, the change in each month between natural flow and regulated release can be split into two parts. For month m in phase k, the total change is the phase-mean release minus the natural mean. The first part, inflow minus natural mean, captures differences in water arriving at the reservoir; it combines climate variability with any difference between the Zarchob gauge and the operator's records. The second part, release minus inflow, is the operational signature of the reservoir. Since inflow is reconstructed as release plus storage change plus evaporation and seepage, this part equals the monthly change in storage with its sign reversed, less those losses and apart from errors in the records. It therefore rests on measured release and water level rather than on a separate estimate of inflow. Means were taken over the years in which both inflow and release were available for that month. A monthly mean of daily release required at least 25 days of record, and a seasonal ratio was formed only when every month of the season was present in both series. Natural annual discharge uses the 56 published annual values for 1930–1985, whereas seasonal natural values, flow-duration curves and the Range of Variability Approach use the 52 years with all twelve months. In the inflow record only May 2011 is missing. The April–July trend test averaged the other three months of that year, and leaving 2011 out changes the result little (Sen slope -9.0 instead of -8.5 m^3/s per decade, $p = 0.13$). Annual inflow is the operator's published annual value, which we kept for 2011. For each year from 1991 to 2024 we also computed the ratio of release to inflow volume for April–July, August–October and November–March and related these ratios to DOR with Spearman's rank correlation. Because DOR, the ratios and inflow all change over time, we checked the result in two ways: with partial rank correlations controlling for the seasonal inflow of each year, and with a regression of each ratio on phase indicators and seasonal inflow. The ratios and the reconstructed inflow share the release term, so controlling for inflow may absorb part of the reservoir's effect, and both checks lean towards understating it. To isolate the effect of regulation on flood peaks, we also compared, for 2009–2024, the largest ten-day and thirty-day release of each year with the largest ten-day and thirty-day inflow of the same year.

2.6. Hydrologic Alteration

Alteration relative to natural conditions was assessed with the Range of Variability Approach [11]. For each calendar month, we set the target range as the 25th to 75th percentile of the 52 complete natural years (1930–1985). Richter et al. [11] used the mean plus or minus one standard deviation by default but noted that the indicators are rarely normally distributed; percentile bounds avoid that assumption for skewed snowmelt flows, and the 25th to 75th percentile range was later used for this purpose by Richter et al. [30]. For each phase, hydrologic alteration was calculated as the observed minus the expected frequency of years falling inside the target range, divided by the expected frequency of 0.5. Absolute values up to 0.33 were classed as low, 0.33 to 0.67 as moderate and above 0.67 as high [30]. The analysis was applied separately to inflow and to release, so that departures already present in the water reaching the reservoir can be distinguished from those added by its operation. Natural daily flow is not available, so daily indicators were computed for release only and compared across phases. They were the annual 7-day and 30-day maxima, the annual 7-day minimum, the number of days with release of 0.5 m^3/s or less, the day of year of the annual maximum, and flow-duration curves [31].

Seasonal ecodeficit and ecosurplus [32,33] express the same comparison as a loss or gain of water. For a given season, the ecodeficit is the area below the reference flow-duration curve and above the altered curve, divided by the area under the reference curve. The ecosurplus is the area above the reference curve and below the altered one, divided by the same quantity. Both are therefore fractions of mean seasonal flow. Gao et al. [33] used median annual curves of daily flow. Natural flow at Zarchob exists only as monthly means, so we built period-of-record curves from the monthly values of each season. The seasons follow the Topalang regime rather than the North American seasons of the original studies: April–July for the snowmelt flood, August–October for the recession and November–March for winter base flow. Three comparisons were made in each phase: inflow against natural flow, release against natural flow, and release against inflow in the same months. The last isolates what the reservoir itself added. Total seasonal ecochange, the sum of the seasonal ecodeficits and ecosurpluses [33], summarises each comparison in one number.

Release was also compared with the environmental-flow benchmark that Mahmood et al. [1] adopted from the Tennant method across the Amu Darya basin. It sets 20% of naturalised mean annual flow in the low-flow months (October–March) and 40% in the high-flow months (April–September), the class that Tennant [34] rated good. Taking the natural mean of 52.6 m^3/s at Zarchob as the naturalised mean gives thresholds of 10.5 and 21.0 m^3/s. For natural flow, inflow and release we counted the share of months below these thresholds. For release we also counted the days per year on which October–March flow fell below 10.5 m^3/s, using years with at least 170 days of record in those months. To test the choice of threshold, the counts were repeated with 10% and 30% of the natural mean and with the flows exceeded 90% and 95% of the time in natural October–March months (10.1 and 9.7 m^3/s).

2.7. Climate Drivers and Flow Frequency

Relations among spring temperature, April–June snow-covered area and annual inflow were measured with Pearson correlation, for 2000–2024 where snow cover is available, for 1991–2024 between temperature and August–October inflow, and for 1961–1985 and 1991–2024 combined between spring temperature and annual discharge. The last comparison joins two gauges and two eras and is reported as indicative only. Annual flow frequency was described with a Pearson type III distribution fitted by moments, with a bias-corrected skewness coefficient, separately for natural flow (1930–1985) and for inflow (1991–2024); fit was checked with the Kolmogorov–Smirnov statistic and the probability-plot correla-

tion coefficient. Because the parameters are estimated from the same data, the standard Kolmogorov–Smirnov probability is too lenient. Both probabilities were therefore obtained from 5000 samples drawn from the fitted distribution, with the parameters estimated again for each sample. Data processing and statistical analyses were conducted using Python 3.13.18 (Python Software Foundation, Wilmington, DE, USA) with the NumPy 2.5.3, pandas 3.0.5, SciPy 1.18.1, pymannkendall 1.4.3 and Matplotlib 3.11.2 libraries. The analysis scripts are provided as Supplementary File S1.

2.8. Uncertainty and Sensitivity Analyses

Because inflow is reconstructed, errors in the release and storage records pass into it. We propagated them with a Monte Carlo simulation of 2000 runs. In each run, a storage-reading error was added at the end of every month, so that it entered the inflow of that month and the next with opposite signs, and the release of each year was scaled by a random bias with a standard deviation of 5%, applied to release and to the inflow built from it. The storage error was sized from the ten-day water-balance residual: its standard deviation was taken as the mean absolute residual times $\sqrt{(\pi/2)}$ and reduced by $\sqrt{3}$ for a monthly mean of three ten-day values. A second, deliberately conservative set of runs applied the largest residual, that of Phase 3, to every phase without the reduction. Phase 1 has no ten-day records and was given the residual of all years. A bias common to release and inflow cancels in their ratio, so the ratios respond mainly to the storage error. For each run we recomputed the seasonal ratios and the total seasonal ecochange of release against inflow, and we report the 2.5th and 97.5th percentiles (Table S2). Random errors of this kind do not represent a systematic error in the elevation–volume table. We therefore also recomputed the inflow of 2009–2024 from the ten-day records with all storage above 0, 100 or 200 × 10^6 m^3 raised or lowered by 5% and by 10% (Table S6).

The sampling uncertainty of each phase, which matters most for the eight years of Phase 3, was estimated by resampling whole years with replacement within each phase (2000 bootstrap samples [35]). The natural reference was also split into 1930–1957 and 1958–1985 to see whether the alteration measures depend on the reference period. Because the degree of regulation and calendar year rise together, we added partial rank correlations of the seasonal ratios with DOR controlling for year and a regression of each ratio on both. To weigh precipitation as an alternative explanation of the inflow decline, we used monthly precipitation and 2 m air temperature from the MERRA-2 reanalysis [36], obtained through the NASA POWER service [37] for the four grid cells (0.5° × 0.625°) that cover the upper catchment, centred at 38.5° and 39.0° N and at 67.5° and 68.125° E (cell elevations 1380–3050 m). Its water-year totals, about 300 mm, are far below the natural runoff depth of about 750 mm, so the series understates mountain precipitation and was used only as an index of year-to-year variation, summed over water years from October to September. As a second product we took daily precipitation from the ERA5 reanalysis [38] at four grid points over the upper catchment (38.75° and 39.0° N, 67.75° and 68.0° E; 1460–3410 m), obtained through the Open-Meteo archive and summed over the same water years. Its totals, about 1240 mm, exceed the runoff depth. Finally, we estimated what a minimum release equal to the low-flow benchmark would have required: for each year, the volume needed to raise every October–March day below 10.5 m^3/s to that value.

2.9. Use of AI Tools

Claude (Anthropic, San Francisco, CA, USA) and GPT (OpenAI, San Francisco, CA, USA) were used to assist with developing and checking Python code for data processing, statistical analysis, and figure preparation, as well as drafting and editing the English text. DeepL (DeepL SE, Cologne, Germany) was used for translation and Grammarly

(Grammarly Inc., San Francisco, CA, USA) for language editing. All four are online services and were used in the versions available in October and November 2026. None of these tools was used to generate, impute, or modify research data. The authors determined the study design and analytical approach, interpreted the results, and formulated the conclusions. They reviewed and verified the AI-assisted code, analytical outputs, translations, and text and take full responsibility for the final manuscript. All code was executed and checked by the authors, every reported numerical result was reproduced using the analysis scripts, and every reference was checked against its original source.

3. Results

3.1. Natural Flow and Reservoir Inflow

Natural annual discharge at Zarchob averaged 52.6 m^3/s over 1930–1985 and showed no trend (Figure 3a; Table 2). Its Sen slope was 0.3 m^3/s per decade, with a 95% confidence interval from −1.2 to 1.8, and the Pettitt test found no change point. No season showed a significant trend in the natural record.

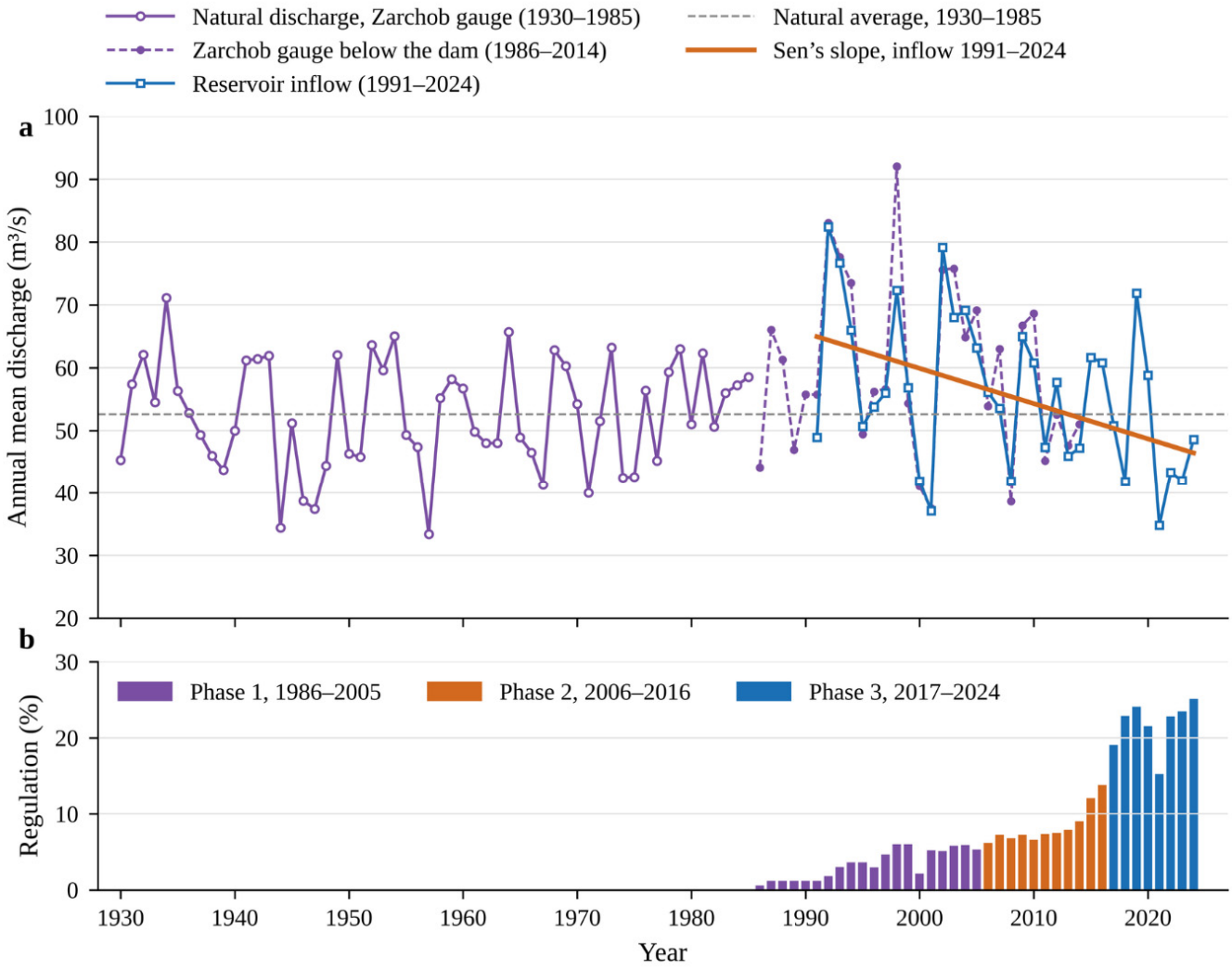

Figure 3. Annual discharge and degree of regulation. (**a**) Natural annual mean discharge at the Zarchob gauge (1930–1985), discharge at the same gauge below the dam (1986–2014), reconstructed reservoir inflow (1991–2024) and the Sen slope of inflow; the dashed line is the natural average. (**b**) Degree of regulation, the annual maximum storage as a percentage of the natural mean annual flow volume, by regulation phase.

Table 2. Trend tests for discharge, air temperature and snow cover.

Series	Period	n	Mean	MK Z	*p*	Sen slope per Decade (95% CI)	Unit
Natural annual discharge (Zarchob)	1930–1985	56	52.6	0.42	0.677	0.30 (−1.24, 1.81)	m^3/s
Reservoir inflow, annual	1991–2024	34	56.2	−2.25	0.024	−5.61 (−10.25, −0.74)	m^3/s
Natural discharge, April–July	1930–1985	52	114.6	0.38	0.705	0.85 (−3.38, 4.49)	m^3/s
Reservoir inflow, April–July	1991–2024	34	120.9	−1.57	0.116	−8.51 (−19.87, 3.59)	m^3/s
Natural discharge, August–October	1930–1985	52	30.6	−0.09	0.931	−0.04 (−1.27, 1.07)	m^3/s
Reservoir inflow, August–October	1991–2024	34	31.9	−3.59	<0.001	−5.93 (−8.91, −2.99)	m^3/s
Natural discharge, November–March	1930–1985	52	16.2	0.99	0.322	0.35 (−0.27, 0.93)	m^3/s
Reservoir inflow, November–March	1991–2024	34	18.8	−2.05	0.041	−1.63 (−2.92, −0.07)	m^3/s
Baysun air temperature, March–May	1961–1990	30	12.8	−0.32	0.748	−0.06 (−0.48, 0.39)	°C
Baysun air temperature, March–May	1991–2025	35	13.8	3.82	<0.001	1.00 (0.57, 1.37)	°C
Baysun air temperature, June–August	1961–1990	30	24.0	0.34	0.735	0.05 (−0.33, 0.33)	°C
Baysun air temperature, June–August	1991–2025	35	24.8	4.74	<0.001	0.88 (0.59, 1.03)	°C
Baysun air temperature, annual	1991–2025	35	14.0	4.77	<0.001	0.62 (0.41, 0.81)	°C
Snow-covered area, April–June	2000–2025	26	28.5	−0.09	0.930	−0.38 (−4.81, 4.46)	%
Snow-covered area, February–April	2000–2025	26	68.6	−0.88	0.378	−1.72 (−5.01, 2.51)	%

MK, Mann–Kendall test; trend-free pre-whitening applied where lag-1 autocorrelation was significant (natural discharge November–March).

Inflow to the reservoir since 1991 has behaved differently. It averaged 59.6 m^3/s in 1991–2008, well above the natural mean, then fell to 52.4 m^3/s in 2009–2024, close to the natural mean, and 50.3 m^3/s in 2016–2024. The Zarchob gauge below the dam, which measures the released water independently of the operator, shows the same course for as long as its record lasts: 62.1 m^3/s in 1991–2008 and 55.3 m^3/s in 2009–2014, against 59.6 and 54.0 m^3/s for inflow in the same years ($r = 0.92$ between annual values, 1991–2014; Figure 3a). The two records differ most in 1998, when Zarchob gives 92 m^3/s and the operator 72 m^3/s. Over 1991–2024 the decline amounts to 5.6 m^3/s per decade (95% CI −10.3 to −0.7; $p = 0.024$). The fall is concentrated in late summer and autumn. August–

October inflow, which averaged 30.6 m^3/s under natural conditions, was 23.4 m^3/s in 2017–2024. It declined by 5.9 m^3/s per decade ($p < 0.001$), with a change point in 2011, and November–March inflow by 1.6 m^3/s per decade ($p = 0.041$), whereas the April–July decline was not significant ($p = 0.116$). The change point does not coincide with a stage in the raising of the dam, since annual maximum storage stayed between 109 and 131 × 10^6 m^3 from 2009 to 2013, and summer temperature at Baysun has its change point in the same year (Table 2). Frequency analysis gives a natural median annual flow of 52.9 m^3/s and a 95% exceedance flow of 37.9 m^3/s; for inflow since 1991 the corresponding values are 55.6 and 37.1 m^3/s, with a larger coefficient of variation (0.22 against 0.16) (Table 3).

Table 3. Pearson type III fit and annual discharge quantiles.

Statistic	Natural, 1930–1985	Reservoir Inflow, 1991–2024
Years	56	34
Mean Q_0 (m^3/s)	52.6	56.2
Coefficient of variation Cv	0.16	0.22
Skewness Cs	−0.20	0.31
Kolmogorov–Smirnov p (simulated)	0.54	0.94
Probability-plot correlation coefficient (simulated p)	0.993 (0.41)	0.995 (0.92)
Q exceeded with probability 1%	71.5	87.7
Q exceeded with probability 5%	66.3	77.5
Q exceeded with probability 10%	63.5	72.4
Q exceeded with probability 25%	58.6	64.2
Q exceeded with probability 50%	52.9	55.6
Q exceeded with probability 75%	46.9	47.6
Q exceeded with probability 90%	41.4	40.9
Q exceeded with probability 95%	37.9	37.1
Q exceeded with probability 99%	31.2	30.4

Moment estimates; Cs bias-corrected. Quantiles in m^3/s. Goodness-of-fit probabilities from 5000 samples simulated from the fitted distribution, with parameters estimated again for each sample.

3.2. Growth of Regulation

The degree of regulation rose in steps (Figure 3b). It stayed between 0.6% and 6.0% of the natural annual volume in Phase 1, reached 6.2% to 13.8% in Phase 2 and lay between 15.2% and 25.1% in Phase 3. The first major increase occurred between 2016 and 2017, when annual maximum storage went from 229 to 317 × 10^6 m^3, and then to 380 × 10^6 m^3 in 2018. Within Phase 3, storage also varied with water supply: in the dry year 2021 it reached only 253 × 10^6 m^3, and it rose to 379 × 10^6 m^3 in 2022.

3.3. Seasonal Redistribution of Flow

In Phase 1 the reservoir passed most water through (Figure 4a). Mean release and mean inflow differed by less than 7 m^3/s in every month except April, when release exceeded inflow by 17.1 m^3/s. The ratio of release to inflow was 1.03 in April–July and 1.00 in November–March, but already 1.14 in August–October (Table 4). Storage explains only part of that excess. Release exceeded inflow in August–October by 39 × 10^6 m^3 a year on average, against a mean annual maximum storage of 67 × 10^6 m^3, but the excess was larger than the

maximum storage in three of the 14 years (1994, 2000 and 2005). Annual release in this phase was also 4% above annual inflow, about the difference found between the Zarchob and operator records, and at Zarchob the flow of August–October was only 3% above inflow. The Phase 1 ratio therefore contains a mismatch between the release and inflow records and should be read as close to 1. In Phases 2 and 3, annual release and annual inflow agree to within 2%. In Phase 1, both inflow and release sat above the natural range in January, March, June and from August to December, so most of the departure from natural flow came from the water arriving rather than from the dam (Figure 4a).

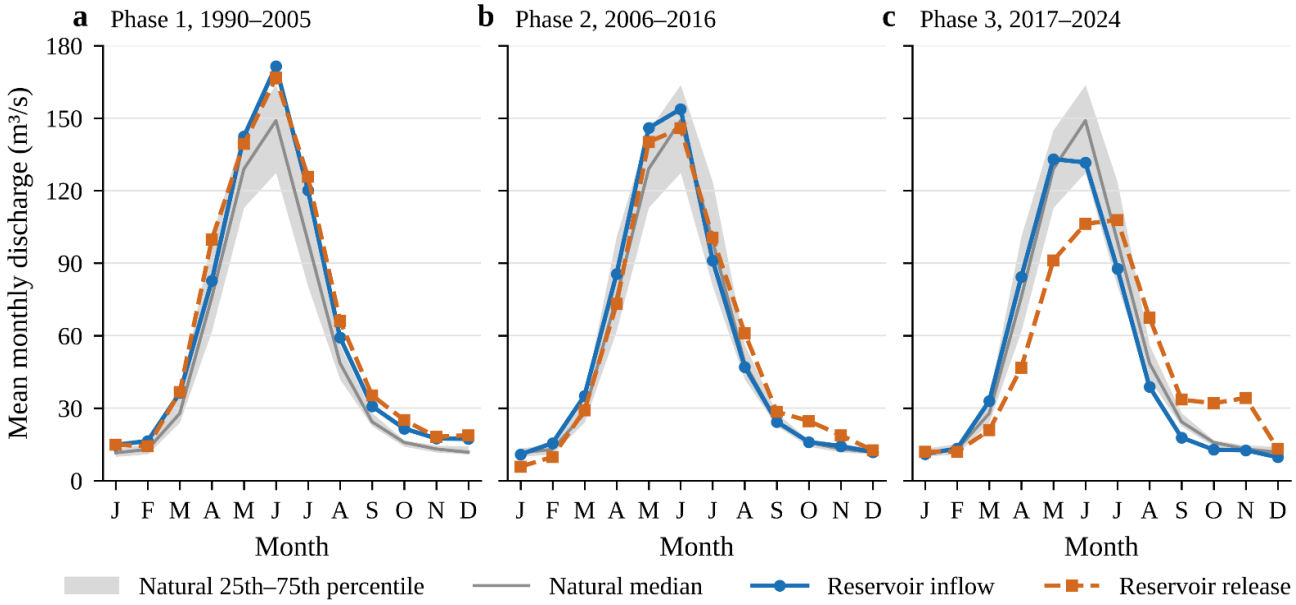

Figure 4. Mean monthly inflow and release in (**a**) Phase 1, (**b**) Phase 2 and (**c**) Phase 3, against the natural median and 25th–75th percentile range (1930–1985).

Table 4. Reservoir operation and release indicators by regulation phase.

Indicator	Phase 1 (1990–2005)	Phase 2 (2006–2016)	Phase 3 (2017–2024)
Degree of regulation (%)	1.2–6.0	6.2–13.8	15.2–25.1
Mean annual maximum storage (10^6 m^3)	66	138	362
Release/inflow, April–July	1.03	0.97	0.80
Release/inflow, August–October	1.14	1.32	1.90
Release/inflow, November–March	1.00	0.87	1.15
Mean annual 7-day maximum release (m^3/s)	204	196	147
Mean annual 30-day maximum release (m^3/s)	179	159	127
Mean annual 7-day minimum release (m^3/s)	4.9	0.5	2.4
Days per year with release $\leq$ 0.5 m^3/s	22	44	13
Mean day of year of maximum release	165	146	159

Release/inflow ratios are means of annual paired ratios (1991–2024). Degree of regulation is given for the years with daily release (Phase 1 from 1990). Daily indicators use 1990–2023 (Phase 3: 2017–2023), without 2004; zero-release days are included as recorded. Maxima and the day of the maximum omit 2011, whose May–June release was excluded.

In Phase 2 the reservoir began to hold back part of the spring rise and return it later (Figure 4b). Release fell short of inflow by 12.4 m^3/s in April and by 5.8 to 8.0 m^3/s from May to June, and exceeded it by 9.5 m^3/s in July and 13.9 m^3/s in August (Figure 5a). Winter release was also lower than inflow, by about 5 to 6 m^3/s from January to March.

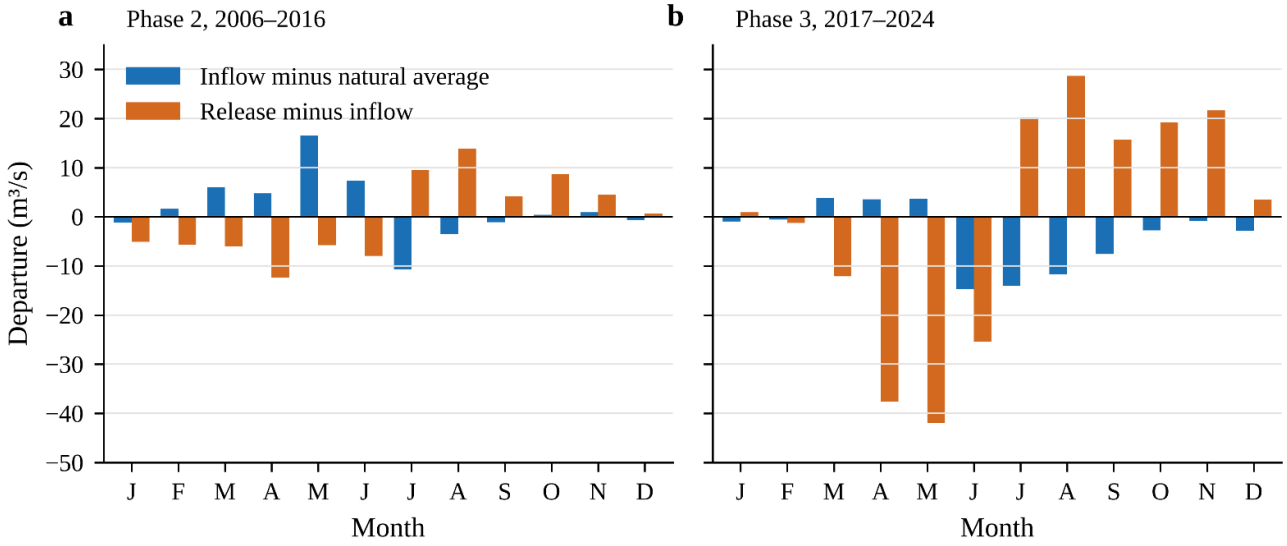

Figure 5. Monthly departure of release from natural flow split into the inflow component (inflow minus natural average) and the reservoir component (release minus inflow) for (**a**) Phase 2 and (**b**) Phase 3.

In Phase 3 the redistribution became the dominant feature of the regime (Figures 4c and 5b). Release was below inflow by 12.1 m^3/s in March, 37.6 m^3/s in April, 41.9 m^3/s in May and 25.4 m^3/s in June. It was above inflow by 15.7 to 28.6 m^3/s in every month from July to November, most of all in August, and by 3.5 m^3/s in December. Mean April–June release was 81.4 m^3/s against an inflow of 116.4 m^3/s and a natural mean of 118.9 m^3/s. Mean August–October release was 44.4 m^3/s, almost double the inflow of 23.2 m^3/s in the same years and well above the natural mean of 30.6 m^3/s. The inflow component in the same phase was small in spring and negative from June to September, by 7.6 to 14.8 m^3/s (Figure 5b). Across Phase 3 the ratio of release to inflow averaged 0.80 in April–July and 1.90 in August–October (Table 4).

3.4. Redistribution and Degree of Regulation

Year by year, the seasonal ratios followed the degree of regulation (Figure 6). The April–July ratio fell as DOR rose (Spearman $\rho = -0.69$, $p < 0.001$, $n = 31$). It ranged from 0.88 to 1.17 at DOR below 6% and from 0.71 to 0.89 at DOR above 15%. The August–October ratio rose with DOR ($\rho = 0.76$, $p < 0.001$, $n = 32$), from 0.86–1.55 at DOR below 6% to 1.36–2.27 above 15%. The November–March ratio showed no relation with DOR ($\rho = -0.01$, $p = 0.96$). The relations held when the seasonal inflow of each year was held constant (partial $\rho = -0.68$ for April–July and 0.66 for August–October, both $p < 0.001$). In a regression on phase and seasonal inflow, Phase 3 lowered the April–July ratio by 0.23 and raised the August–October ratio by 0.71 relative to Phase 1 (both $p < 0.001$). Seasonal inflow itself had no detectable effect ($p = 0.95$ and 0.53). With DOR for 2017–2024 taken from licensed capacity, the correlations were almost identical ($\rho = -0.69$ and 0.75, both $p < 0.001$). Calendar time is harder to separate, because DOR and year rose together ($\rho = 0.96$). Controlling for year weakened the rank correlations to −0.35 for April–July ($p = 0.05$) and 0.17 for August–October ($p = 0.35$). In a regression on both DOR and year,

however, DOR remained significant for both seasons ($p = 0.001$ and $p < 0.001$) and year did not ($p = 0.48$ and 0.85).

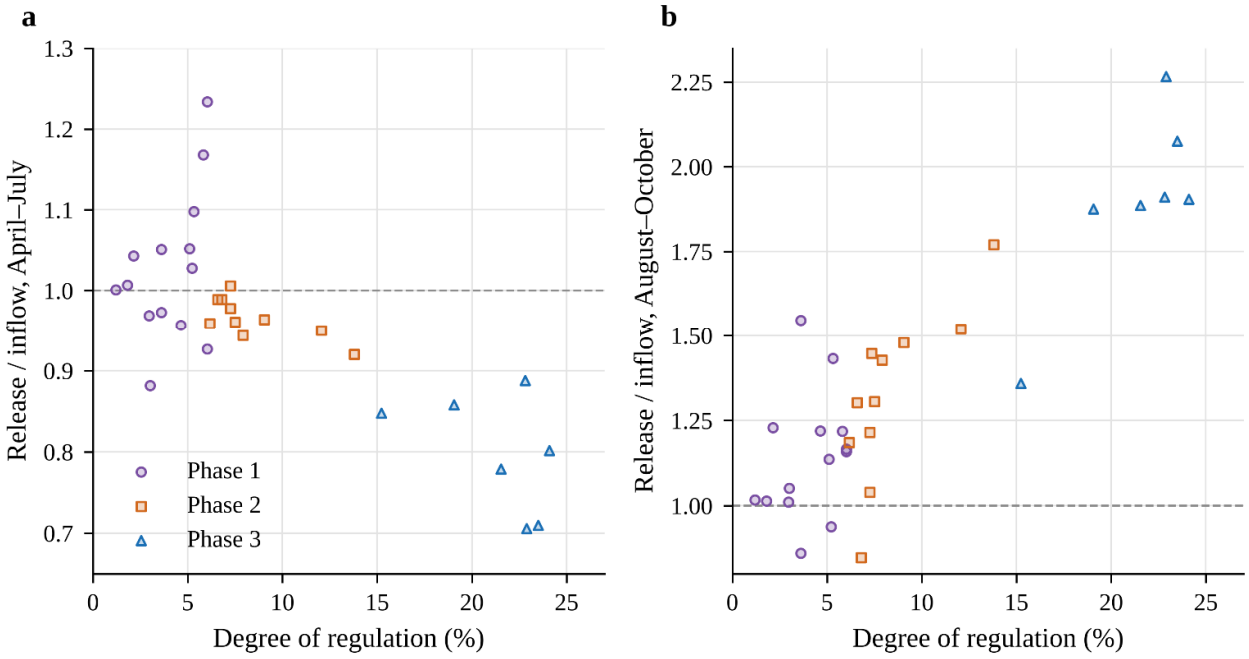

Figure 6. Annual ratio of release to inflow against degree of regulation for (**a**) April–July and (**b**) August–October, 1991–2024. The dashed line marks equal release and inflow.

3.5. Daily Release

Daily release shows a marked loss of flood peaks (Figure 7; Table 4). The mean annual 7-day maximum fell from 204 m^3/s in 1990–2005 to 196 m^3/s in 2006–2016 and 147 m^3/s in 2017–2023, and the 30-day maximum from 179 to 159 and then 127 m^3/s. Part of this fall reflects lower inflow peaks in recent years. Measured against the same year's inflow, the largest ten-day release was 0.95 of the largest ten-day inflow in 2009–2016 and 0.83 in 2017–2024; for thirty-day peaks the ratios were 0.94 and 0.84. The annual maximum occurred on average on day 165 in Phase 1, day 146 in Phase 2 and day 159 in Phase 3. The date of a single daily maximum varied widely between years (standard deviation 15 to 41 days), so these means differ by less than their scatter, and the Phase 1 mean is raised by one year whose maximum fell in October. The later maximum of Phase 3 nonetheless did not come from later snowmelt. In the ten-day records the inflow peak fell in late May or early June in both phases, and the monthly inflow peaked in May in five of eight years of Phase 3, against three of ten in Phase 2. Release, by contrast, peaked on average 0.4 ten-day periods after inflow in 2009–2016 and 1.6 periods, about 16 days, after it in 2017–2024. The reservoir held back the first part of the melt and released its maximum later. Recorded low releases were most extreme in Phase 2, when the mean annual 7-day minimum was 0.5 m^3/s and release was 0.5 m^3/s or less on 44 days per year, all of them recorded as zero and mostly in January and February. The corresponding figures were 4.9 m^3/s and 22 days in Phase 1, when these days fell mainly in September–December, and 2.4 m^3/s and 13 days in Phase 3, of which 10 were recorded as zero. Treating these days as missing raised the August–October ratio of Phase 1 from 1.14 to 1.28 and of Phase 2 from 1.32 to 1.37, and the November–March ratios of all phases by 0.10 to 0.16. The April–July ratios and the Phase 3 August–October ratio were almost unchanged (0.80 and 1.91 against 0.80 and 1.90). The flow-duration curves for the three phases cross at roughly the median (Figure 7). In Phase

3, flows exceeded less than about 50% of the time were lower than in Phase 1, while the curve flattens in the middle range, where the autumn releases sit.

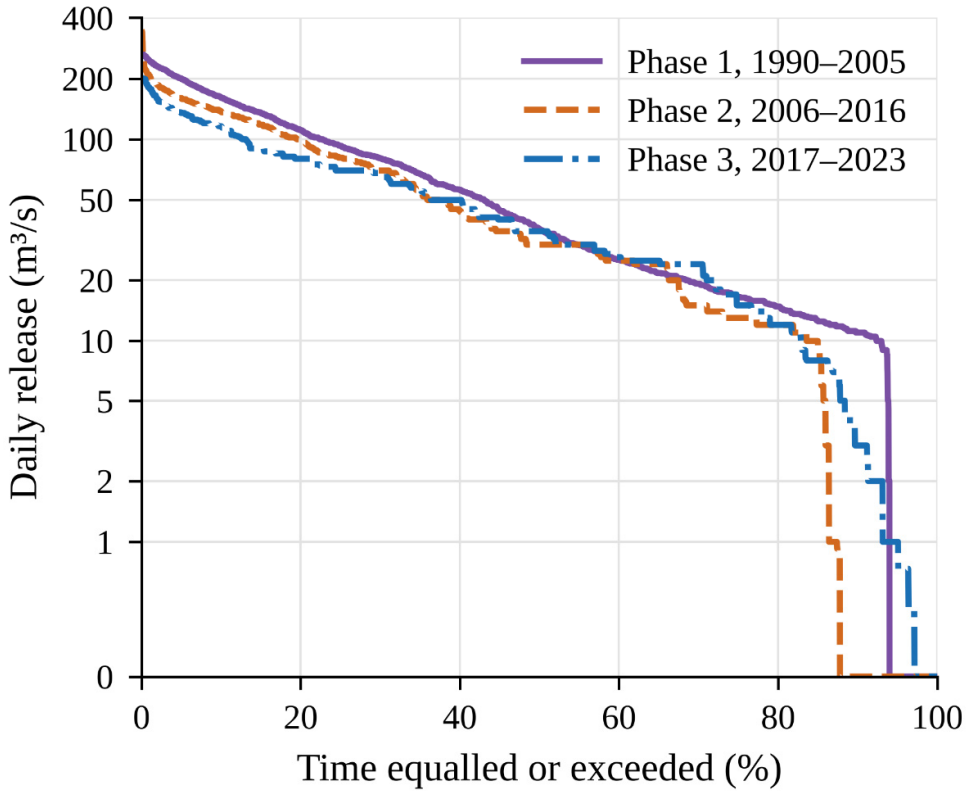

Figure 7. Flow-duration curves of daily release by regulation phase. The vertical axis is logarithmic above 1 m^3/s and linear below, so that zero-release days are shown.

3.6. Alteration Relative to the Natural Range

Measured against the natural 25th to 75th percentile range, alteration of monthly release increased from Phase 1 to Phase 3 while alteration of inflow did not (Table 5). Mean absolute hydrologic alteration of release was 0.42 in Phase 1, 0.47 in Phase 2 and 0.65 in Phase 3, and the number of months with high alteration rose from one to two and then seven. For inflow the corresponding means were 0.47, 0.25 and 0.48, with four, zero and two highly altered months. In Phase 3, release was highly altered from September to January and in March and April; in March and from October to December no year of Phase 3 fell inside the natural range. In Phase 1, by contrast, the highly altered months for inflow (August to November) were matched by moderate alteration of release from August to October and high alteration only in November. The result depends little on the reference period. Against the 1930–1957 and 1958–1985 halves of the natural record, the mean absolute alteration of Phase 3 release was 0.56 and 0.63, with six and eight highly altered months (Table S3).

Ecodeficit and ecosurplus show a consistent pattern in terms of water (Table 6). Against inflow in the same months, the reservoir's April–July ecodeficit rose from 0.01 in Phase 1 to 0.04 in Phase 2 and 0.20 in Phase 3, equivalent to about a fifth of mean spring inflow. Its August–October ecosurplus rose from 0.14 to 0.30 and then to 0.88. In winter the reservoir produced a deficit of 0.16 in Phase 2, the phase with the most zero-release days, and a surplus of 0.16 in Phase 3. Total seasonal ecochange attributable to the reservoir rose from 0.25 to 0.53 and then 1.29. The inflow changed differently. Against natural flow, Phase 1 inflow was in surplus in every season (total ecochange 0.75), whereas Phase 3 inflow showed a deficit concentrated in August–October (0.22). Combining the two, Phase 3

release was in deficit in spring (0.24 against natural flow) and in surplus in late summer (0.46) and winter (0.20).

Table 5. Hydrologic alteration of mean monthly discharge relative to the natural 25th–75th percentile range (1930–1985).

Month	Natural Range (m^3/s)	P1 Inflow	P1 Release	P2 Inflow	P2 Release	P3 Inflow	P3 Release
January	10.0–13.3	−0.60	−0.47	+0.45	−0.45	+0.00	−0.75
February	11.0–15.2	−0.47	−0.47	−0.09	−0.45	−0.25	−0.50
March	24.1–34.9	−0.20	−0.20	−0.27	−0.27	−0.50	−1.00
April	61.9–101.0	+0.20	+0.20	+0.45	−0.27	−0.25	−0.75
May	113.0–145.0	−0.33	−0.47	−0.40	−0.40	−0.50	+0.00
June	127.5–163.8	−0.47	−0.47	+0.09	+0.00	−0.50	−0.50
July	80.5–123.5	−0.20	−0.20	−0.09	+0.27	−0.25	+0.14
August	42.0–56.1	−0.73	−0.47	+0.45	−0.64	−0.50	−0.43
September	22.6–28.0	−0.73	−0.60	−0.45	−0.64	−1.00	−0.71
October	14.2–16.8	−0.87	−0.60	−0.09	−1.00	−0.50	−1.00
November	11.8–14.6	−0.73	−0.73	−0.09	−1.00	−1.00	−1.00
December	10.9–14.2	+0.07	−0.20	−0.09	+0.27	−0.50	−1.00

Hydrologic alteration = (observed − expected)/expected frequency of years inside the natural range; expected frequency 0.5. |HA| ≤ 0.33 low, 0.33–0.67 moderate, >0.67 high. P1 1990/1991–2005, P2 2006–2016, P3 2017–2024.

Table 6. Seasonal ecodeficit and ecosurplus by regulation phase.

Comparison	Season	P1 Deficit	P1 Surplus	P2 Deficit	P2 Surplus	P3 Deficit	P3 Surplus
Release vs. inflow	April–July	0.01	0.04	0.04	0.00	0.20	0.00
	August–October	0.00	0.14	0.00	0.30	0.00	0.88
	November–March	0.03	0.03	0.16	0.03	0.04	0.16
	Total	0.25		0.53		1.29	
Inflow vs. natural	April–July	0.01	0.14	0.01	0.04	0.05	0.01
	August–October	0.01	0.27	0.05	0.02	0.22	0.00
	November–March	0.00	0.31	0.01	0.11	0.06	0.08
	Total	0.75		0.25		0.43	
Release vs. natural	April–July	0.00	0.15	0.03	0.02	0.24	0.00
	August–October	0.00	0.36	0.01	0.26	0.01	0.46
	November–March	0.01	0.28	0.13	0.08	0.06	0.20
	Total	0.80		0.52		0.96	

Areas between period-of-record flow-duration curves of monthly mean discharge, as fractions of the area under the reference curve [32,33]. Reference: natural flow 1930–1985, or inflow in the same months for release against inflow. Total, total seasonal ecochange (sum of the three seasonal deficits and surpluses). P1 1990/1991–2005, P2 2006–2016, P3 2017–2024.

Against the environmental-flow benchmark, the low-flow months showed the greatest stress (Table 7). Natural monthly flow fell below 10.5 m^3/s in 13.5% of October–March months and below 21.0 m^3/s in only 2.9% of April–September months. Release fell below

the low-flow threshold in 5.6% of low-flow months in Phase 1, 24.2% in Phase 2 and 17.8% in Phase 3. Phase 3 inflow fell below it more often than release did, in 33.3% of low-flow months, and it also fell below the high-flow threshold in 14.6% of high-flow months, against 4.4% for release. In Phase 3, inflow fell below 10.5 m^3/s in October or November in four of eight years, while release, recorded in seven of them, never did. On a daily basis, October–March release fell below 10.5 m^3/s on 25 days a year in Phase 1 and on 57 and 55 days a year in Phases 2 and 3, three quarters of them in Phase 3 between December and February.

Table 7. Flow below the environmental-flow benchmark of Mahmood et al. [1].

Period	Series	October–March Months <10.5 m^3/s (%)	April–September Months <21.0 m^3/s (%)	October–March Days per Year with Release <10.5 m^3/s
1930–1985	Natural	13.5	2.9	–
Phase 1 (1990/1991–2005)	Inflow	3.3	3.3	–
	Release	5.6	1.1	25
Phase 2 (2006–2016)	Inflow	15.2	4.6	–
	Release	24.2	4.7	57
Phase 3 (2017–2024)	Inflow	33.3	14.6	–
	Release	17.8	4.4	55

Thresholds are 20% (October–March) and 40% (April–September) of the natural mean annual flow at Zarchob, 52.6 m^3/s (the Tennant class rated good, as adopted by Mahmood et al. [1]). Daily counts use 1990–2023 without 2004 and years with at least 170 days of October–March record.

Treating days of 0.5 m^3/s or less as missing changes the low-flow counts more than the seasonal transfers. Counting only days above 0.5 m^3/s in the same years, October–March release fell below 10.5 m^3/s on 8, 14 and 43 days a year in the three phases, and monthly release fell below it in 1.1%, 5.4% and 14.0% of low-flow months. The reservoir's Phase 3 spring ecodeficit and late-season ecosurplus were almost unchanged at 0.20 and 0.90, and total seasonal ecochange still rose across the phases, from 0.40 to 0.59 and 1.35. The Phase 2 winter deficit, by contrast, fell from 0.16 to 0.04, so it rests largely on the zero days.

The pattern does not hinge on the 20% threshold (Table S4). With 10% of the natural mean (5.3 m^3/s), Phase 3 release fell below the threshold on 39 days a year, 27 of them above 0.5 m^3/s, and with 30% (15.8 m^3/s), a level that natural flow itself did not reach in 63% of low-flow months, on 83 days. The natural flows exceeded 90% and 95% of the time in October–March, 10.1 and 9.7 m^3/s, gave 55 days, almost the same as the benchmark. Raising every October–March day of Phase 3 to 10.5 m^3/s would have needed on average 34×10^6 m^3 a year, at most 72×10^6 m^3. That is about 2.2% of the mean annual release of 1520×10^6 m^3 in those years, and between 0.1% and 6.2% of the release of single years. In the same years the reservoir released on average about 108×10^6 m^3 more than it received in October and November. Holding back about a third of that autumn surplus for the winter months would therefore have covered the shortfall in an average year. Season by season, the October–November surplus exceeded the volume needed in the following months in five of the seven years; in the dry years 2021 and 2022 it fell short.

3.7. Temperature, Snow Cover and Inflow

Spring temperature at Baysun showed no trend over 1961–1990 but rose by 1.0 °C per decade over 1991–2025 (95% CI 0.6 to 1.4; $p < 0.001$), with a change point in 2000 (Figure 8a; Table 2). Summer temperature rose by 0.9 °C per decade over the same period. The March–May mean was 12.8 °C in 1961–1990, 13.8 °C in 1991–2025 and 14.9 °C in 2016–2025.

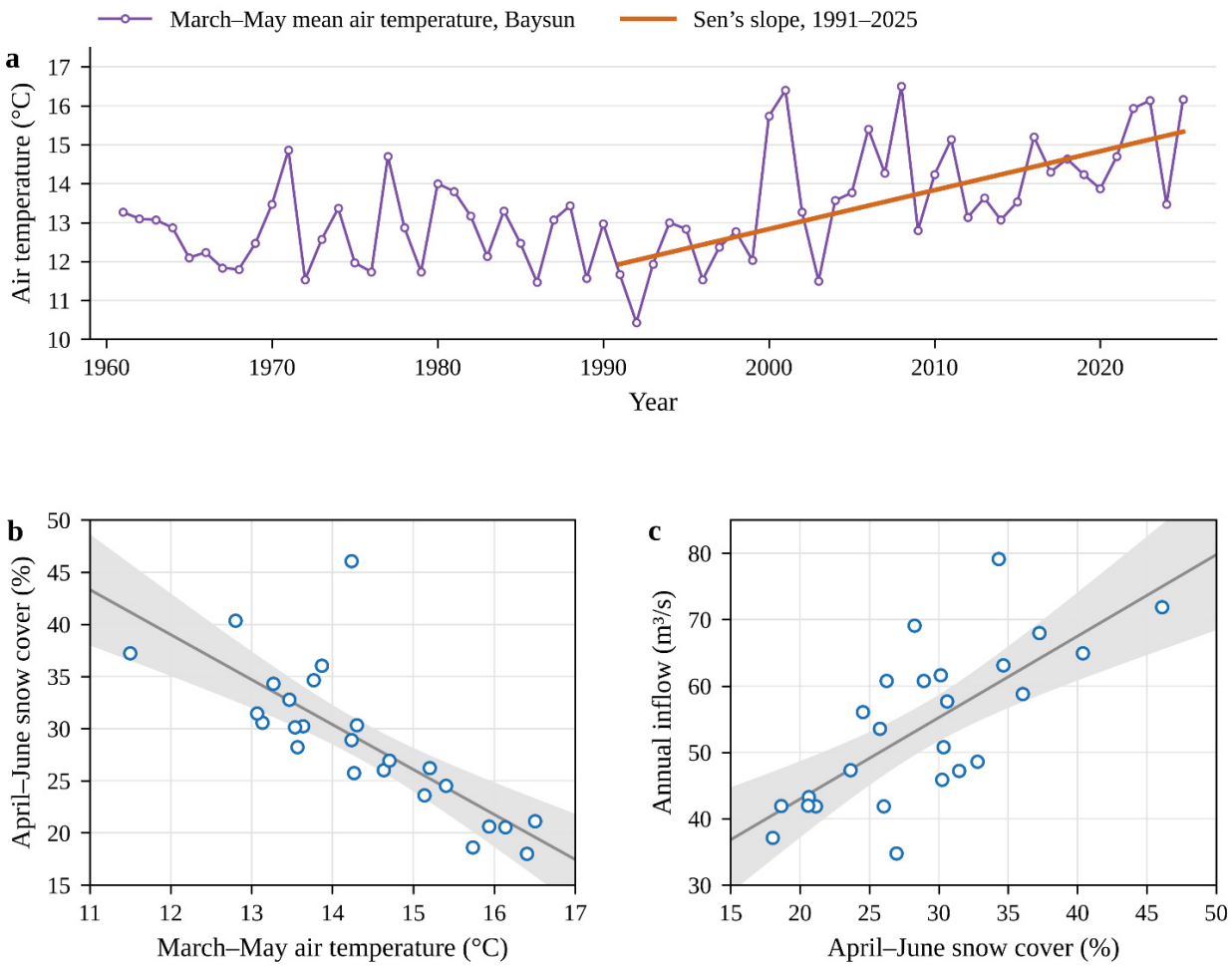

Figure 8. Temperature, snow cover and inflow. (**a**) March–May air temperature at Baysun, 1961–2025, with the Sen slope for 1991–2025. (**b**) April–June snow-covered area against March–May temperature, 2000–2024. (**c**) Annual inflow against April–June snow-covered area, 2000–2024. Lines in (**b**,**c**) are least-squares fits with 95% confidence bands, and circles are individual years.

Snow-covered area in April–June ranged from 18% to 46% between 2000 and 2024. Neither the April–June mean nor any single month from April to July showed a trend over 2000–2025 (Table 2). Year-to-year variation of this size leaves 26 years too short to detect a moderate trend: the 95% confidence interval of the April–June slope runs from −4.8 to +4.5 percentage points per decade. From year to year, however, snow cover was closely tied to spring temperature ($r = -0.78$, $p < 0.001$; Figure 8b) and accounted for about half of the variation in annual inflow ($r = 0.72$, $p < 0.001$; Figure 8c). August–October inflow was lower in warmer years: its correlation with summer temperature over 1991–2024 was −0.77 and with spring temperature −0.68 (both $p < 0.001$). Both series changed over the period, but the relation held after removing linear trends from each ($r = -0.61$ and −0.52, $p \leq 0.002$) and after controlling for DOR (partial $r = -0.68$ and −0.59). Over 1961–1985 and 1991–2024 combined, spring temperature and annual discharge were negatively correlated ($r = -0.45$, $p < 0.001$, $n = 59$).

Neither reanalysis showed a significant decline in precipitation over the upper catchment, but the two products differ in what they say about inflow. In MERRA-2, water-year totals had no significant trend over 1991–2024 (Sen slope +22 mm per decade, $p = 0.25$) and averaged 276 mm in 1991–2008 and 339 mm in 2009–2024, or 317 mm without the exceptionally wet 2024 (Table S5). April–July and annual inflow rose with water-year precipitation ($r = 0.42$ and 0.38, $p < 0.05$), as expected. August–October inflow, by con-

trast, was unrelated to the precipitation of the same water year (r = 0.15, $p = 0.41$) or of the two or three years before it (r = 0.07 and −0.08) and remained strongly related to summer temperature when precipitation was held constant (partial r = −0.78, $p < 0.001$). ERA5, whose totals exceed the runoff depth, follows inflow much more closely: r = 0.80 with annual inflow, 0.78 with April–July inflow and 0.71 with August–October inflow. Its water-year totals averaged 1280 mm in 1991–2010 and 1181 mm in 2011–2024, a fall of 8% that is not significant (Welch test $p = 0.15$; Sen slope −42 mm per decade over 1991–2024, $p = 0.29$). With ERA5 precipitation held constant, August–October inflow was still lower after warmer summers (partial r = −0.64, $p < 0.001$), and with temperature held constant it was higher in wetter years (partial r = 0.54, $p = 0.001$). In a regression on both, the lower precipitation after 2010 corresponds to about 2 m^3/s of the 12 m^3/s fall in August–October inflow between 1991–2010 and 2011–2024, and the higher summer temperature to about 8 m^3/s. Warm summers also tended to follow dry years (r = −0.55), so the two shares cannot be separated cleanly. Baysun temperature tracked the reanalysis temperature of the mountain cells closely (r = 0.94 for March–May and 0.77 for June–August), so the station follows the year-to-year variation of the catchment even though it lies below most of it and about 70 km south-west of the dam.

3.8. Robustness of the Main Estimates

The contrast between the phases was stable under the measurement-error simulation and the bootstrap (Table 8). With storage errors sized from the water-balance residual, the 95% range of the Phase 3 ratios was 0.79–0.81 for April–July and 1.76–2.10 for August–October, and total seasonal ecochange stayed between 1.13 and 1.43. Even the conservative runs, which applied the largest residual to every phase, left Phase 3 ecochange between 1.07 and 1.59, well above Phase 1 (Table S2). Random error can only add to ecochange, so the simulated ranges lie at or above the estimates, most visibly in Phase 1. Resampling years gave wider intervals for Phase 3, as expected from so short a record, yet for none of the three measures did they overlap those of Phase 1: 0.75–0.85 against 0.98–1.08 for the April–July ratio, 1.69–2.07 against 1.05–1.24 for August–October and 1.12–1.56 against 0.18–0.39 for ecochange. The number of October–March days below the benchmark was the least certain estimate, 32 to 81 days a year in Phase 3. A systematic error in the elevation–volume table also changed little (Table S6). With storage above 0, 100 or 200 × 10^6 m^3 raised or lowered by 5%, mean August–October inflow in Phase 3 moved by at most 1.1 m^3/s, against a fall of 15.0 m^3/s from Phase 1. Its Sen slope over 1991–2024 stayed between −6.3 and −5.5 m^3/s per decade, and the Phase 3 ratios moved by at most 0.01 in April–July and 0.10 in August–October. With 10% the corresponding figures were 2.2 m^3/s, −6.9 to −4.9 m^3/s per decade ($p \leq 0.002$ throughout), 0.02 and 0.21. The storage record is also consistent with the other two. In 2011–2014 the Zarchob gauge shows August–October flow 4.1 m^3/s lower than in 1991–2010, whereas reconstructed inflow was 10.9 m^3/s lower. The difference corresponds to the autumn drawdown read from water level, on average 81 × 10^6 m^3 between the end of July and the end of October, or 10.2 m^3/s, against 10.5 m^3/s for release minus inflow. In Phase 3 the same drawdown averaged 179 × 10^6 m^3, against 169 × 10^6 m^3 for release minus inflow in August–October.

Table 8. Robustness of the main estimates by regulation phase.

Measure	Phase 1	Phase 2	Phase 3
Release/inflow, April–July			
Estimate	1.03	0.97	0.80
Measurement-error range	1.02–1.03	0.96–0.97	0.79–0.81

Table 8. *Cont.*

Measure	Phase 1	Phase 2	Phase 3
Bootstrap 95% interval	0.98–1.08	0.95–0.98	0.75–0.85
Release/inflow, August–October			
Estimate	1.14	1.32	1.90
Measurement-error range	1.11–1.18	1.29–1.36	1.76–2.10
Bootstrap 95% interval	1.05–1.24	1.18–1.46	1.69–2.07
Total seasonal ecochange, release against inflow			
Estimate	0.25	0.53	1.29
Measurement-error range	0.23–0.31	0.46–0.54	1.13–1.43
Bootstrap 95% interval	0.18–0.39	0.45–0.74	1.12–1.56
Days of 0.5 m^3/s or less treated as missing	0.40	0.59	1.35
October–March days per year with release below 10.5 m^3/s			
Estimate	25	57	55
Bootstrap 95% interval	13–37	40–74	32–81
Days above 0.5 m^3/s only	8	14	43

Measurement-error range: 2.5th–97.5th percentiles of 2000 Monte Carlo runs with storage and release errors sized from the ten-day water-balance residual. Bootstrap: 95% interval from 2000 resamples of whole years within each phase. P1 1990/1991–2005, P2 2006–2016, P3 2017–2024. Rows in italics are headings for the indicators listed below them.

4. Discussion

4.1. Storage and the Transfer of Water Between Seasons

The clearest result is that the reservoir's effect on the seasons grew in step with its storage. We use the degree of regulation in a form adapted from Grill et al. [5]: the volume the reservoir actually held at its annual maximum, relative to the river's natural annual flow. Below about 6% the reservoir passed most water through, although release already exceeded inflow in some late seasons. Between 6% and 14% it began to hold back part of the spring rise. Above 15% the transfer of water from spring to late summer and autumn became the dominant feature of the regime.

Observed maximum storage depends partly on how much water arrives, so a correlation between storage and the seasonal ratios could in principle reflect wet and dry years rather than regulation. Two checks argue against that reading. The relations hold when seasonal inflow is held constant, and in a regression on phase and seasonal inflow the inflow term has no detectable effect while the Phase 3 effect is large. The progression is also visible in flood peaks: the largest ten-day release fell from 95% of the largest ten-day inflow in 2009–2016 to 83% in 2017–2024. Because inflow is reconstructed from release and storage, neither check is fully independent of the ratios, and both are better read as consistent with the regulation reading than as proof of it. Phase, storage and calendar time move together in this record, however. Storage and year rose so closely together ($\rho = 0.96$) that statistics cannot fully separate them: in a regression on both, storage carried the effect and year did not, but a rank correlation controlling for year was weak. The analysis therefore shows that regulation intensified with each stage. It cannot say which part of that intensification came from capacity and which from changes in how the reservoir was operated.

Set against studies elsewhere, the peak reduction is of a similar order and the seasonal signature is typical. Across 21 dams in the United States, the mean changes in 7-day and 30-day maxima were falls of 37% and 23% [6]. At the Tupalang, the mean annual 7-day and 30-day maxima of release were about 28% and 29% lower in Phase 3 than in Phase 1, a smaller fall in the 7-day and a larger one in the 30-day maximum. Part of that fall reflects

smaller inflow peaks in recent years, and Phase 1 was itself lightly regulated, so the figures are not directly comparable with pre-dam baselines. The seasonal pattern, by contrast, is the one Magilligan and Nislow [6] describe: lower flows in spring and higher flows in late summer and early autumn, with September flows up by 88% on average across their sites. At the Tupalang, August–October release in Phase 3 was 45% above the natural mean and 91% above the same years' inflow.

The operating rules were not available to us, so what the pattern says about operation must be stated with care. In the model scenarios of Jalilov et al. [18] for the Amu Darya, energy-oriented storage fills in summer and releases in winter, whereas irrigation-oriented storage holds water until the growing season. The Tupalang follows neither scenario exactly. It fills from March to June and releases more than it receives from July to November, with the largest surpluses in August and November. January and February release is essentially unchanged. The late-summer surplus is consistent with extending irrigation supply, while the October and November surplus is more consistent with drawing the reservoir down before winter or with generation. The 175 MW station commissioned in 2023 may shift the balance further towards winter release, but the record does not yet contain enough years to show it. If winter generation gains priority, November–March release would probably rise and storage would be drawn lower before the melt. The winter ratio would then climb further above one, and more of the spring flood would be needed to refill the reservoir, deepening the April–July deficit.

4.2. Consistent Alteration of a Regular Regime

From an ecological standpoint, the most consequential change may be in the timing and shape of the regime rather than in its volume. Snowmelt rivers have among the most regular flood timing of any river type [9]. The Topalang's natural regime was regular: outside the spring months the natural range of monthly flow was narrow, and flow peaked in May and June. Under Phase 3 regulation, no year fell inside that range in March or from October to December. Most departures were one-sided: March release was below the range in seven of eight years and November release above it in every year, although October and December swung both ways. Outside those two months the regime has not become erratic. It has been displaced in a consistent direction, with less water in the early melt season and much more in autumn than the river naturally carried. The months most altered were the shoulders of the year rather than the peak. In October and November, release in Phase 3 exceeded the natural mean by 16 to 21 m^3/s, more than doubling the natural flow of those months. According to the reservoir administration, most of this autumn water flows on down the river towards the Surkhandarya, and some is at times diverted into the Hazarbog canal to leach salts from irrigated land. Our records cannot show how much of it reaches the lower basin and how much is lost to evaporation and seepage on the way.

The spring pulse itself was lowered more than it was displaced. The monthly peak of Phase 3 release was spread almost evenly across June and July, and the mean date of the annual maximum in Phase 3 was within a week of that in Phase 1. Poff et al. [8] note that irrigation reservoirs often shift peak flows from spring to summer, with consequences for species whose life cycles are keyed to the spring rise. At the Tupalang the change so far is a flattening of the spring pulse combined with a surplus in autumn.

Vogel et al. [32] warn that a surplus is not benign despite its name. Ecosystems depend on both high and low flows, so a gain in a naturally low season is as much a departure as a loss in a high one. At the Tupalang, the August–October ecosurplus of release against inflow in Phase 3 (0.88) was more than four times the April–July ecodeficit (0.20), but each is a fraction of the mean flow of its own season, and autumn flow is much the smaller. In volume the two sides balance: in Phase 3 the reservoir withheld about 275×10^6 m^3 from

April to June and released about 279 × 10^6 m^3 more than it received from July to November, 169 × 10^6 m^3 of it in August–October. In simulated reservoirs and 189 regulated rivers in the United States, Gao et al. [33] found that total seasonal ecochange and the summer and winter ecosurpluses explained the most variation in the full set of 32 Indicators of Hydrologic Alteration. A rise in total ecochange from 0.25 to 1.29 across the three phases is therefore consistent with alteration across many facets of the regime, not only the few reported here. With monthly data, though, we cannot test that directly, and the absolute values are not comparable with those computed from daily flow.

Low flows deserve separate comment, with a caveat about the record. Release was recorded as zero on 44 days a year in Phase 2, mostly in January and February, and the mean annual 7-day minimum fell to 0.5 m^3/s. Mahmood et al. [1] estimated environmental flows from naturalised flow at 34 points across the Amu Darya basin, on the main stem and its tributaries. Averaged across those points, the low-flow months need 20% to 30% of naturalised mean annual flow, about 10.5 to 16 m^3/s for the Topalang. Because natural flow at Zarchob fell below the lower figure in about one low-flow month in seven, the benchmark is a yardstick here rather than a target. The Tennant method sets fixed shares of mean annual flow for two halves of the year [34] and ignores the timing and variability to which the biota of a snowmelt river are adapted, which is why holistic methods linking flow components to ecological needs have been developed for rivers where such data exist [39]. We use it because it is the benchmark already applied across the Amu Darya basin, and with every alternative threshold tested here, release fell below it on more days in Phases 2 and 3 than in Phase 1. Even so, taking the recorded zero days at face value, Phase 2 release fell below it on 57 days a year between October and March, and its January mean of 5.8 m^3/s was far below both the benchmark and the natural range. In Phase 3 the reservoir kept October and November release above the threshold in years when inflow fell short of it, yet daily release still dropped below it on about 55 days a year, mostly from December to February. Counting only days above 0.5 m^3/s, the figure is still 43 days. A closed outlet did not mean a dry channel, though. In months with almost no recorded release, the Zarchob gauge 1 km downstream still measured 1.1 to 5.5 m^3/s, at least in Phase 2, the only phase in which the two records overlap such months. Those residual flows are themselves below the benchmark, so the day counts stand, but the shortfall on such days is smaller than a recorded zero implies. Even so, winter low flow is the most acute ecological pressure in the regulated record. A recent survey of leeches found an almost unpolluted, oxygen-rich upper reach and strong pollution in the lower reach [19]. Our data cannot show whether low winter release contributes to that gradient, but they identify winter low flow as the first thing a monitoring programme should test.

4.3. A Declining Late-Season Supply and a Reservoir That Offsets It

The relation between the two signals needs equal care. Natural flow showed no trend over 1930–1985, and the inflow record since 1991 should not be read as a long decline. Annual inflow was high from 1991 to 2008 and has since returned to about the natural mean. The decline that matters is seasonal. August–October inflow in Phase 3 was about a quarter below the natural mean of those months, and only a small part of that gap can be explained by the difference of about 4% between the Zarchob record and the operator's figures. Late summer and autumn are where Barnett et al. [3] expect warming to reduce flow in snow-fed rivers. Our data are consistent with that expectation: August–October inflow was lower in warmer years, and spring snow cover was smaller in warmer springs and tracked annual inflow closely.

These are year-to-year associations, not a demonstrated cause of the trend. Snow cover in April to July showed no trend over 2000–2025 even though spring temperature

rose, although that record is probably too short and variable to reveal one. No gauged precipitation record was available, and the two reanalyses disagree. MERRA-2, which captures less than half of the runoff depth, shows no decline and no relation with August–October inflow. ERA5, whose totals exceed the runoff depth and which follows annual inflow closely, shows precipitation about 8% lower after 2010, though not significantly so, and a clear relation with late-season inflow. In both products the relation of that inflow with summer temperature held when precipitation was controlled. Lower precipitation therefore probably contributed to the decline, by roughly a fifth on the ERA5 regression, but does not account for most of it. The contrast with the Kyrgyz rivers, whose flow has risen since the 1990s with more precipitation and a larger glacier contribution [14], is at least consistent with the observation that basins with little glacier ice behave differently from glacierised ones [13]. Settling the attribution will need a verified precipitation record for the basin.

Whatever its cause, the late-season decline in inflow meets an opposite change in release. In Phase 3 the water reaching the reservoir in August–October was about a quarter below the natural mean. In the same months the reservoir released about 45% more than the natural mean. Mountain snowpack has long acted as a natural store that delays runoff into the dry season [3], and on the Topalang the reservoir now performs a similar function artificially. This has two consequences for interpreting records below the dam. A gauge there shows plentiful late-season water and would not reveal the decline in late-season inflow. And the water released in autumn is spring water taken from the river's flood pulse, so a regime that looks well supplied in autumn has in fact moved further from its natural shape.

The redistribution matters beyond the regime statistics. For irrigation, the reservoir now delivers more water in late summer, when natural flow and inflow are lowest, to the 117,000 ha served by the Hazarbog canal, which is the purpose of storage in an arid valley. For the river, the most exposed period is winter, when daily release fell below the benchmark on about 55 days a year in Phase 3. Our estimate of the cost of a minimum release points to a practical rule. Because the reservoir already releases more than it receives in October and November, keeping back about a third of that surplus for December–February would hold winter release above 10.5 m^3/s in most years without changing the volume released over the year. We did not examine whether storage levels and the outlet works allow water to be held until midwinter, which is for the operator to judge. Any such rule would have to be weighed against winter generation at the 175 MW station and the leaching releases to the Hazarbog canal, and its ecological benefit tested in the field.

The methodological lesson is that, where reservoirs have been built in stages, a gauge below the dam can show changes that belong to neither climate nor regulation alone. Release and storage records of the kind kept at the Tupalang allow the two to be separated even where no gauge stands above the reservoir, and their wider use would help with the attribution problem that limits basin-scale studies [16].

That separation is likely to become harder. In November 2023, twenty prospective hydropower projects with a combined capacity of 264 MW were announced for the upper Topalang [40]. In April 2026 a government review of the Upper Tupalang watercourses considered 42 small plants on the streams feeding the reservoir, with about 541 MW of capacity [2]. If they are built, the inflow to the reservoir will no longer describe an unregulated headwater, and the streams above it will be divided by new structures. Records at the reservoir would then need gauges above the new schemes to keep climate and regulation apart, and the headwater streams themselves would need ecological baselines before construction.

4.4. Limitations

Several limitations follow from the data. First, inflow is not gauged. The operator reconstructs it from release, storage change and an allowance for evaporation and seepage, so the reservoir component is only as reliable as those records, while the inflow, and with it the inflow component, carries the errors of all of them. In the years when the reservoir passed most water through, Uzhydromet's Zarchob record and the operator's figures differed by about 4%. That is small next to the seasonal changes reported here, but it affects comparisons of annual totals between the Zarchob record before 1991 and the operator's record after it. The Zarchob record available to us ends in 2014, so in Phase 3 the operator's figures have no independent check, and the autumn decline of inflow after 2010 rests on the storage record as well as on release. Simulated errors of the size indicated by the water balance moved the Phase 3 ratios and ecochange only within the ranges given in Table 8. Second, natural flow is available only as monthly means, so daily indicators could be compared only among regulated phases, and the ecodeficit and ecosurplus were computed from monthly curves that miss alteration within the month. Phase 3 also contains only eight years, so its estimates carry wide sampling intervals, above all the count of low-flow days. Third, the release figure includes water that the Hazarbog canal takes from the river about 13 km below the dam. The reach below the canal head therefore carries less than the release, and the environmental-flow comparisons apply strictly to the reach between the dam and the canal. We hold no records of the canal's diversions, so the flow of the lower river, where the ecological concern is greatest, could not be estimated. Fourth, several years contain duplicated or missing records, which we excluded rather than repaired; zero-release days are recorded closures that the records do not document as such; the Baysun temperature record, compiled from a public climate archive, appears inhomogeneous before 1961; and no gauged precipitation record was used. The reanalysis index that replaced it cannot resolve precipitation at the scale of the catchment. The only long gauged series available, from Denov in the valley about 35 km from the dam, has gaps from 1995 to 2010 and implausibly low annual totals in several otherwise complete years, such as 45 mm in 1977 and 2016. We did not attempt projections of future flow. With a reconstructed inflow, no gauge above the reservoir and no verified precipitation record, a hydrological model of future scenarios would rest on weaker ground than the observed record analysed here. The trend tests and correlations were not adjusted for multiple testing. With Holm's correction applied to the 15 trend tests of Table 2, the decline in August–October inflow and the temperature trends since 1991 remain significant (adjusted $p < 0.01$), whereas the declines in annual and November–March inflow do not (adjusted $p = 0.26$ and 0.41) and are indicative only. Nor did we examine how evaporation from a larger reservoir surface and from a warming catchment enters the water balance, or how release rules changed with the generating schedule of the power station as it grew from 30 to 175 MW. Both questions need the operator's evaporation and generation records. Finally, the study contains no biological data. The ecological interpretations offered here are hypotheses for field testing, not findings.

5. Conclusions

The Topalang River offers a rare chance to follow a dam's influence stage by stage against a long natural record. As storage rose from a few percent to about a fifth of mean annual flow, the reservoir moved from passing water through to transferring a large part of the spring snowmelt into late summer and autumn. The ratio of release to inflow fell to 0.80 in April–July and rose to 1.90 in August–October, and both ratios followed storage from year to year even after allowing for inflow, although storage and calendar time cannot be separated in this record. In March and from October to December, release now lies outside the natural range in every year. Measured as total seasonal ecochange, the reservoir's

own contribution grew three- to fivefold between the first and third phases, and Phase 3 remained well above Phase 1 under simulated measurement error and resampling of years.

Over the same period the water reaching the dam in late summer and autumn has declined. At Baysun, spring temperature has risen by about 1 °C per decade since 1991, and warmer years have had less snow and less late-season inflow. Reanalysis precipitation fell little and not significantly over the same years, and on the better of the two products it accounts for only a small part of the decline. The reservoir now more than offsets that decline downstream. This keeps late-season supply high but hides the change in the water arriving and moves the regime further from its natural shape. Managing the river for both irrigation and ecological health will require explicit environmental-flow rules, above all for winter low flows and for the spring pulse. In most years, holding back about a third of the October–November surplus would have been enough to keep winter release above the benchmark. Managing the river will also require continued monitoring of release and storage, a gauge above the reservoir and a verified precipitation record, so that regulation and climate can be told apart as both intensify.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/hydrology13120319/s1, Table S1: Record of excluded and corrected observations; Table S2: Seasonal ratios and ecochange under simulated measurement error, both error settings; Table S3: Hydrologic alteration and ecochange against two halves of the natural record; Table S4: Flow below alternative environmental-flow thresholds; Table S5: Water-year precipitation and temperature from the MERRA-2 and ERA5 reanalyses and correlations with inflow; Table S6: Sensitivity of inflow and the seasonal ratios to a systematic error in the elevation–volume table; File S1: Analysis scripts.

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Data Availability Statement: Reservoir release, storage and inflow records were provided by the Tupalang reservoir administration of Uzbekhydroenergo JSC, and the Zarchob discharge series by the Uzbek Hydrometeorological Service (Uzhydromet). They are available from the corresponding author on reasonable request, with the permission of the data owners. Air temperature data are available from Pogoda i Klimat (https://www.pogodaiklimat.ru), and reanalysis data from the NASA POWER service (https://power.larc.nasa.gov) and the Open-Meteo archive (https://open-meteo.com). The analysis scripts are provided as Supplementary File S1.

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Abbreviations

The following abbreviations are used in this manuscript:

DOR	Degree of regulation
ERA5	Fifth-generation ECMWF atmospheric reanalysis
HA	Hydrologic alteration
IHA	Indicators of Hydrologic Alteration
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA POWER	NASA Prediction of Worldwide Energy Resources
RVA	Range of Variability Approach
Uzhydromet	Uzbek Hydrometeorological Service

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