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From Summer Peak to Winter Release: Nine Decades of Flow Regime Alteration by the Lower Naryn Hydropower Cascade, Central Asia

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Abstract

How far can reservoir operation displace a river's calendar? We address the question with 92 years of monthly discharge on the Naryn River, the transboundary artery of the Syr Darya basin, together with an unregulated headwater gauge, two mountain weather stations, 46 years of release data and two years of daily reservoir balances. Annual flow shows no trend, yet the centre of timing of flow moved from late June to mid-January, a displacement of 164 days (bootstrap 95% interval 158 to 173) that inverts the hydrograph. Both weather stations warmed significantly over the same decades, but the headwater gauge kept its summer regime and advanced its timing by only five days, and a paired-gauge counterfactual assigns two to five days of the downstream displacement to changing inflow and 160 to 162 days to operation. Change points near 1986, 1990 and 1994, confirmed by independent segmentation methods, coincide with the documented transition from irrigation-oriented to energy-oriented operation. Roughly 4.8 km^3 per year (4.0 to 5.6) now arrives outside the growing season. Reservoir operation is the dominant driver of the inversion, and the displacement volume quantifies the seasonal redistribution at the centre of a thirty year allocation dispute.

Keywords: flow regime alteration; hydropower cascade; Naryn River; Toktogul reservoir; Syr Darya; centre of timing; socio-hydrology; environmental flows; transboundary rivers

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1. Introduction

Dams have altered the hydrology of most large river systems, and the majority of long free-flowing rivers that remain are found far from the regions where water demand is concentrated [1,2]. Their consequences reach beyond the volume of water a river carries, because the natural flow regime concept holds that the timing, magnitude, frequency, duration and variability of flows together structure riverine ecosystems and the human economies built on them [3], and quantifying departures from that regime, rather than changes in annual totals alone, has become the standard way to assess what a reservoir does to a river [4]. The stakes of such departures are well documented: in a review of 165 studies of ecological response to altered flows, 92% reported degraded ecological metrics [5].

Nowhere is the question more consequential than in the endorheic basins of Central Asia. The Syr Darya, formed by the confluence of the Naryn and the Kara Darya in the Fergana Valley, sustains irrigated agriculture in Uzbekistan, Tajikistan and Kazakhstan before reaching what remains of the Aral Sea [6]. The basin is also a textbook case of a transboundary water–energy conflict. The Toktogul reservoir, the only facility in the basin able to store flow across years, lies in Kyrgyzstan, whose energy system depends on winter hydropower, while the downstream states need the same water in summer [7–9]. Below Toktogul the five stations of the Lower Naryn cascade, with a combined installed capacity of 2870 MW and a mean annual generation close to 10 TWh, about 4.1 TWh of it from Toktogul alone (Table 1), form the backbone of that energy system. After the dissolution of the Soviet Union the barter arrangements that had exchanged summer water for winter fuel eroded, and Toktogul was progressively shifted from an irrigation-oriented to an energy-oriented release schedule [10]. Climate change adds a further layer. Tien Shan glaciers and snowpack, which generate the Naryn's flow, are shrinking, spring snow cover duration is declining across the headwaters [11,12], and glacio-hydrological modelling of the Naryn basin projects earlier melt peaks, higher spring and lower summer runoff, and eventual reductions in total flow as the glaciers waste away [13–15].

Soviet-era and post-Soviet scholarship built a rich descriptive picture of the region's reservoirs [16–19], recent work in Uzbek has documented the operational shift at Toktogul and its problems [20,21], and quantitative studies of Central Asian catchments and allocation systems are beginning to appear in the international literature [22,23]. What this body of work has not yet delivered is a statistical account of the alteration itself: how large the seasonal restructuring is, when the regime actually changed as detected from the data rather than asserted from operational history, and what has happened to the timing and extremes of the regime that matter most for downstream water security.

Two strands of hydrological research sharpen the question. Research on streamflow timing treats the calendar position of flow as a quantity in its own right, and has shown that climate warming moves snowmelt timing by one to four weeks over decades, shifts large enough to headline the field's flagship journals [24,25]. Research on dam operations in other transboundary basins, above all the Mekong, has documented dry-season flow increases in the order of tens to roughly a hundred per cent attributable to upstream hydropower [26]. Both strands invite a comparative question: how far can operational alteration go? The emerging programme of socio-hydrology supplies a complementary lens, treating river records as archives of coupled human-water dynamics rather than of nature alone [27,28]. A river whose timing responds to fuel prices and treaty failures is a socio-hydrological object, and its hydrograph can be read accordingly.

This paper provides such a reading for the Naryn. We ask four questions. First, has regulation changed how much water the Naryn delivers, or only when it delivers it? Second, when did the flow regime change, and how do the detected break points relate to the documented phases of Toktogul's operation? Third, how much of the change in timing can be traced to the inflow arriving from the headwaters, which a warming climate is also altering, and how much to operation? Fourth, how strongly do Toktogul's releases control the flow that Uzbekistan receives at the Uchkurgan gauge, and how does the daily operation of the reservoir produce the seasonal shift under the present energy regime? We answer these questions with a 92 year monthly series (1930 to 2021), a monthly series from an unregulated headwater gauge (1931 to 2022), temperature and precipitation at two mountain weather stations (1960 to 2022), 46 years of annual release and gauge data (1975 to 2020) and two years of daily reservoir balances (2022 and 2023), using trend, change point and homogeneity statistics, timing and concentration metrics, a period-based alteration analysis and a paired-gauge counterfactual. The contribution lies in the application and

the synthesis rather than in new statistical machinery: the tests and timing metrics used here are established tools. What the Naryn adds is an exceptionally long record on which those tools can be combined, a decomposition of the alteration into phase and concentration, statistically detected operational transitions cross-checked by independent methods, an observational bound on the climatic contribution, and a seasonal displacement volume that expresses the result in units downstream planners use. A river whose annual flow is trend free also offers the alteration literature a rare benchmark, because the operational signal can be examined with comparatively little confounding from changing water supply. A trend-free annual total does not by itself exclude climatic redistribution within the year, however, and we therefore test that possibility directly rather than assume it away.

2. Study Area: The Lower Naryn Cascade

The Naryn rises in the inner Tien Shan and flows roughly 800 km westward before joining the Kara Darya near Namangan to form the Syr Darya. In its lower course in Kyrgyzstan the river drops through a series of gorges that concentrate an unusual hydropower potential within a short reach. Five stations exploit this drop and together form the Lower Naryn cascade: Toktogul, Kurpsai, Tash-Kumyr, Shamaldy-Say and Uch-Kurgan (Figure 1a). The Uchkurgan gauging station (G1 in Figure 1a), situated immediately downstream of the last station of the cascade, integrates the outflow of the whole system and is the reference point at which Uzbekistan receives Naryn water. Far upstream, above all five stations, the Naryn town gauge (G2) records the river as it leaves the inner Tien Shan. Its catchment of 10,474 km^2, gauged at 2039 m, is about 18% of the 57,833 km^2 that drain to Uchkurgan [14] and is not regulated by any of the cascade's reservoirs. The Naryn and Tien-Shan weather stations (M1 and M2), at 2041 m and 3639 m, represent the climate of this source region.

The cascade was assembled over three decades. Uch-Kurgan, the lowest and oldest station, was commissioned in 1961; Toktogul followed in the mid 1970s, Kurpsai in the early 1980s, Tash-Kumyr in the second half of the 1980s and Shamaldy-Say in the 1990s (Table 1). The longitudinal scheme in Figure 1b shows how the stations share the fall of the river. Each dam raises the water to its normal support level, the full operating level of the reservoir, and the five levels form a staircase from 900 m at Toktogul through 724 m at Kurpsai, 628 m at Tash-Kumyr and 572 m at Shamaldy-Say to 539.5 m at Uch-Kurgan, a total fall of about 360 m. The dam heights decline in the same order, from 215 m at Toktogul to 113, 75, 41 and 31 m at the four stations below, so the uppermost step provides the highest head and, as Table 2 shows, by far the largest store.

Table 1. Hydropower stations of the Lower Naryn cascade.

	Toktogul	Kurpsai	Tash-Kumyr	Shamaldy-Say	Uch-Kurgan
First unit commissioned	1975	1981	1985	1992	1961
Number of units	4	4	3	3	4
Maximum head (m)	180	106	58.5	31.0	36.0
Minimum head (m)	110	90.5	40.0	25.2	18.5
Design head (m)	140	91.5	53.0	26.0	20.0
Installed capacity (MW)	1200	800	450	240	180
Mean annual generation (GWh)	4100	2630	1550	900	820

Source: compiled from [17,29] and operator data.

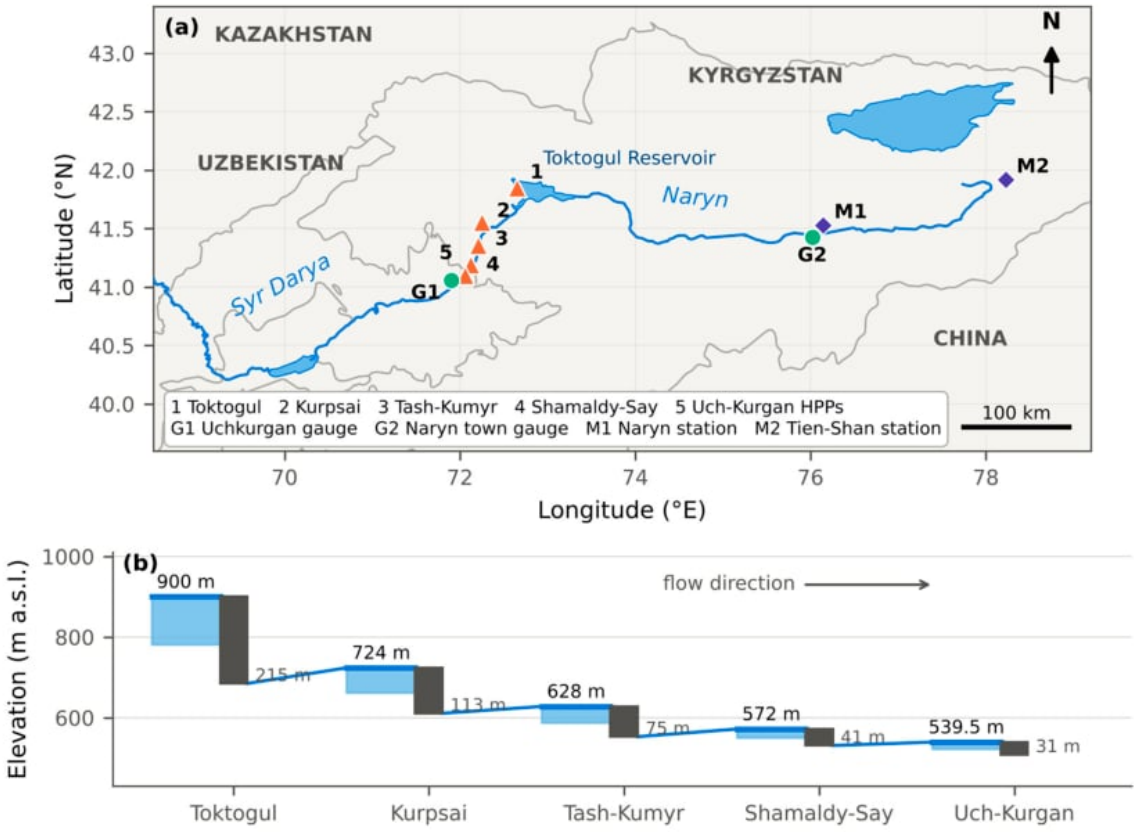


Figure 1. The Lower Naryn cascade. Note: (**a**) the five hydropower stations (triangles, numbered from Toktogul downstream), the Uchkurgan (G1) and Naryn town (G2) gauges (circles) and the Naryn (M1) and Tien-Shan (M2) weather stations (diamonds; M1 stands beside G2 in Naryn town and is offset slightly for legibility); (**b**) longitudinal scheme with the normal support level of each reservoir and the height of each dam. Source: authors' elaboration; base geography from Natural Earth.

Table 2. Hydrological characteristics of the cascade reservoirs.

	Toktogul	Kurpsai	Tash-Kumyr	Shamaldy-Say	Uch-Kurgan
NSL (m a.s.l.)	900	724	628	572	539.5
DVL (m a.s.l.)	837	721.6	626.5	569.9	536.5
Working depth (m)	63	2.4	1.5	2.1	3.0
Dam height (m)	215	113	75	41	31
Dam length (m)	292	364	336.5	260	100
Total volume (10^6 m^3)	19,500	370	144	40.8	52.5
Useful volume (10^6 m^3)	14,000	35	16	5.5	20.9
Dead volume (10^6 m^3)	5500	335	128	35.3	31.6
Max culvert discharge at NSL (m^3 s^{-1})	3500	2537	3293	3090	3250

Note: NSL, normal support level; DVL, dead volume level. Source: compiled from [17,29].

The reservoirs behind the five dams differ by three orders of magnitude in useful storage (Table 2). Toktogul, with a 215 m dam and a design volume of 19.5 km^3, of which 14 km^3 is useful storage, was built for interannual regulation of the entire Naryn flow. The four downstream reservoirs are essentially run-of-river ponds whose useful volumes, between 5.5 and 35 million m^3, allow daily re-regulation at most. The cascade's regulation capacity is therefore centralised to an unusual degree: 99.4% of the total useful storage

of the system sits behind one dam, and the operating mode of Toktogul dictates the flow through every station below it and onward into the Syr Darya.

3. Data and Methods

3.1. Data

Five data sets are used. The first is the monthly mean discharge series of the Naryn at the Uchkurgan gauge for 1930 to 2021, drawn from the archive fund of the national hydrometeorological service of Uzbekistan (Uzhydromet). Observations at the gauge were interrupted in 1963 and 1965. Uzhydromet reconstructed these two years from the analogue record of the gauge at the Uch-Kurgan hydropower station immediately downstream; over the 1960 to 1990 calibration window the annual relation between the two gauges is $Q = 0.825\ Q_{hpp} + 34.7\ m^3\ s^{-1}$ with $r = 0.903 \pm 0.023$, and the monthly values were reconstructed from the analogue record on that basis. The assembled series therefore contains no missing months, and the sensitivity of every principal result to the exclusion of the two reconstructed years is reported with the results. According to the station history held by Uzhydromet, the gauge was established in 1896 about 4 km below the headworks of the Big Fergana Canal, was reorganised as the Uchkurgan station in 1931 and has not been moved since; discharge has been derived throughout from current-metre measurements and the stage-discharge rating curves checked against them, referenced to a fixed benchmark. The homogeneity of the record before regulation was also tested statistically. The second is the mean annual release from the Toktogul reservoir for 1975 to 2020, taken from the official reporting of the cascade operator, the open joint-stock company Electric Power Plants under the Ministry of Energy of the Kyrgyz Republic, paired with the mean annual discharge registered at Uchkurgan. The third is the daily water balance of the Toktogul reservoir, inflow, release and storage, for the calendar years 2022 and 2023, drawn from the operational data published by the same operator (www.energo-es.kg). Published sources show minor inconsistencies in reservoir storage at the boundary between the two years, so the storage series are treated as separate annual records rather than one continuous one. The fourth is the monthly mean discharge of the Naryn at Naryn town for 1931 to 2022, from the same Uzhydromet archive. The gauge lies above every station of the cascade; 88 years between 1933 and 2022 are complete, and the incomplete years 1931, 1932, 1936 and 1938 were excluded. For 1942 and 1968 the annual values printed in the archive table disagree with the mean of the monthly values, which were used throughout; excluding both years changes the headwater and counterfactual results reported below by 0.3 days at most. The fifth is monthly mean air temperature and monthly precipitation at the Naryn (2041 m) and Tien-Shan (3639 m) weather stations for 1960 to 2022, also supplied through Uzhydromet. These series contain gaps, and annual and seasonal values were computed only for years in which every relevant month was observed. Annual mean discharges were computed from the monthly series with month lengths as weights. The growing season is defined as April to September and the non-growing season as October to March, following irrigation practice in the basin.

3.2. Methods

Monotonic trends were tested with the non-parametric Mann–Kendall test [30,31] and trend magnitudes estimated with Sen's slope [32]. Abrupt changes were detected with the Pettitt test [33]. The test was applied to each full series and, where a significant break was found, once more to the sub-series following it; a third level was attempted only for the seasonal ratio, where it returned no significant break, and the search stopped there. Because each additional test is conditioned on the previous result, *p*-values at the second level are indicative rather than exact, and for each break we report the years at which the Pettitt

statistic lies within 10% of its maximum as an uncertainty window. Reservoir storage and regime shifts induce serial correlation in annual indicators, so the lag-one autocorrelation of every series was computed and trend significance was re-assessed with the variance-corrected Mann–Kendall test of Hamed and Rao [34] and, more conservatively, after trend-free pre-whitening. As an independent check on the change points, each indicator series was segmented with the PELT algorithm under a BIC-type penalty and with binary segmentation constrained to two or three breaks [35]; these methods locate multiple breaks jointly rather than sequentially. Significance was assessed at the 0.05 level throughout. Treating the detection of alteration as a formal hypothesis test, rather than as visual comparison of periods, guards against reading natural variability as regime change and is increasingly urged in the assessment of dam effects [36].

The comparisons that follow treat 1930 to 1971 as a single natural baseline, so the stationarity of that period was tested in its own right. For the annual mean, the growing season share, the centre of timing and the Gini coefficient defined below, and for the January and February means, we applied the variance-corrected Mann–Kendall test and the Pettitt test to the whole period, the Mann–Kendall test separately to its two halves (1930 to 1950 and 1951 to 1971), and the Mann–Whitney test to the difference between the halves. Three absolute homogeneity tests were added: the standard normal homogeneity test [37], the Buishand range test [38] and the von Neumann ratio test [39], a combination widely used to screen climatological series for inhomogeneities when no reference series is available [40]. Because the Uch-Kurgan station began operating immediately above the gauge at the end of 1961, the principal results were also recomputed with 1930 to 1961 as the baseline.

Flow regime alteration was quantified in the spirit of the indicators of hydrologic alteration approach [4], at the resolution the record allows and with a deliberately parsimonious indicator set, since many of the standard indices are mutually redundant [41]. The indicators are the twelve monthly means, the annual mean, the growing season share of annual flow, the ratio of non-growing season to growing season flow, the highest and lowest monthly mean of each year and their timing, and the interannual coefficient of variation; Table 3 gives the definition and hydrological meaning of each, together with the timing, concentration and volume metrics introduced next. Following the operational history of Toktogul documented in earlier work [20], five candidate periods were used for descriptive comparison: a natural period (period I, 1930 to 1971), an irrigation-dominated period (II, 1972 to 1987), a transitional period (III, 1988 to 1994), a period of establishment of the energy regime (IV, 1995 to 2007) and a period of consolidated energy regime (V, 2008 to 2021). We treat this periodisation as a hypothesis to be tested against the detected change points rather than as a given.

Two further metrics separate the phase of the annual cycle from its concentration. The centre of timing of annual flow is the circular mean date of the year's discharge mass, computed by weighting the mid-dates of the twelve months by their flow volumes (Table 3); it is the monthly resolution analogue of the centre-of-mass timing used in studies of snowmelt regimes [24], made circular so that midwinter dates are handled correctly. Concentration is measured in two ways: by the resultant length of the same circular calculation, and by the Gini coefficient of the twelve monthly volume shares, which is independent of phase. Both metrics were computed for every year, and the same trend and change point tests were applied to the resulting series. Uncertainty in the difference in circular mean timing between the natural period (I) and the consolidated energy regime (V), and in the displacement volume defined next, was estimated by bootstrap: years were resampled with replacement within each period 5000 times and the statistic recomputed, and the 2.5th and 97.5th percentiles are reported as a 95% interval. From the period means we additionally derive a seasonal displacement volume, the difference between the growing season flow

volume of the natural period and that of a later period, which expresses the alteration in units directly relevant to downstream planning (Table 3). The link between reservoir operation and downstream flow was quantified by correlation and ordinary least squares regression of annual Uchkurgan discharge on annual Toktogul release.

Table 3. Flow regime indicators.

Indicator	Definition	Unit	Hydrological Meaning
Monthly mean discharge, Q_m	Mean discharge of month m (m = I to XII)	$m^3\ s^{-1}$	Magnitude of flow in each month; basis of all other indicators
Annual mean discharge, Q	$Q = \Sigma\ d_m Q_m / \Sigma\ d_m$	$m^3\ s^{-1}$	Total water supply of the year
Growing season share, S	$S = \Sigma$(IV to IX) V_m / Σ(I to XII) V_m	%	Fraction of the annual volume arriving in the irrigation season
Seasonal ratio, K	$K = \Sigma$(X to III) V_m / Σ(IV to IX) V_m	dimensionless	Balance of cold-season to warm-season flow; K > 1 means winter dominance
Highest and lowest monthly mean, Qmax and Qmin	max Q_m and min Q_m within the year, with the month of occurrence	$m^3\ s^{-1}$; month	Magnitude and timing of the seasonal extremes
Centre of timing, CT	$CT = (365.25/2\pi)\ \mathrm{atan2}(\Sigma\ V_m \sin \theta_m, \Sigma\ V_m \cos \theta_m)$	day of year	Phase of the annual cycle: calendar position of the year's flow mass
Circular concentration, R	$R = \sqrt{[(\Sigma\ V_m \cos \theta_m)^2 + (\Sigma\ V_m \sin \theta_m)^2]} / \Sigma\ V_m$	0 to 1	Concentration of flow around CT; 1 if all flow fell in one instant, 0 if spread evenly
Gini coefficient, G	$G = \Sigma_i\ (2i - 13)\ V_{(i)} / (12\ \Sigma\ V_m)$, with $V_{(i)}$ ranked in ascending order	0 to 1	Inequality of the monthly volumes, independent of phase; 0 if all months were equal
Interannual coefficient of variation, CV	CV = s(Q)/mean(Q) within a period	dimensionless	Year to year variability of annual flow
Seasonal displacement volume, ΔV	ΔV = W(IV to IX, period I) − W(IV to IX, period k)	$km^3\ yr^{-1}$	Mean volume moved out of the growing season relative to the natural period

Note: Q_m, mean discharge of month m; d_m, its length in days (28.25 for February); $V_m = d_m Q_m$, its flow volume; $\theta_m = 2\pi t_m / 365.25$, with t_m the mid-date of month m as day of year; W(IV to IX), mean April to September flow volume of a period. Seasonal sums refer to months of the same calendar year. Source: authors' elaboration after [4,24,41].

Three analyses address the attribution of the change. First, the regime indicators were computed for every complete year at the Naryn town gauge and tested in the same way as at Uchkurgan; because the headwater catchment lies above the cascade, any shift in its timing or seasonal share reflects changing climate and inflow rather than operation. Temperature and precipitation trends at the two weather stations were estimated with Sen's slope and tested with the variance-corrected Mann–Kendall test. Second, a paired-gauge counterfactual estimated what Uchkurgan would have recorded in 2008 to 2021 had the river remained unregulated. For each calendar month, discharge at Uchkurgan was regressed on discharge at Naryn town over the common pre-regulation years (1933 to 1971, 37 complete years), and the twelve regressions were applied to the Naryn town record of 2008 to 2021 (model A). As a check that does not depend on the regressions, the pre-regulation Uchkurgan climatology was scaled month by month by the ratio of Naryn town flow in 2008 to 2021 to its pre-regulation mean (model B). The difference between the observed natural regime and the counterfactual is attributed to changing inflow, and the difference between the counterfactual and the observed regulated regime to operation. Uncertainty in model A was estimated by resampling years in both periods, with resampled monthly regression residuals added to the counterfactual, 3000 times. Third, the daily balances of 2022 and 2023 were divided into the six cold-season months (January to March and October to December) and the six months from April to September, and in each the

volume drawn from or added to storage was computed as the difference between release and inflow.

4. Results

4.1. Stable Volume, Restructured Timing

Annual volume at Uchkurgan is statistically stable across the record. The annual mean discharge over 1930 to 2021 shows no significant monotonic trend (Figure 2a; $Z = 0.71$, $p = 0.48$), and the Pettitt test finds no significant break in the annual series ($p = 0.09$). Mean annual flow was 393 $m^3\ s^{-1}$ in the natural period (I) and 407 $m^3\ s^{-1}$ under the consolidated energy regime (V, 2008 to 2021). Every seasonal indicator, by contrast, changed profoundly (Table 4). The growing season share of annual flow carries a strong negative trend and a break in 1986 (Figure 2b), after which its mean dropped from around three quarters to under two fifths. January flow rose at 6.1 $m^3\ s^{-1}$ per year with a break in 1981; June flow fell at 10.0 $m^3\ s^{-1}$ per year with a break in 1973, the first full year of impoundment. The highest monthly mean of the year broke downward in 1973 and the lowest monthly mean broke upward in 1987. The seasonal series are strongly autocorrelated, with lag-one coefficients between 0.32 and 0.94, the highest values belonging to the share and ratio series whose step change itself generates the persistence. After variance correction for serial correlation every seasonal indicator remains significant at the 0.05 level (growing season share $p = 0.003$, seasonal ratio $p = 0.005$, centre of timing $p = 0.025$, Gini coefficient $p < 0.001$, January mean $p = 0.013$, lowest monthly mean $p = 0.037$), while the more conservative pre-whitened test retains all but the seasonal ratio and the lowest monthly mean. Because the alteration is a step rather than a gradual drift, the change point tests rather than the trend tests carry the inferential weight in what follows.

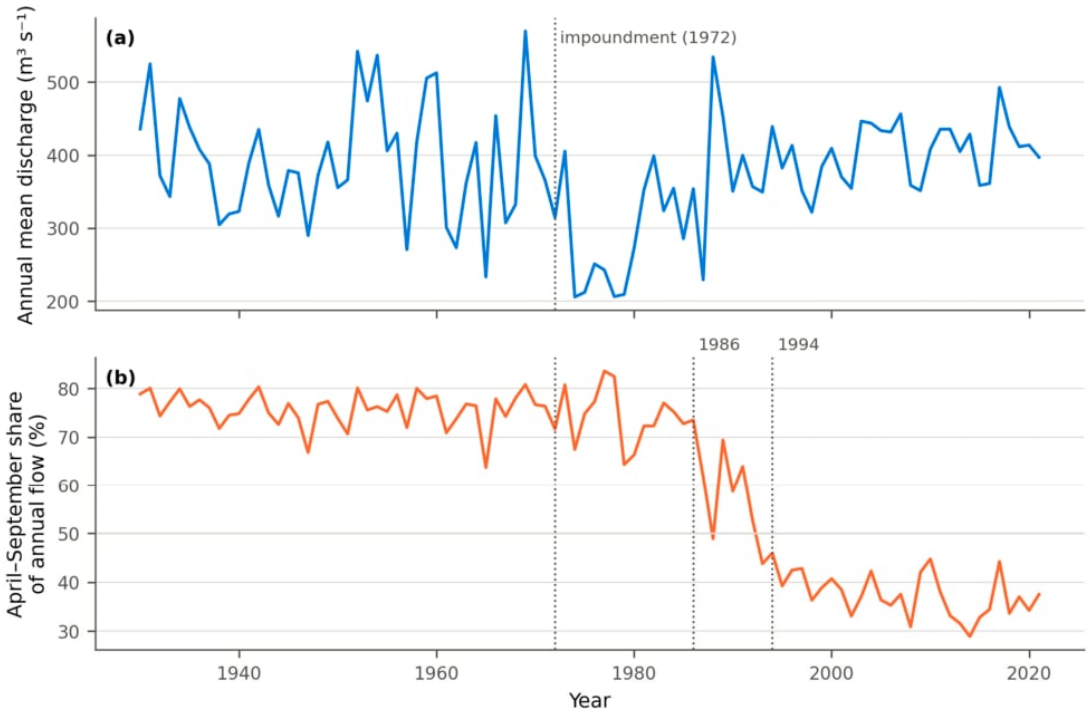


Figure 2. Annual flow and its growing season share, 1930 to 2021. Note: (**a**) annual mean discharge at Uchkurgan; (**b**) April to September share of annual flow. Dotted lines mark the 1972 impoundment and the 1986 and 1994 change points. Source: computed from Uzhydromet records.

Table 4. Trend and change point statistics for flow indicators, 1930 to 2021.

Indicator	MK Z	MK *p*	Sen Slope (yr^{-1})	Break Year	Pettitt *p*	Mean Before	Mean After
Annual mean (m^3 s^{-1})	0.71	0.48	+0.23	1987	0.09	364	405
Apr–Sep share of annual flow	−8.35	<0.001	−0.54% pt	1986	<0.001	75%	40%
Oct–Mar/Apr–Sep ratio	8.35	<0.001	+0.018	1986	<0.001	0.35	1.55
January mean (m^3 s^{-1})	7.34	<0.001	+6.11	1981	<0.001	147	554
June mean (m^3 s^{-1})	−7.55	<0.001	−10.0	1973	<0.001	999	389
July mean (m^3 s^{-1})	−7.06	<0.001	−6.66	1991	<0.001	764	344
Highest monthly mean (m^3 s^{-1})	−4.37	<0.001	−4.45	1973	<0.001	1028	675
Lowest monthly mean (m^3 s^{-1})	3.13	0.002	+0.68	1987	<0.001	133	205
CT of annual flow (day of year)	−6.80	<0.001	−1.91	1990	<0.001	178	31
Gini of monthly flow shares	−6.25	<0.001	−0.0024	1986	<0.001	0.36	0.21

Note: Z, *p* and Sen slope from the Mann–Kendall test; break year and *p* from the Pettitt test; means refer to the sub-periods before and after the break. CT, centre of timing, as day of year with December of the preceding calendar year counted negatively. Source: computed from Uzhydromet records. Significance after correction for serial correlation and the uncertainty windows of the break years are reported in the text.

The natural period itself behaves as a single stationary baseline. Over 1930 to 1971 none of the four regime indicators carries a trend after correction for serial correlation (annual mean $p = 0.58$, growing season share $p = 0.76$, centre of timing $p = 0.21$, Gini coefficient $p = 0.57$) or a significant Pettitt break (p between 0.34 and 0.92), and none fails the standard normal homogeneity, Buishand or von Neumann test at the 5% level. Neither half of the period has a significant trend in the growing season share ($p = 0.09$ for 1930 to 1950 and 0.79 for 1951 to 1971) or in the centre of timing ($p = 0.93$ and 0.26), and the halves do not differ: the growing season share averaged 75.9% and 75.7% and the centre of timing fell on day 180 and day 182 (Mann–Whitney $p = 0.82$ and 0.35). The only inhomogeneity lies in the two lowest months. January and February flows dropped in 1961 and 1962 (Pettitt $p = 0.010$ and 0.007; standard normal homogeneity statistic 16.2 and 15.4 against a 5% critical value of about 8.5), from 163 and 162 m^3 s^{-1} in 1930 to 1961 to 123 and 127 m^3 s^{-1} in 1962 to 1971. The step coincides with the closure of the river at Uch-Kurgan in October 1961 and the start of the station in December of that year, immediately above the gauge. It outlasts by far the filling of a reservoir of 52.5 million m^3, and the station history does not explain why it persisted, so we treat it as an effect of the first station of the cascade on low flows at the gauge. Because January and February carried only about 6% of the natural annual volume, the step leaves the annual and seasonal indicators homogeneous, and ending the baseline in 1961 changes the principal results only slightly: the natural growing season share becomes 75.9% instead of 75.8%, the phase displacement 163 instead of 164 days, the displacement volume 5.00 instead of 4.83 km^3, and the ratio of January flow under the consolidated energy regime to its natural mean 3.9 instead of 4.2.

The change point analysis condenses the history of the river into a sequence of transitions rather than three exact dates. The first, in 1972 and 1973, is the impoundment itself: it appears in the summer months and in the annual maxima, which respond to any storage of the flood wave regardless of the purpose of storage, and its uncertainty window is narrow (1970 to 1974 for the annual maximum). The second is the onset of seasonal redistribution: the growing season share, the seasonal ratio and the Gini coefficient all place their principal Pettitt break in 1986. The windows around these breaks are wide, from 1977 to 1993, because the Pettitt statistic is flat-topped when a transition unfolds in steps, and the joint

segmentation methods resolve the transition accordingly: for the growing season share and the seasonal ratio, PELT and binary segmentation both start new segments in 1987 and in 1992 or 1993, while PELT segments the Gini coefficient once, in 1990. The centre of timing registers its principal single break in 1990, the midpoint of a rotation that the segmentation methods split into steps beginning in 1988 and 1993. The third transition, in 1993 and 1994, is the consolidation of winter-dominant operation: it appears when the Pettitt test is repeated on the post-1971 sub-series of the seasonal ratio and coincides with the last segment boundary that PELT and binary segmentation agree on. Beyond 1994 the recursive Pettitt search finds no further significant break (best candidate 2011, $p = 0.13$); PELT adds minor segments in the share and ratio series (1979 and 1998 in the share, 1998, 2012 and 2016 in the ratio) that have no counterpart in the timing or concentration series and do not alter the seasonal state. The five-period scheme used in the regional literature is thus partly confirmed: its boundaries near 1987 and 1994 correspond to real structural breaks, but its last two periods, 1995 to 2007 and 2008 to 2021, belong statistically to a single consolidated state.

4.2. Seasonal Redistribution

Figure 3 shows what the breaks did to the shape of the year. The natural hydrograph, drawn as the dashed reference in both panels, was a snowmelt regime: a single broad peak from May to August carrying just over three quarters of the annual volume, with June the highest month in most years and January the lowest. In the irrigation-dominated period (II) the peak flattened as the reservoir filled, but the summer orientation of releases preserved the phase of the cycle (Figure 3a). The transitional period (III) appears in the same panel as an intermediate shape with an emerging winter limb. In the two energy-regime periods (IV and V) the cycle is fully inverted (Figure 3b): the hydrograph peaks in December and January and reaches its minimum in September, the mirror image of the natural regime.

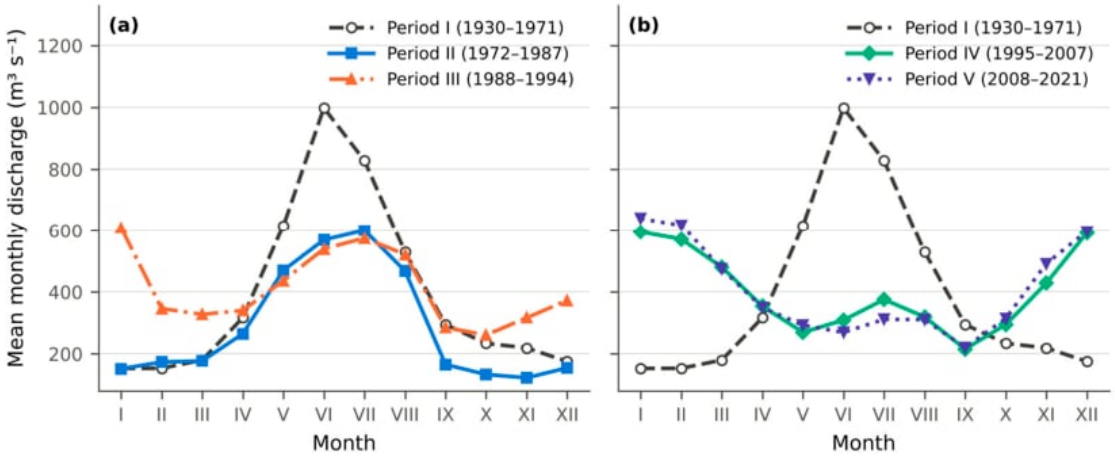


Figure 3. Mean monthly discharge by period. Note: (**a**) periods I, II and III; (**b**) periods I, IV and V; the natural period I is dashed in both panels. Source: computed from Uzhydromet records.

Against the natural baseline of period I, the consolidated energy regime (V) raises winter flows by factors of three to four and cuts summer flows by half to nearly three quarters (Figure 4). January flow is 4.2 times its natural mean, December 3.4 times, while June carries 27% and July 38% of their natural values. The growing season share falls from 75.8% to 35.9% between periods I and V, and the ratio of cold season to warm season flow rises from 0.32 to 1.84 (Table 5). Period II stands apart in volume rather than shape: its mean annual flow, 289 m^3 s^{-1}, is the lowest of any period, reflecting the filling of 19.5 km^3 of storage on top of a run of dry years in the 1970s and 1980s.

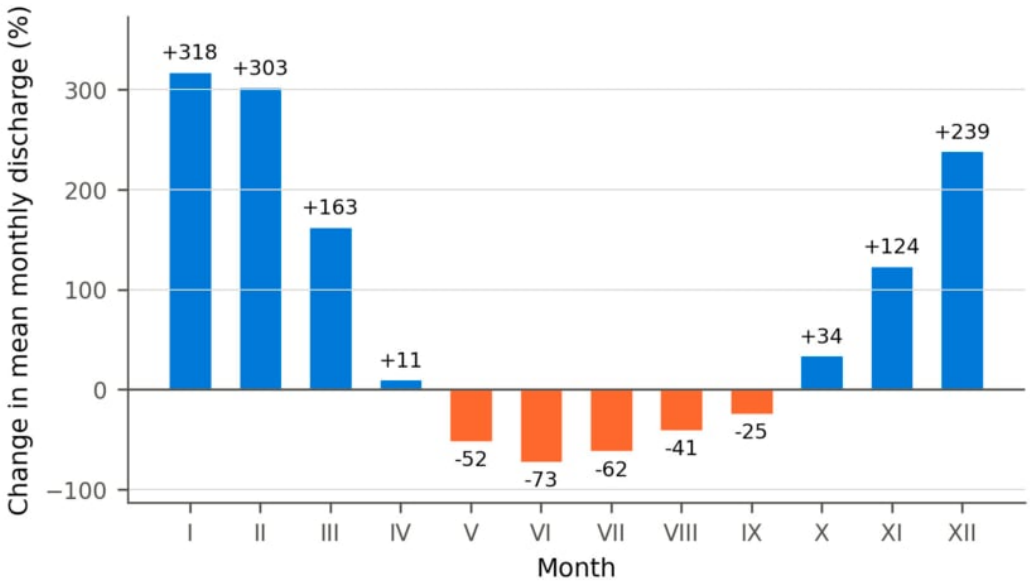


Figure 4. Monthly flow change between periods V and I. Note: percentage change in mean monthly discharge from 1930–1971 to 2008–2021. Source: computed from Uzhydromet records.

Table 5. Flow regime characteristics by period.

	I 1930–1971	II 1972–1987	III 1988–1994	IV 1995–2007	V 2008–2021
Years	42	16	7	13	14
Annual mean (m^3 s^{-1})	393	289	412	400	407
W (km^3)	12.40	9.11	13.00	12.62	12.84
Apr–Sep share (%)	75.8	73.4	54.8	38.5	35.9
Oct–Mar/Apr–Sep ratio	0.32	0.37	0.88	1.62	1.84
Highest monthly mean (m^3 s^{-1})	1030	666	881	618	682
Lowest monthly mean (m^3 s^{-1})	146	98	228	194	205
Modal peak month	June	July	July	January	December
Modal minimum month	January	January	September	September	September
CV of annual mean	0.20	0.24	0.17	0.11	0.10

Note: W, mean annual flow volume; CV, interannual coefficient of variation in annual mean discharge; highest and lowest monthly means averaged within each period. Source: computed from Uzhydromet records.

Regulation has also compressed variability at both ends of the regime. The mean of the highest monthly discharge of the year fell from 1030 to 682 m^3 s^{-1} between periods I and V, a reduction of 34%, while the mean of the lowest monthly discharge rose from 146 to 205 m^3 s^{-1}, an increase of 40%. The interannual coefficient of variation in annual flow halved, from 0.20 in the natural period (I) to 0.10 under the consolidated energy regime (V). The reservoir thus does exactly what an interannual regulator is designed to do, smoothing both the seasonal cycle and year to year differences; the point at issue is that the smoothing now serves a winter peak.

4.3. The Rotation and Flattening of the Annual Cycle

Decomposing the alteration into phase and concentration shows that these are two distinct processes (Figure 5, Table 4). The centre of timing of annual flow held at late June, near day 180, for more than half a century (Figure 5a), through impoundment and the whole irrigation-dominated period (II): storing the flood and releasing it for summer irrigation left the calendar of the river intact. From the late 1980s the centre of timing collapses. It swings widely during the transitional period (III), snapping back to summer in the high-water years around 1990, when ample inflow allowed summer releases, and

settles at mid January, near day 16, from 1994 onward. The net phase displacement between the natural period (I) and the consolidated energy regime (V) is 164 days (bootstrap 95% interval 158 to 173 days), close to the maximum possible of half a year. The trend and break statistics confirm the visual reading: the centre of timing falls at 1.9 days per year over the full record, with its principal Pettitt break in 1990, inside an uncertainty window of 1980 to 1995 and at the midpoint of a collapse that the joint segmentation methods resolve into steps in 1988 and 1993.

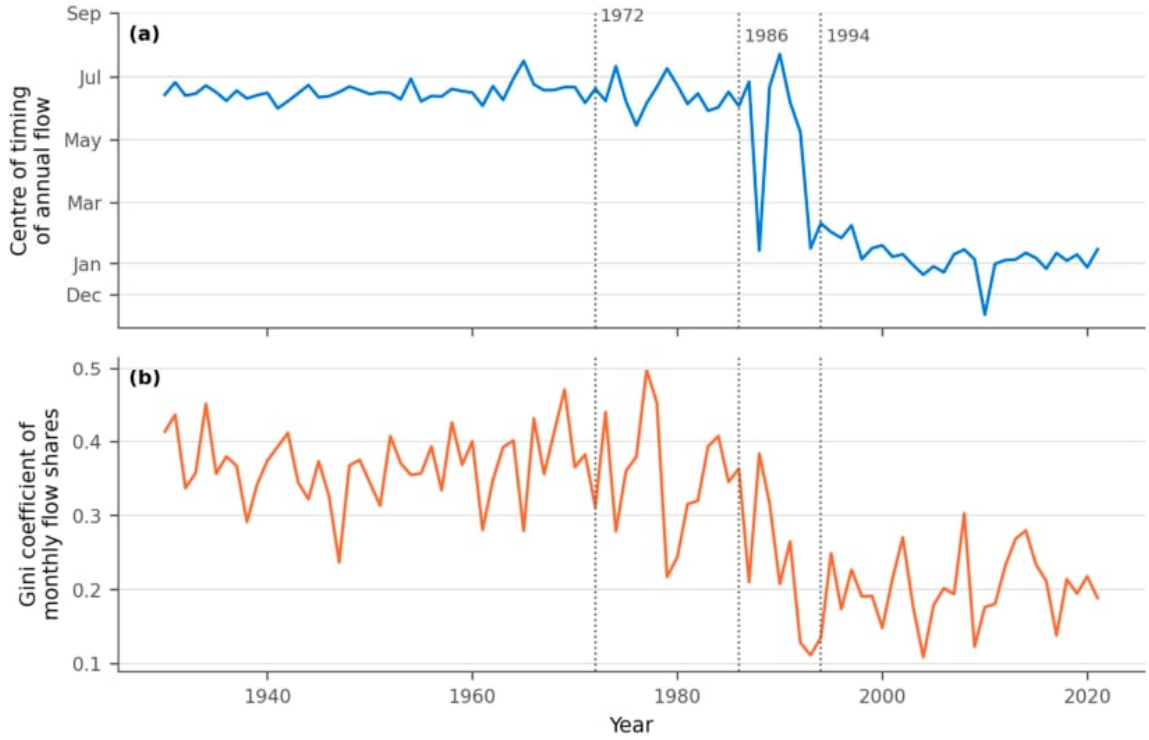


Figure 5. Timing and concentration of annual flow. Note: (**a**) centre of timing, with December values of the preceding calendar year shown below the January line; (**b**) Gini coefficient of the twelve monthly flow shares. Dotted lines as in Figure 2. Source: computed from Uzhydromet records.

Concentration followed a different path. The Gini coefficient of monthly flow shares declined from a natural mean of 0.37 to 0.21, with its break in 1986 (Figure 5b), and the circular concentration of the annual cycle roughly halved. The flattening therefore began with the operational transition, before the phase had fully rotated, and the two metrics separate what a single monthly comparison conflates: the cascade first blunted the annual cycle and then rotated its phase. Expressed as volume, the rotation moved 4.83 km^3 (bootstrap 95% interval 4.03 to 5.60 km^3) of an average year out of the growing season: April to September carried 9.46 km^3 in period I and carries 4.63 km^3 in period V, while the annual total is essentially unchanged. This displacement volume quantifies the mean annual volume shifted out of the growing season and therefore provides a first-order measure of the seasonal re-regulation challenge; it is not itself a storage requirement, which would depend on inflow and release trajectories, target reliability, losses, operating rules and existing infrastructure. None of these results depends on the two reconstructed years: excluding 1963 and 1965 moves the natural period growing season share from 75.8% to 76.1%, leaves the phase displacement within one day of its value, changes the displacement volume from 4.83 to 4.97 km^3, and leaves every break year unchanged except that of the Gini coefficient, which shifts from 1986 to 1988 within the same transition window.

4.4. Headwater Inflow and the Counterfactual Regime

The unregulated headwater record offers the most direct check on whether climate, rather than operation, moved the river's calendar (Figure 6). At Naryn town annual flow is as stable as at Uchkurgan: it averaged 89.4 m^3 s^{-1} before 1972 and 89.0 m^3 s^{-1} in 2008 to 2021, with no trend ($p = 0.65$), and the growing season share stayed near 82% (82.7% and 82.0%; trend $p = 0.06$). The timing of headwater flow did change. Its centre of timing advanced significantly ($p < 0.001$), with a Pettitt break in 1977 ($p < 0.001$), from day 195 before 1972 to day 190 in 2008 to 2021, a shift of 4.9 days towards spring (Figure 6a). Both weather stations warmed over 1960 to 2022, by 0.36 °C per decade at Naryn and 0.48 °C per decade at Tien-Shan in the annual mean and by 0.30 and 0.29 °C per decade from April to September (all $p < 0.001$), while precipitation showed no significant annual trend at either station and a modest cold-season increase of 5.7 mm per decade at Tien-Shan ($p = 0.03$). Year to year, April to June temperature is only weakly and not significantly related to the headwater timing (r = −0.17 at Naryn and −0.24 at Tien-Shan). The climate signal expected in the headwaters is therefore present in these data, but at the scale of days: the five-day advance at Naryn town is comparable to snowmelt timing shifts reported elsewhere [24], while over the same years the centre of timing at Uchkurgan moved by 164 days.

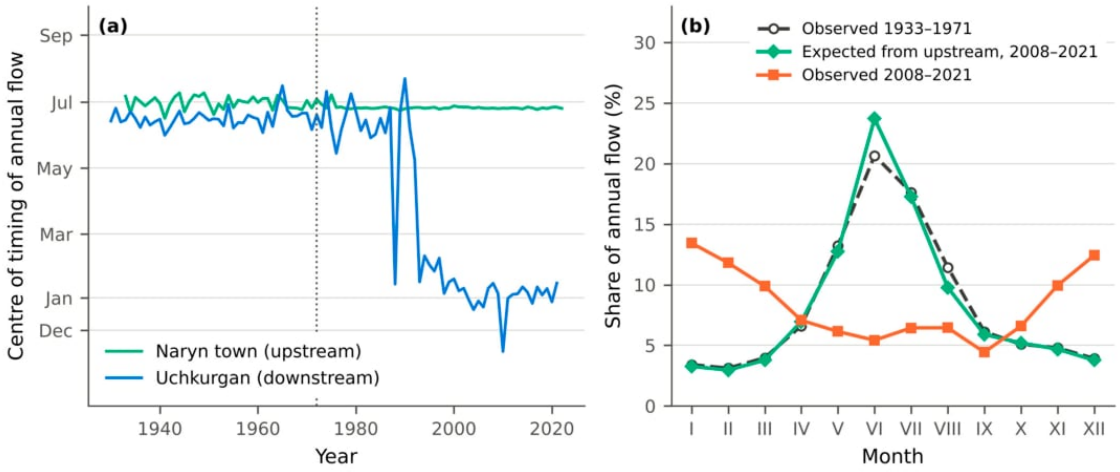


Figure 6. Headwater timing and the counterfactual regime. Note: (**a**) centre of timing of annual flow at the Naryn town gauge (upstream, unregulated) and at Uchkurgan, with December values shown below the January line; the dotted line marks the 1972 impoundment; (**b**) monthly shares of annual flow at Uchkurgan observed in 1933 to 1971 and in 2008 to 2021, and expected in 2008 to 2021 from the Naryn town record with the pre-regulation monthly regressions (model A). Source: computed from Uzhydromet records.

Before regulation the two gauges varied together. Their annual means correlate at r = 0.60, their growing season shares at r = 0.58 and their centres of timing at r = 0.36 (n = 37, all $p < 0.03$). The monthly regressions explain much more of the variance in summer (R^2 up to 0.65 in June) than from November to March (R^2 below 0.1), when most of the flow at Uchkurgan came from the larger catchment below the headwater gauge. Driven by the headwater record of 2008 to 2021, the counterfactual keeps Uchkurgan in a summer regime (Figure 6b): its centre of timing falls on day 179 (model A) or day 177 (model B), against day 181 in the calibration years, and its growing season share is 76.3% or 75.7%, against 75.7%. Changing inflow thus accounts for a phase shift of 2.6 days (model A; bootstrap 95% interval −1.4 to 6.5) or 4.7 days (model B) and for less than one percentage point of the change in growing season share, while operation accounts for 162.0 days (155.3 to 171.2) or 160.0 days of the phase displacement and for 40.4 (37.4 to 42.9) or 39.7 percentage points of

the loss in growing season share. Whichever model is used, changing inflow explains less than 5% of the displacement in timing observed at the border gauge.

4.5. The Reservoir at Daily Resolution, 2022 and 2023

The daily balances of Toktogul in 2022 and 2023 show the consolidated regime in operation (Figure 7). In both years the inflow hydrograph retains the natural snowmelt shape (Figure 7a for 2022, Figure 7b for 2023), with about three quarters of annual inflow arriving between April and September (75.5% in 2022, 75.0% in 2023). The release hydrograph is close to its mirror image: only 37.7% and 41.6% of annual releases fell in those months. In January 2022 the reservoir released a mean of 749 m^3 s^{-1} against an inflow of 155 m^3 s^{-1}, and in January 2023 a mean of 784 m^3 s^{-1} against 144 m^3 s^{-1}, ratios of 4.8 and 5.4. At the opposite pole, on the day of maximum inflow, 1426 m^3 s^{-1} on 9 May 2022 and 1475 m^3 s^{-1} on 17 June 2023, the release was 251 and 389 m^3 s^{-1}, so that 82% and 74% of the peak day's water went into storage. Annual releases exceeded inflow in both years, 13.75 against 11.59 km^3 in 2022 and 12.89 against 12.21 km^3 in 2023, and storage declined accordingly over each year (Figure 7c), from 12.25 to 10.15 km^3 in 2022 and from 11.08 to 10.45 km^3 in 2023.

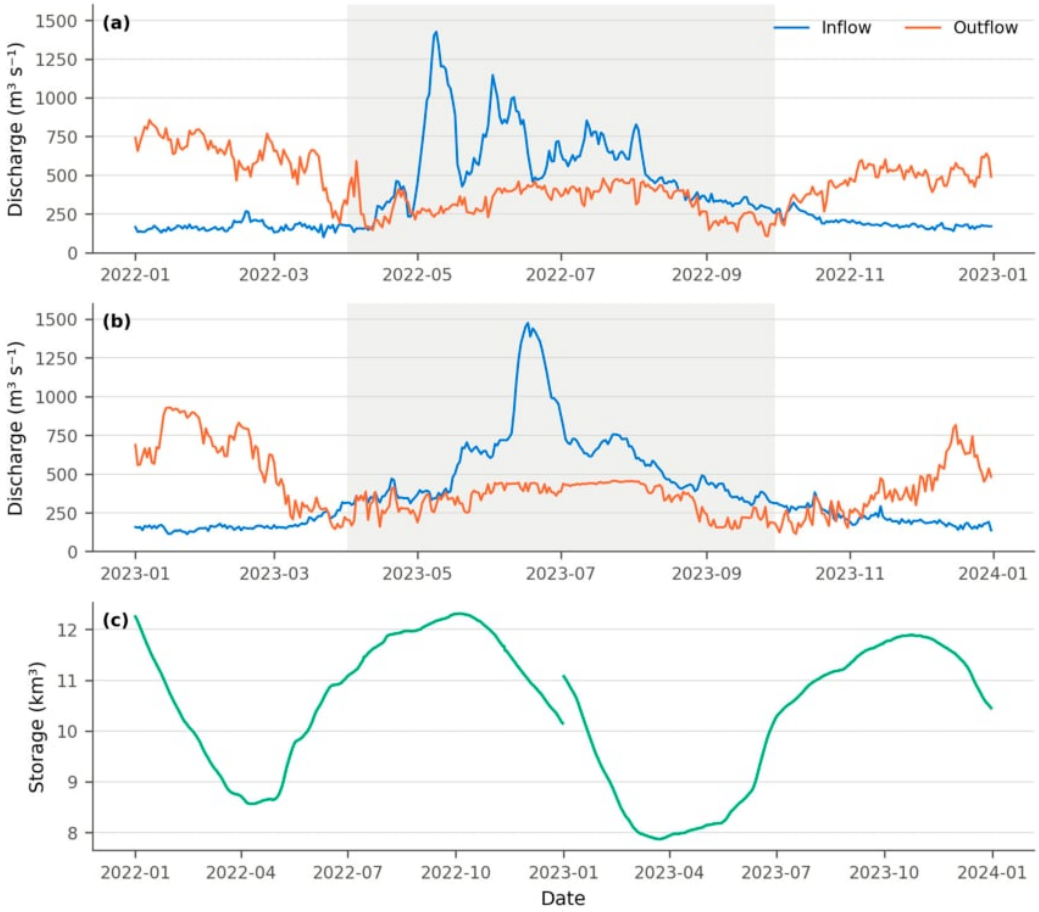


Figure 7. Daily water balance of the Toktogul reservoir, 2022 and 2023. Note: (**a**,**b**) inflow and release, with shading marking April to September; (**c**) storage, the two years drawn separately because the published series are not continuous across the year boundary. Source: Electric Power Plants JSC (www.energo-es.kg).

The storage trajectory shows how the inversion is produced (Figure 7c). From April to September the reservoir retained 3.57 km^3 in 2022 and 3.79 km^3 in 2023, 41% of the inflow in both years, and storage rose from its minimum of 8.57 km^3 on 10 April 2022 and

7.87 km^3 on 23 March 2023 to its maximum of 12.31 km^3 on 4 October 2022 and 11.89 km^3 on 23 October 2023. In the six cold-season months of each year the operation reversed: storage supplied 5.72 km^3 in 2022 and 4.47 km^3 in 2023, 67% and 59% of the release in those months. Winter generation is thus carried by water captured in the melt season, and the seasonal displacement measured at Uchkurgan is the downstream image of this annual cycle of filling and drawdown. The monthly water balances close to within 23 m^3 s^{-1}, so the inflow, release and storage records are mutually consistent and the decomposition is not an artefact of the data.

The daily balances also bear on attribution. The monthly distribution of inflow to Toktogul in these two years correlates at r = 0.93 and r = 0.98 with the monthly distribution of the pre-impoundment gauge record, and its growing season share, 75%, matches the natural share of 76% almost exactly. The monthly distribution of releases correlates negatively with the same natural pattern. In these two years the regime arriving at the reservoir is still, in its seasonal shape, the regime the gauge recorded before 1972, and the regime leaving it is inverted, so the seasonal transformation occurs between the reservoir's inlet and its outlet. Two years cannot show what inflow looked like across the whole post-1972 period, so this evidence corroborates the operational reading for the present regime, while the headwater comparison and the counterfactual extend it across the whole record.

4.6. From the Dam to the Border Gauge

Whatever Toktogul releases, Uchkurgan largely receives. Over 1975 to 2020 the annual mean release and the annual mean discharge at the gauge move in near synchrony (Figure 8a), and the regression of gauge discharge on release explains 77% of the interannual variance (r = 0.878, $n = 46$, $p < 0.001$; Figure 8b). The scatter is widest in the low-flow years of the filling period and tightens along the regression line at higher discharges, which correspond to the post-1990 energy regime. A slope of 0.88 with a small intercept indicates that the lower cascade, with its negligible useful storage, transmits most of the release signal; the departure of the slope from unity and the residual scatter reflect lateral inflows and abstractions between the dam and the gauge, small storage changes in the re-regulating ponds, differences between operator and gauge measurement, and annual aggregation. Since the two series are hydrologically connected mass flows, the relationship establishes transmission of annual volume rather than operational control of seasonality, which would require monthly release records that are not available to us. At annual resolution, however, the Naryn entering Uzbekistan is an operated flow.

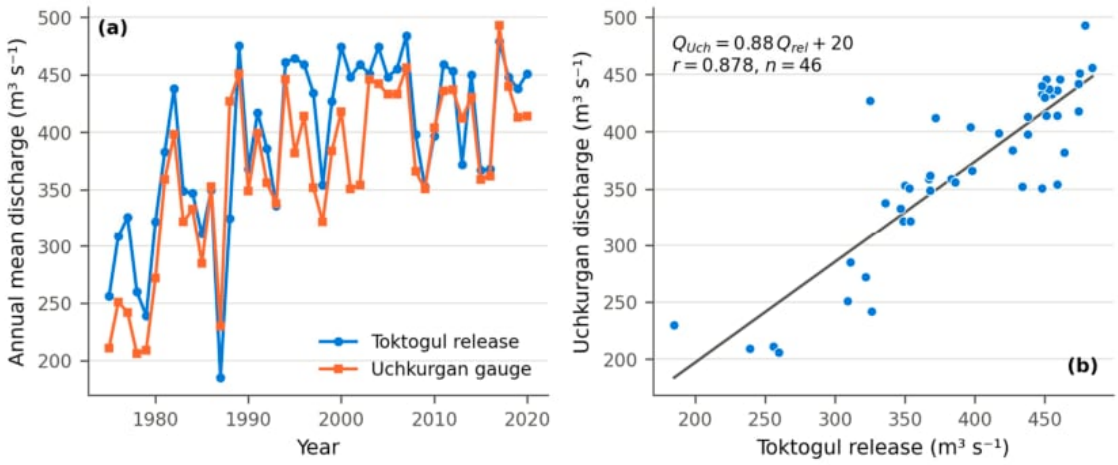


Figure 8. Toktogul releases and Uchkurgan discharge, 1975 to 2020. Note: (**a**) annual mean series; (**b**) their relationship with the least squares fit. Source: operator reporting and Uzhydromet records.

5. Discussion

5.1. An Inverted River on the Spectrum of Alteration

Judged by annual volume, the Naryn is unimpaired; judged by regime, it has been turned upside down. This distinction is the central lesson of the natural flow regime literature [3,4], and the Naryn offers an unusually clean demonstration because annual flow is trend-free over nine decades. A stable annual total does not by itself exclude climatic redistribution within the year, and the headwaters have indeed warmed; but the unregulated gauge above the cascade kept its summer regime and advanced its timing by about five days, and the counterfactual built from it assigns no more than a few days of the downstream displacement to changing inflow. Reservoir operation is therefore the dominant driver of the observed inversion, with climate a measurable but minor contributor to the change in timing. What the timing metrics add is a sense of scale. The literature on streamflow timing treats shifts in one to four weeks per half century, driven by earlier snowmelt, as major findings [24], continental analyses of flood timing report displacements of days to a few weeks over similar spans [25], and spectral analyses of dammed rivers show regulation rewriting the dominant periodicities of flow rather than merely damping them [42]. The Naryn's centre of timing moved 164 days. The metrics, resolutions and settings of those studies differ from ours, so the comparison is directional rather than like for like, but the displacement observed here is substantially larger than the week-scale shifts commonly reported for climate-driven change, and it moved the river's calendar in a direction that warming-driven snowmelt change does not.

The comparison with other regulated rivers sharpens the point. On the Mekong, the filling and operation of the Lancang cascade raised dry-season discharge at Chiang Saen by 121 to 187% in the most affected months of 2014 and cut wet-season flows by roughly a third to a half, changes that generated a substantial literature and considerable interstate friction [26]. On the Lena, regulation by the Vilyui reservoir reduced summer flows by up to 55% and raised winter low flows by up to thirty times [43], a winter augmentation larger in ratio than the Naryn's. What distinguishes the Naryn is not the size of any single monthly change but the completeness and persistence of the inversion: January flow has run at 318% above its natural mean for three decades, sustained rather than episodic, and the centre of timing has crossed from one half of the year to the other. On the spectrum of documented dam-induced seasonal alteration the lower Naryn sits with the most heavily regulated cold-region rivers, at the end where the natural signal is replaced rather than attenuated. Ecological consequences are to be expected rather than demonstrated here. This study contains no biological observations from the Naryn, but the environmental flows literature finds degraded ecological metrics in the overwhelming majority of systems subject to far smaller alterations [5], and even small hydropower schemes have been shown to restructure downstream fish assemblages within a decade of operation [44]. The compression of extremes cuts both ways: the 34% reduction in the annual maximum lowers flood risk along the middle Syr Darya, while the 40% rise in the annual minimum, in most systems a benefit, here arrives with the minimum displaced to September, the tail of the irrigation season. Variability has not disappeared; it has been transferred from the hydrograph into the reservoir's storage trajectory, and thereby from a natural risk into an operational one.

5.2. The Hydrograph as a Socio-Hydrological Record

Socio-hydrology asks that rivers be studied as parts of coupled human–water systems whose feedbacks leave traces in the water record [27,28]. The Naryn is a strong case of such coupling: after 1994 the seasonal structure of its flow at Uchkurgan is set predominantly by release scheduling rather than by weather, and the hydrograph can be read as an institutional record as well as a hydrological one. Reading it that way requires keeping three levels of

claim apart. What the data establish is that statistical breaks occurred around 1986, 1990 and 1994. What the documentary record establishes is that these years fall within the known transition of Toktogul from irrigation-oriented to energy-oriented operation [20]. What remains interpretation is why operating practice changed when it did, and on that level we offer a reading, not a demonstration. The 1986 break precedes the dissolution of the Soviet Union by five years, which cautions against the shorthand that attributes the regime shift wholly to 1991: the reorientation of releases began while the barter system of summer water for winter fuel was still nominally in place, and one plausible interpretation is that the system was already under strain in the late Soviet period. The hydrological data cannot establish this on their own; the operational archives of the period would be needed to test it. The 1994 break coincides with the contraction of the successor states' fuel deliveries to Kyrgyzstan documented in the political science literature [7–10]. The wobble of the centre of timing in the transitional period is consistent with the same reading: in the high-water years around 1990 it returned to summer, as would be expected if abundance temporarily relaxed the trade-off between energy and irrigation. The absence of any further significant break after 1994 is a finding at the first level, and its correspondence with three decades of negotiation, including the framework agreements of the late 1990s, is a finding at the second: whatever those agreements achieved, they did not move the seasonal regime at Uchkurgan. The trilateral arrangements on Toktogul releases concluded by Kyrgyzstan, Uzbekistan and Kazakhstan in the mid 2020s will, if effective, eventually appear in this record as a further change point, and the series analysed here provides the baseline against which any such shift can be measured.

5.3. Attribution, Limitations and Ways Forward

The attribution of the documented alteration to reservoir operation rests on four lines of evidence. Annual flow carries no trend at either gauge, so the total water supply did not change. The break years at Uchkurgan coincide with documented operational transitions, whereas the headwater timing changed by days rather than months, with its break in 1977. The counterfactual driven by the headwater record keeps Uchkurgan in a summer regime and assigns 160 to 162 days of the 164 day displacement, and about 40 percentage points of the loss in growing season share, to operation. And the daily balances of 2022 and 2023 show a natural-shaped inflow entering the reservoir and an inverted release leaving it, with the seasonal transfer carried by storage. This design falls short of a full naturalisation. The headwater gauge drains only about 18% of the catchment above Uchkurgan, so climatic change in the lower catchment enters the counterfactual only through its pre-regulation relation with the headwaters; the monthly regressions are weak in winter; and the weather records begin in 1960. Contemporary attribution studies go further by reconstructing natural flow statistically from pre-dam relations between streamflow and climate covariates [45], with machine learning trained on a reference period [46], or by explicit separation of natural and regulated runoff in a transboundary basin [47], and regression-based reconstruction of monthly flows on the Lena showed how downstream records mix reservoir and climate signals in ways that bias trend estimates [43]. The bound obtained here is nevertheless tight enough to settle the order of magnitude: for climate to explain the inversion, the catchment below Naryn town would have had to move the timing of its flow by months while the headwaters moved theirs by days, although before regulation the two parts of the catchment varied together. Climate change is present all the same and will not remain a background factor. Modelling of the Naryn basin projects peak runoff advancing by about a month with higher spring and lower summer flows [13], and a high-resolution assessment under a high-emission scenario projects runoff declining by 16% basin-wide by late century, with the seasonal snowpack peaking a month earlier [15]. Those changes would move

the natural calendar by weeks, consistent in direction with the five-day advance already measured at Naryn town, which is one reason a half-year displacement is implausible as a climatic effect; the two processes will nonetheless interact, since an advancing melt season and declining total flow alter both the volume available for winter generation and the inflow forecasts on which storage decisions rest, so the displacement volume of 4.83 km^3 should be read as a present-day, not a stationary, quantity.

Four limitations bound the interpretation. First, the analysis works at monthly resolution, so the sub-monthly indicators of the full alteration suite, rise rates, reversals and one-day extremes, are outside its reach; the two years of daily balances partially compensate, and a parsimonious monthly indicator set is defensible on redundancy grounds [41], but a multi-decadal daily record at Uchkurgan would allow a complete assessment. Second, the separation of climate and regulation effects achieved here is a bound derived from the headwaters, not a naturalisation of the whole catchment. Suitable tools exist for this basin: a snow and glacier hydrological model has been demonstrated at monthly resolution for the Naryn [14], and statistical reconstruction of naturalised flows has recently been applied in the neighbouring Ili basin [48]; applying either to the Uchkurgan record, with the station climate series analysed here as forcing, is the natural next step. Third, two years of the archival series, 1963 and 1965, are reconstructions from an analogue gauge rather than direct observations; the exclusion test reported with the results shows that no principal result depends on them, and both years fall deep inside the natural period, far from any detected change point. The low-flow step of 1961 and 1962 is likewise immaterial to the principal results, but its persistence could not be explained from the station history. Fourth, the sequential change point search involves conditional testing, so the reported second-level p-values are indicative; we have addressed this by reporting uncertainty windows and by cross-checking with joint segmentation methods, whose agreement on boundaries in 1987 and 1993 is the strongest evidence that the chronology is not an artefact of the search. Sampling uncertainty of this kind is what formal decision frameworks for alteration testing are designed to handle [36].

The practical implication for the downstream states follows directly from the numbers. Under the consolidated regime roughly three fifths of the Naryn's annual volume arrives outside the growing season. Water that once arrived as summer streamflow must now be captured in winter and carried into summer by storage downstream of the border, which explains the renewed interest of Uzbekistan in re-regulating capacity in the Fergana Valley and the middle Syr Darya. The displacement volume computed here, 4.83 km^3 per year, gives that challenge its first-order scale without being a storage requirement, and scenario-based allocation tools of the kind now being applied to other Central Asian transboundary basins [23] could translate it into storage and reliability terms for specific demand nodes, accounting for inflow and release trajectories, losses and existing infrastructure. Quantifying the storage required to restore a given fraction of the natural intra-annual distribution, using the monthly series analysed here as input, is a tractable next step.

6. Conclusions

Ninety-two years of discharge observations at the Uchkurgan gauge show that the Lower Naryn cascade has left the volume of the Naryn's flow statistically unchanged while inverting its calendar. Annual mean discharge carries no significant trend, but the centre of timing of annual flow moved from late June to mid January, a phase displacement of 164 days (158 to 173), the growing season share of annual flow fell from 76% to 36%, and about 4.8 km^3 (4.0 to 5.6) of an average year now arrives outside the growing season that once received it. Change point analysis, cross-checked by joint segmentation methods and robust to serial correlation, to the choice of baseline and to the exclusion of two reconstructed

years, dates the transformation as a sequence: impoundment effects from 1972 and 1973, the onset of seasonal redistribution in 1986, the principal rotation of timing around 1990, consolidation of the winter regime in 1993 and 1994, and no structural change since. The alteration decomposes into two distinct processes, a flattening of the annual cycle that began with the operational transition and a rotation of its phase that followed, and its magnitude is substantially larger than the week-scale timing shifts reported for climate-driven change. The contribution is one of application and synthesis: established tests and timing metrics, combined on an exceptionally long Central Asian record, yield an interpretable chronology and a displacement volume that expresses the result in the units downstream planners use. Over the same decades an unregulated headwater gauge, despite significant warming at two mountain weather stations, advanced its timing by only five days, and a paired-gauge counterfactual assigns two to five days of the downstream displacement to changing inflow and 160 to 162 days to operation. Reservoir operation is the dominant driver of the inversion, and a catchment-wide naturalised flow series would refine rather than overturn that attribution. Toktogul's releases explain 77% of the variance of annual flow at the border gauge, and in the two years for which daily balances exist the seasonal shape of inflow still matches the pre-impoundment record while the shape of releases is inverted, with storage supplying three fifths to two thirds of cold-season release. The Naryn reaching Uzbekistan is, at annual and seasonal resolution, an operated river; its hydrograph can be read as an institutional record, and the series assembled here is the baseline against which any future operational or negotiated change in the basin can be detected.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/hydrology13110297/s1; Files S1 to S9 (the monthly discharge series at Uchkurgan and Naryn town, the annual release and gauge series, the daily reservoir balances for 2022 and 2023, and the monthly temperature and precipitation series of the Naryn and Tien-Shan stations), together with the analysis code (analysis.py, analysis_R1.py) and its outputs, which reproduce every statistic, table and figure.

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Data Availability Statement: The assembled monthly discharge series at Uchkurgan (1930 to 2021) and Naryn town (1931 to 2022), the monthly temperature and precipitation series of the Naryn and Tien-Shan stations (1960 to 2022), the annual release and gauge series (1975 to 2020), the daily reservoir balances for 2022 and 2023, and the analysis code that reproduces every statistic, table and figure are provided as Supplementary Material and will be deposited in a public repository with a persistent identifier on acceptance. The monthly discharge and meteorological series were compiled from the Uzhydromet archive fund. The Toktogul release and daily balance data were obtained from the official website of the open joint-stock company Electric Power Plants of the Kyrgyz Republic (www.energo-es.kg); the historical balance pages have since been removed from that site.

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