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Environmental flow assessment in the Chirchik River Basin using multi-method hydrological indicators

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Abstract

Environmental flow assessment is increasingly important for maintaining riverine ecosystems amid climate variability, reservoir regulation, and rising water demand. However, information on environmental flow requirements remains limited for regulated river basins in Central Asia, including the Chirchik River Basin in Uzbekistan. This study aims to estimate and compare environmental flow requirements at three hydrological stations—Chinaz, Ugam, and G'azalkent—using long-term monthly discharge data from 1971 to 2020. Seven hydrological methods were applied: Tennant, Tessman, average annual flow, flow duration curve, dynamic mean flow, median flow, and flushing-flow assessment. Trend analysis was conducted using the Mann–Kendall test to examine station-wise environmental flow gradients across the basin. The results showed substantial differences among the stations: mean annual flows were 80.4, 23.1, and 227.7 m^3/s at Chinaz, Ugam, and G'azalkent, respectively. The Tessman method yielded seasonal environmental flow ranges of 30.4–63.3 m^3/s, 8.6–22.8 m^3/s, and 91.1–147.1 m^3/s, respectively. The findings indicate that fixed-percentage methods underestimate seasonal ecological requirements, especially in reaches affected by snowmelt and flow regulation. Seasonal and station-specific environmental flow rules are recommended to support sustainable basin management.

Keywords: Environmental flow assessment; Hydrological methods; Tessman method; Chirchik River; Flushing flow

1. Introduction

Freshwater ecosystems are increasingly altered by climate change, reservoir regulation, irrigation withdrawals, hydropower production, urban expansion, and land-use change.[1] Because riverine ecological processes depend on the magnitude, timing, duration, frequency, and variability of flow, environmental flow assessment aims to identify the quantity and temporal distribution of water required to sustain ecosystem functions while supporting human water use.[2,3] In snowmelt-dominated and semi-arid basins, ecological stress may arise from seasonal low flows, altered recession patterns, and the loss of high-flow pulses even when annual water availability appears adequate.[4]

Hydrological environmental flow methods remain widely used where hydraulic, habitat, biological, or ecohydrological data are limited.[5] They estimate ecological-flow requirements from observed discharge records using fixed percentages of mean flow, flow-duration percentiles, monthly medians, or seasonally adaptive rules. Although these methods cannot directly represent species-specific habitat suitability, they are useful for screening river reaches, comparing hydrological settings, and supporting preliminary water-allocation decisions in data-scarce basins.

Central Asian rivers are particularly relevant for environmental flow assessment because they simultaneously support irrigation, hydropower, urban water supply, riparian ecosystems, and transboundary water security. In Uzbekistan, runoff generated in mountain headwaters is strongly modified downstream by reservoirs and irrigation diversions. These controls can alter low-flow duration, seasonal hydrographs, sediment transport, ecological connectivity, and water quality.[1,3,5]

The Chirchik River Basin is a highly managed, mountain-fed system in which tributary, transitional, and regulated reaches experience contrasting hydrological conditions. Despite its importance, environmental flow research in the basin remains limited. Previous studies have focused mainly on water quality, dissolved loads, hydrological drought, climate-change impacts, and annual runoff trends,[6-9] but have not translated long-term flow variability into comparative seasonal environmental flow thresholds for multiple monitoring locations.

This study addresses that applied knowledge gap by comparing seven established hydrological environmental flow approaches using a consistent 50-year monthly discharge record (1971–2020) at Chinaz, Ugam, and G'azalkent. The contribution is therefore not the development of a new environmental flow method, but a systematic comparison of fixed-percentage, low-flow, seasonal, median-flow, and flushing-flow indicators within a poorly studied regulated Central Asian basin. The analysis further uses normalized station-wise indicators to distinguish differences in absolute discharge magnitude from relative seasonal behavior.[10]

The comparative framework is intended to test whether a single basin-wide environmental flow threshold is defensible or whether station-specific and seasonally adaptive rules are more appropriate for the Chirchik River Basin. Accordingly, the analysis is interpreted as a station-wise longitudinal comparison rather than as a continuous basin-wide spatial assessment. The study combines environmental flow estimation with Mann–Kendall trend analysis to place the derived thresholds in the context of long-term hydrological change.

Accordingly, this study aims to (i) estimate environmental flow requirements at Chinaz, Ugam, and G'azalkent using seven hydrological methods; (ii) compare seasonal and station-wise longitudinal differences in environmental flow requirements; and (iii) interpret environmental flow variability in relation to long-term hydrological change and methodological choice.

This comparative environmental flow assessment can support adaptive water allocation, ecological flow planning, and future ecohydrological monitoring in a regulated Central Asian river basin.

2. Materials and methods

2.1. Study area and hydrological stations

The study was conducted in the Chirchik River Basin, Uzbekistan, using long-term monthly discharge records from three hydrological monitoring stations: Chinaz, Ugam, and G'azalkent. In Figure 1, the stations denoted as S1, S2, and S3 correspond to Ugam, G'azalkent, and Chinaz, respectively. These stations represent distinct hydrological settings rather than equivalent gauges along a uniform river reach. Ugam represents a smaller snowmelt-dominated tributary, G'azalkent represents a higher-flow regulated reach influenced by upstream infrastructure, and Chinaz represents a downstream transitional reach affected by water redistribution and abstraction.[11]

The mean annual discharges for the 1971–2020 study period were approximately 23.1 m^3/s at Ugam, 227.7 m^3/s at G'azalkent, and 80.4 m^3/s at Chinaz. Thus, the mean discharge at Chinaz was approximately 65% lower than at G'azalkent. This substantial downstream decrease is mainly associated with differences in contributing drainage area, tributary inputs, river-network position, water abstraction and redistribution, irrigation withdrawals, and reservoir regulation. In particular, water diversion and redistribution

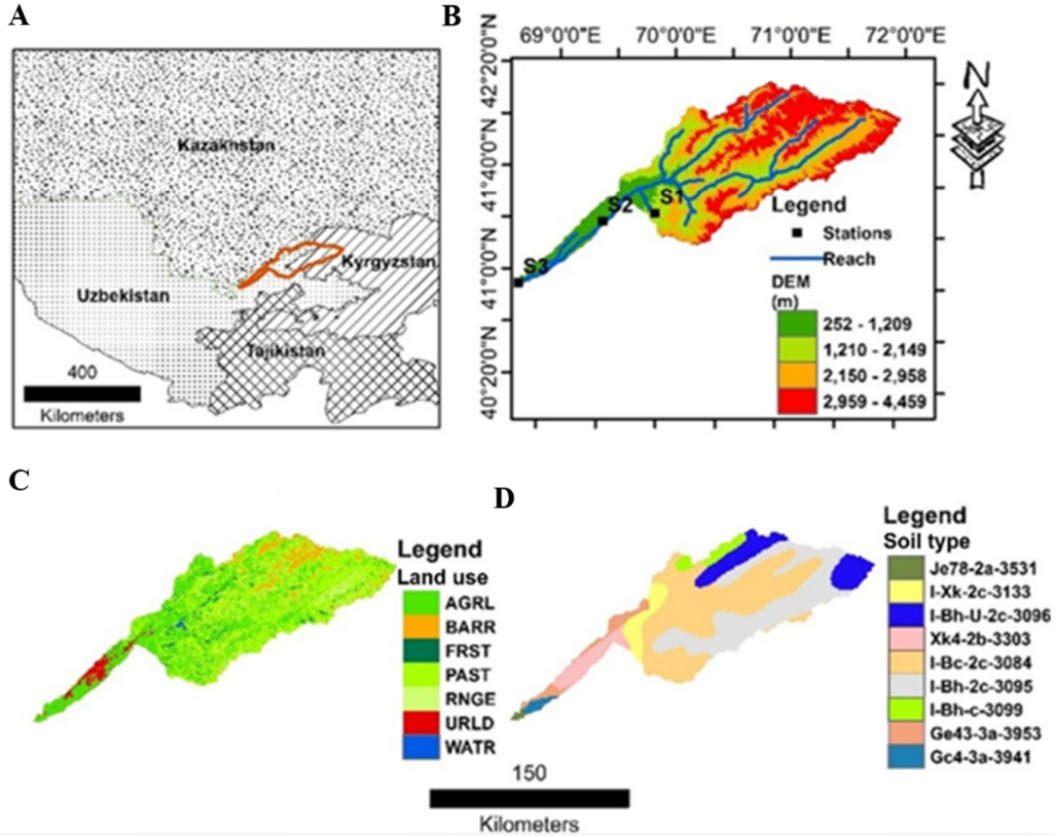


Figure 1. Chirchik River Basin showing (A) regional location, (B) basin topography and hydrological stations, (C) land use, and (D) soil type. In panel (B), S1, S2, and S3 denote the Ugam, G'azalkent, and Chinaz hydrological stations, respectively.
Abbreviations: AGRL: Agricultural land; BARR: Barren land; FRST: Forest land; PAST: Pasture; RNGE: Rangeland; URLD: Urban land; WATR: Water.

within the middle and lower Chirchik Basin reduce the amount of flow remaining downstream. Therefore, the large discharge difference between G'azalkent and Chinaz should not be interpreted as a natural downstream hydrological decrease alone, and the station comparison is not intended as a simple upstream–downstream water-balance calculation.

The Chirchik River, a right-bank tributary of the Syr Darya within a transboundary river system, has a length of 303.77 km and a drainage area of 13,192 km^2. The basin features steep, snow-fed headwaters that transition into intensively cultivated lowlands. As the river flows through the Tashkent region, a major industrial and agricultural hub, it receives untreated wastewater, agricultural runoff, and industrial effluents, increasing its vulnerability to contamination.[12]

2.2. Mann–Kendall trend analysis

The Mann–Kendall nonparametric trend test was applied to annual maximum, annual minimum, and annual mean flow series derived from archived monthly mean discharge records at each station. For each year, the annual maximum and minimum therefore refer to the highest and lowest of the 12 monthly mean discharges, not to instantaneous daily extremes. No natural-flow reconstruction was performed in this study; the analysis used the available monitored monthly series, which may include the effects of reservoir operation and water abstraction. Seasonal trend analysis was also performed using the monthly flow series. The Mann–Kendall test statistic (S) was calculated using **Equation 1**.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \quad (1)$$

where the sign function, $\mathrm{sgn}(x_j - x_i)$, is defined in **Equation 2**.

$$\mathrm{sgn}\left(x_j - x_i\right) = \begin{cases} 1 & \text{if } x_j > x_i \\ 0 & \text{if } x_j = x_i \\ -1 & \text{if } x_j < x_i \end{cases} \quad (2)$$

The variance of the test statistic (S), adjusted for tied

observations in the dataset, was computed using **Equation 3**.

$$VAR(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k (t_k - 1)(2t_k + 5)}{18} \quad (3)$$

where m is the number of tied groups, and t_k is the number of observations in the kth tied group. The standardized Mann–Kendall test statistic Z was then calculated using **Equation 4**.

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & \text{if } S < 0 \end{cases} \quad (4)$$

Positive values of Z indicate an increasing trend, whereas negative values indicate a decreasing trend. Trends were considered statistically significant at $p < 0.05$, based on the adopted significance criterion.[13,14] Sen's slope estimator was used to quantify the magnitude of each trend. The slope (β) was calculated as the median of all pairwise slopes calculated between observations, as shown in **Equation 5**.

$$\beta = \text{median}\left(\frac{x_j - x_i}{j - i}\right) \text{for all } i < j \quad (5)$$

2.3. Environmental-flow assessment methods

Seven hydrological approaches were applied to estimate environmental flows, following the comparative framework used by Khan *et al.*[15] for seasonal rivers. The methods were selected because they are well established in hydrological environmental flow studies and require relatively limited input data.

2.3.1. Tennant method

The Tennant method expresses environmental flow as a fraction of average annual flow (AAF) and provides a range of habitat-protection classes.[16] Because species-specific spawning information for the Chirchik River was not available, no single Tennant class was treated as a definitive local ecological requirement. Instead, 10%, 20%, 30%, and 60% of AAF were evaluated to span progressively higher protection levels and to support comparison with the other hydrological methods. Environmental flow was calculated using **Equation 6**.

$$E_{Tennant} = p \times AAF \quad (6)$$

where p is the selected Tennant fraction (0.10, 0.20, 0.30, or 0.60). These values were used here as comparative hydrological screening thresholds rather than species-specific habitat prescriptions. AAF was calculated as the arithmetic mean of all monthly flows over the 50-year period.[16,17]

2.3.2. Tessman method

The Tessman method ($E_{Tessman}$) accounts explicitly for monthly flow variability, in contrast to fixed-percentage annual approaches.[18] Under this method, the environmental flow requirement is determined from the relationship between mean monthly flow (*AMF*) and AAF, as shown in **Equation 7**.

$$E_{Tessman} = \begin{cases} AMF & \text{if } AMF \le 0.40 \times AAF \\ 0.40 \times AAF & \text{if } 0.40 \times AAF < AMF \le AAF \\ 0.40 \times AMF & \text{if } AMF > AAF \end{cases} \quad (7)$$

This method was included because its monthly decision rules retain seasonal hydrological variability and are therefore well suited to evaluating the strongly seasonal flow regime of the Chirchik River.[19,20]

2.3.3. Average annual flow method

The AAF method estimates the environmental flow requirement as a fixed percentage of the long-term AAF, as expressed in **Equation 8**. In this study, the recommended range was taken as 10%–25% of AAF. It is a widely used hydrological approach in environmental flow studies.[21,22]

$$EF_{AAF} = p \times AAF \quad (8)$$

where the coefficient ranges from 0.10 to 0.25, representing minimum and moderate levels of environmental protection. This method is straightforward and useful as a preliminary estimate of minimum environmental flow, particularly in data-scarce regions where more sophisticated approaches are not feasible. However, because the AAF method uses a single annual mean value, it does not capture seasonal variation in flow or ecological requirements. This limitation is particularly important in snowmelt-fed and regulated river systems, where seasonal ecological needs may differ substantially from the annual average.

2.3.4. Flow duration curve method

Flow duration curves (FDCs) were constructed for each station by ranking monthly flows in descending order and calculating the corresponding exceedance probabilities,[23] as expressed mathematically in **Equation 9**.

$$P = \left(\frac{m}{n+1}\right) \times 100 \quad (9)$$

where P is the exceedance probability, m is the rank of a flow value in descending order, and n is the total number of observations. The Q_{80}, Q_{85}, and Q_{90} discharges were extracted as low-flow indicators. Q_{80} represents the discharge that is equaled or exceeded 80% of the time, while

Q_{90} represents a more restrictive low-flow threshold. These flow-duration indices are useful for defining conservative ecological baseflow thresholds.

2.3.5. Dynamic mean flow method

The 30% Q_D method releases 30% of the daily mean flow, thereby preserving temporal variation in daily flow. Because daily data were unavailable, AAF was used as a proxy for the long-term mean flow, as expressed in **Equation 10**.

$$E_{DMF} = 0.30 \times AAF \quad (10)$$

Because only monthly data were available, the method was approximated using the long-term mean discharge. The resulting value is numerically equivalent to the 30% Tennant threshold when both methods use the same AAF value and was treated as a fixed ecological baseline in this study.

2.3.6. Median flow method

The median flow method assumes that the median monthly discharge can serve as an environmental flow threshold for aquatic habitat protection.[15] For each calendar month at each station, the median environmental flow was calculated using **Equation 11**.

$$EF_{MFM,m} = \text{median}\left(Q_{1,m}, Q_{2,m}, \ldots, Q_{Y,m}\right) \quad (11)$$

where $EF_{MFM,m}$ is the median-flow environmental requirement for calendar month m, and $Q_{y,m}$ represents the discharge in year y during month m. This method is less sensitive to extreme high-flow events than the monthly mean. However, in highly regulated rivers, the monthly median may already reflect anthropogenic alteration and therefore may not represent natural ecological requirements.

2.3.7. Flushing-flow assessment

A flushing-flow assessment was included to represent high-flow requirements for sediment transport, channel maintenance, and removal of accumulated organic matter and fine sediments. Following the recommendations of the Central Water Commission (CWC),[24] flushing flows—high-flow events required to transport sediment, prevent stagnation, and maintain channel morphology—were calculated using **Equation 12**.

$$Q_{flush} = 6.0 \times Q_{75} \quad (12)$$

where Q_{75} is the 75% dependable annual flow. For rivers where 10-day Q_{99} flow is unavailable, the CWC recommendation, summarized by Jain and Kumar,[24] allows the minimum flow to be approximated as 0.5% of Q_{75}, while one flushing flow during the monsoon period should have a peak of not less than 600% of Q_{75}. Accordingly, this study used $0.005 \times Q_{75}$ for the CWC-type minimum-flow benchmark and $6.0 \times Q_{75}$ for the flushing-flow benchmark. Because this guideline was developed for Indian rivers, these values are treated here only as comparative hydrological screening benchmarks, not as locally validated ecological-flow requirements for the Chirchik River Basin.

2.4. Station-wise longitudinal comparison of environmental flow requirements

Environmental flow estimates were compared among Chinaz, Ugam, and G'azalkent as discrete monitoring locations. Station coordinates were linked to the river network and relevant basin layers (digital elevation model, basin boundary, reservoirs, irrigation canals, and land use) to provide hydrological context. Because only three stations were available, no continuous basin-wide environmental flow surface was inferred. Instead, maps and graphics were used only to locate the stations and support reach-based comparison. Absolute environmental flow estimates were supplemented with normalized metrics, including environmental flow as a fraction of mean annual flow and the normalized seasonal range, to distinguish the effect of discharge magnitude from relative hydrological behavior.

3. Results

3.1. Long-term hydrological characteristics

The three stations showed marked differences in mean discharge and flow regime. Chinaz had an AAF of 80.4 m^3/s, indicating a reach with moderate discharge and pronounced seasonal redistribution. Ugam had the lowest AAF (23.1 m^3/s), representing a smaller tributary system strongly influenced by snowmelt during spring and early summer. G'azalkent had the highest AAF (227.7 m^3/s), reflecting a substantially larger flow regime that may also be more strongly regulated. The observed minimum and maximum monthly flows were 2.4 and 534.0 m^3/s at Chinaz, 5.4 and 96.6 m^3/s at Ugam, and 71 and 1,580 m^3/s at G'azalkent. Because the available metadata do not identify the cause of the isolated high value of 1,580 m^3/s, it is reported without attributing it to a reservoir release, flood-routing event, or data-entry error. Figure 2 shows the mean monthly and annual variability and trends in streamflow across the three stations.

3.2. Mann–Kendall trend analysis results

Trend analyses were conducted for annual and monthly mean streamflow for the three stations (Chinaz, Ugam, and G'azalkent) using the Mann–Kendall test and Sen's slope estimator. The results revealed a consistent pattern of declining river discharge across all stations, although marked intra-annual variability was observed. At the annual

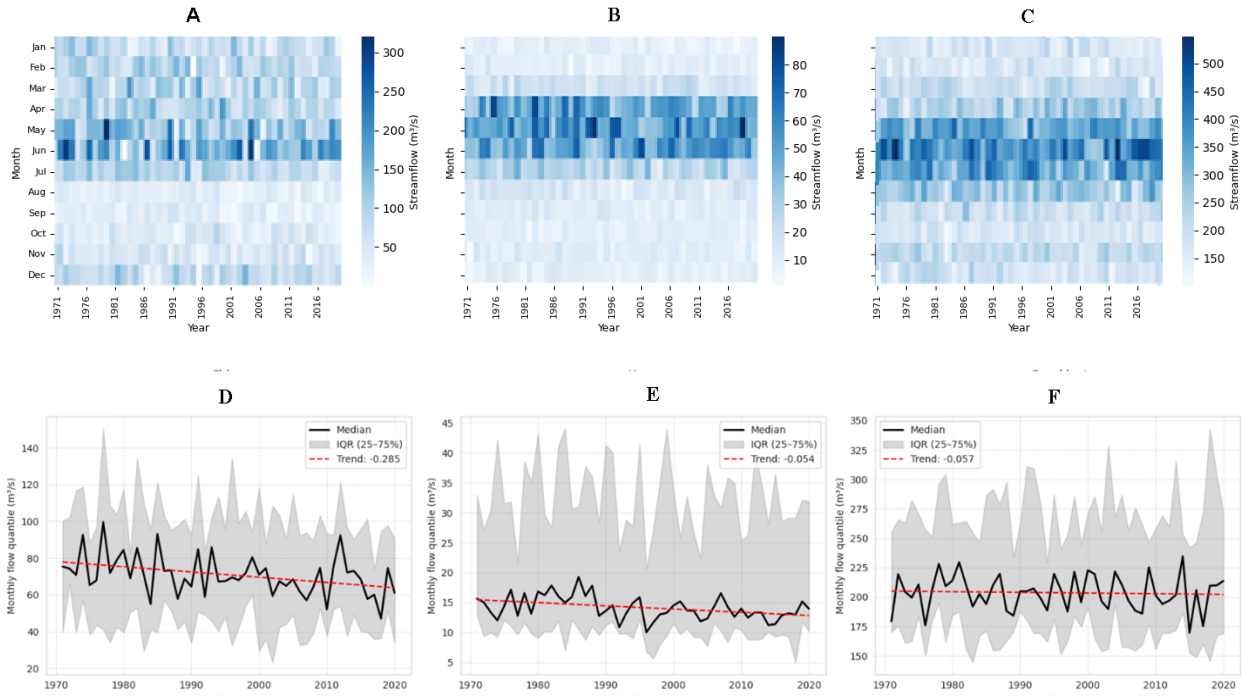


Figure 2. Mean monthly and annual (A–C) streamflow variability and (D–F) trends at the three stations: (A, D) Chinaz; (B, E) Ugam; (C, F) G'azalkent. Abbreviation: IQR: Interquartile range.

scale, all three stations exhibited statistically significant decreasing trends ($p < 0.01$). The largest absolute decline was observed at G'azalkent, with a slope of −0.970 m³/s/year ($Z = -5.62$), followed by Chinaz at −0.617 m³/s/year ($Z = -5.65$) and Ugam at −0.097 m³/s/year ($Z = -3.95$). These results indicate a sustained long-term reduction in mean annual flows at the three stations. Monthly trend analyses revealed that the annual declines were primarily associated with decreases in specific seasons, although monthly patterns differed markedly among stations (Table 1). For Chinaz, significant negative trends ($p < 0.05$) were detected in nearly all months except March and June. The steepest declines occurred in July (−1.205 m³/s/year, $p = 0.0002$) and May (−1.144 m³/s/year, $p = 0.0272$), whereas June had a nonsignificant positive slope (+0.217 m³/s/year, $p = 0.7889$). Ugam showed a more strongly seasonal trend pattern. Significant decreasing trends were concentrated in January, February, and July–December, with slopes ranging from −0.070 to −0.209 m³/s/year. However, the spring and early summer months (March through June) showed no statistically significant trends, with p-values exceeding 0.05, indicating insufficient evidence of a monotonic trend during this period. G'azalkent exhibited the strongest and most widespread monthly declines. Significant reductions were observed in January, February, March, August, October, November, and December, with the largest slope recorded in December (−1.326 m³/s/year). Conversely, no statistically significant trends were detected from April through July or in September, indicating that the annual decrease at this station was primarily associated with reductions in January–March, August, and October–December. In summary, the annual trends confirm that G'azalkent had the largest absolute annual decline, while Chinaz exhibited significant negative trends during most months. The monthly results highlight distinct seasonal and station-specific responses, with G'azalkent showing the most persistent and intense declines throughout the year. Figure 3 shows the mean monthly streamflow trends at the Chinaz, Ugam, and G'azalkent stations.

3.3. Environmental flow

3.3.1. Tennant and dynamic mean flow estimates

The Tennant method yielded fixed environmental flow thresholds expressed as proportions of AAF. At Chinaz, the 10%, 20%, 30%, and 60% Tennant thresholds were 8.04, 16.07, 24.11, and 48.22 m³/s, respectively. At Ugam, these values were 2.31, 4.62, 6.94, and 13.86 m³/s. At G'azalkent, the corresponding values were 22.76, 45.53, 68.29, and 136.59 m³/s. Under the dynamic mean flow (DMF) method, environmental flow was calculated as 30% of AAF, yielding values identical to the 30% Tennant

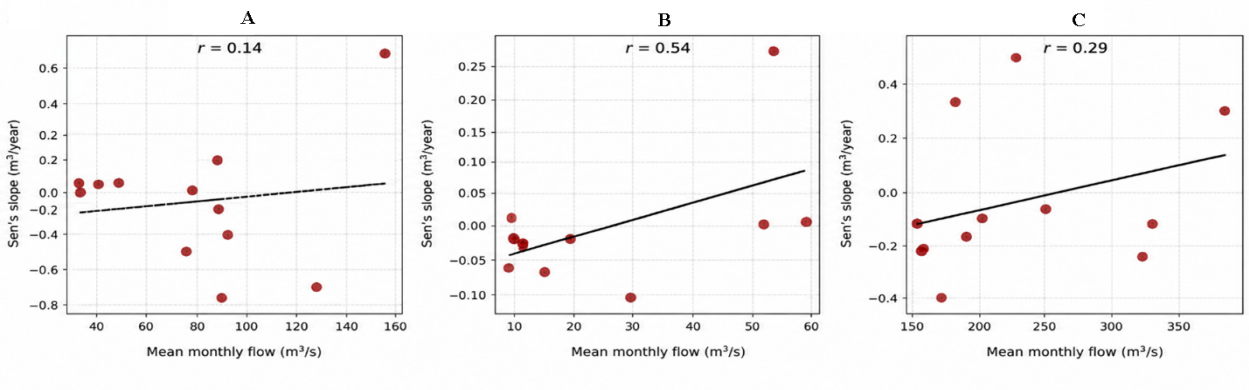


Figure 3. Mean monthly streamflow trends at the (A) Chinaz, (B) Ugam, and (C) G'azalkent stations

thresholds: 24.11 m^3/s at Chinaz, 6.94 m^3/s at Ugam, and 68.29 m^3/s at G'azalkent. Figure 4 presents a station-based comparison of environmental flow estimates obtained using the Tennant method and the approximated DMF method. Because the approximated DMF was calculated as 30% of AAF, its values coincide with the 30% Tennant thresholds.

Table 1. Monthly discharge trend slopes for the three stations

Month	Chinaz slope (m^3/s/year)	Ugam slope (m^3/s/year)	G'azalkent slope (m^3/s/year)
Jan	−0.930*	−0.156*	−1.147*
Feb	−0.683*	−0.115*	−1.037*
Mar	−0.401	−0.113	−1.091*
Apr	−0.841*	−0.087	−0.397
May	−1.144*	−0.080	−1.169
Jun	0.217	0.182	−0.598
Jul	−1.205*	−0.209*	−1.039
Aug	−0.483*	−0.166*	−0.985*
Sep	−0.541*	−0.119*	−0.567
Oct	−0.527*	−0.070*	−1.140*
Nov	−0.516*	−0.124*	−1.020*
Dec	−0.573*	−0.112*	−1.326*

Note: *$p < 0.05$.

3.3.2. Average annual flow method

The AAF method produced fixed annual-percentage thresholds that were consistently lower than the corresponding seasonal estimates from the Tessman and median-flow approaches (Table 2). This contrast is most relevant during spring and early summer, when seasonal flow requirements can exceed fixed annual-percentage benchmarks.

Table 2. Environmental flow estimates derived using the average annual flow (AAF) method

Station	10% AAF (m^3/s)	25% AAF (m^3/s)
Chinaz	8.04	20.09
Ugam	2.31	5.78
G'azalkent	22.76	56.91

3.3.3. Flow duration curve estimates

The FDC method yielded low-flow thresholds corresponding to Q_{80}, Q_{85}, and Q_{90}. At Chinaz, Q_{80}, Q_{85}, and Q_{90} were 30.40, 26.02, and 21.20 m^3/s, respectively. At Ugam, these values were 8.28, 7.91, and 7.50 m^3/s, indicating a relatively narrow range among the low-flow thresholds. At G'azalkent, Q_{80}, Q_{85}, and Q_{90} were 158.00, 137.30, and 117.00 m^3/s, respectively, indicating substantially higher low-flow thresholds than those at the other stations. Table 3 summarizes the environmental flow estimates obtained using the FDC method.

Table 3. Environmental flow estimates derived using the flow duration curve method

Station	Q_{80} (m^3/s)	Q_{85} (m^3/s)	Q_{90} (m^3/s)
Chinaz	30.4	26.0	21.2
Ugam	8.3	7.9	7.5
G'azalkent	158.0	137.3	117.0

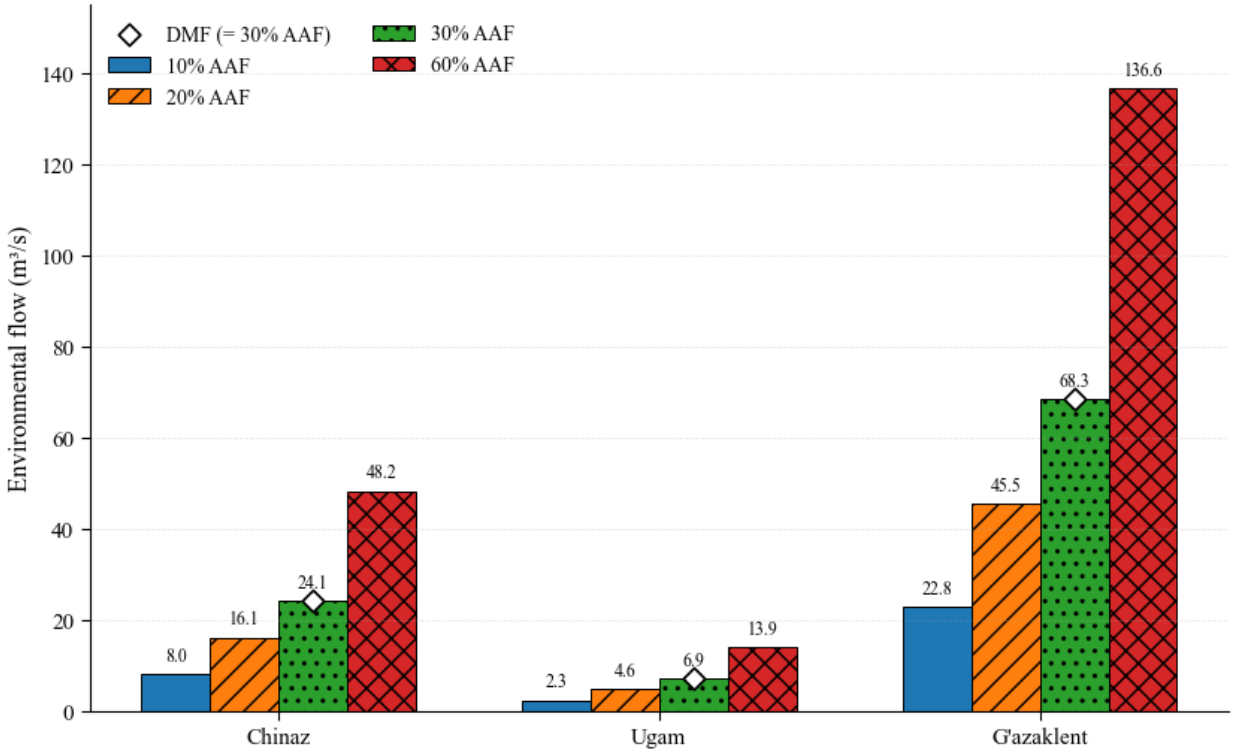


Figure 4. Station-based comparison of environmental flow estimates derived from the Tennant and approximated dynamic mean flow (DMF) methods. Values are shown only at the three monitored stations; no spatial interpolation is applied.
Abbreviation: AAF: Average annual flow.

3.3.4. Tessman seasonal environmental flow estimates

The Tessman method indicated marked station-wise differences in seasonal environmental flow requirements. G'azalkent had the highest mean environmental flow (103.52 m^3/s), followed by Chinaz (37.36 m^3/s) and Ugam (12.28 m^3/s). The absolute seasonal range was also largest at G'azalkent (56.00 m^3/s), compared with 32.92 m^3/s at Chinaz and 14.23 m^3/s at Ugam. These absolute values largely reflect differences in discharge magnitude among stations; therefore, they should be interpreted together with the normalized indicators presented in Section 3.4. Figure 5 presents the monthly environmental flow estimates derived using the Tessman method.

3.3.5. Median flow method estimates

The median flow method yielded higher monthly environmental flow estimates than the AAF method and the lower-percentage Tennant thresholds. At Chinaz, monthly median flow ranged from 26.00 m^3/s in August to 124.00 m^3/s in June. At Ugam, it ranged from 7.98 m^3/s in January to 56.45 m^3/s in May. At G'azalkent, it ranged from 170.00 m^3/s in October and November to 342.00 m^3/s in July. The median-flow method therefore preserved substantially more intra-annual variability than fixed annual-percentage approaches. The resulting monthly estimates are presented in Figure 6.

3.3.6. Flushing-flow assessment

The Q_{75} was 45.33 m^3/s at Chinaz, 18.49 m^3/s at Ugam, and 201.83 m^3/s at G'azalkent. Applying the corrected CWC-type minimum-flow coefficient of 0.5% of Q_{75} yielded 0.23 m^3/s at Chinaz, 0.09 m^3/s at Ugam, and 1.01 m^3/s at G'azalkent. The corresponding flushing-flow benchmarks (600% of Q_{75}) were 271.96, 110.97, and 1,211.00 m^3/s, respectively. These CWC-derived values are presented as comparative hydrological benchmarks rather than locally validated ecological requirements (Table 4).

3.4. Station-wise longitudinal variability in environmental flow estimates

Absolute environmental flow estimates differed substantially among the three stations. Mean Tessman environmental flow increased from 12.28 m^3/s at Ugam to 37.36 m^3/s at Chinaz and 103.52 m^3/s at G'azalkent,

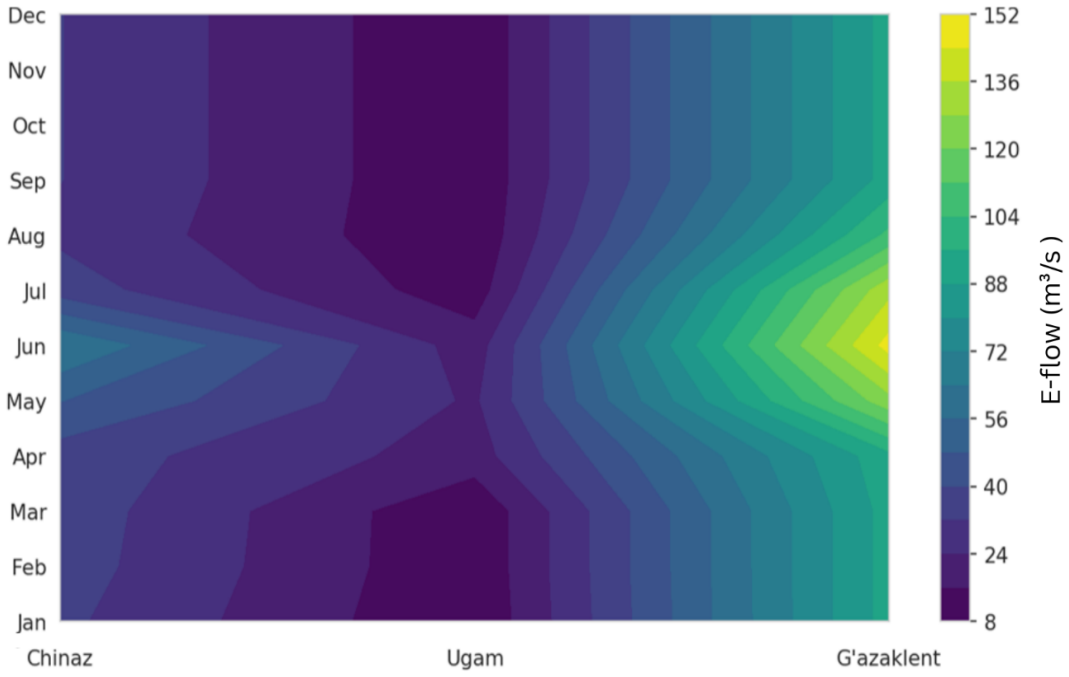


Figure 5. Tessman monthly environmental flow (E-flow) estimates at the Chinaz, Ugam, and G'azalkent stations in the Chirchik River Basin

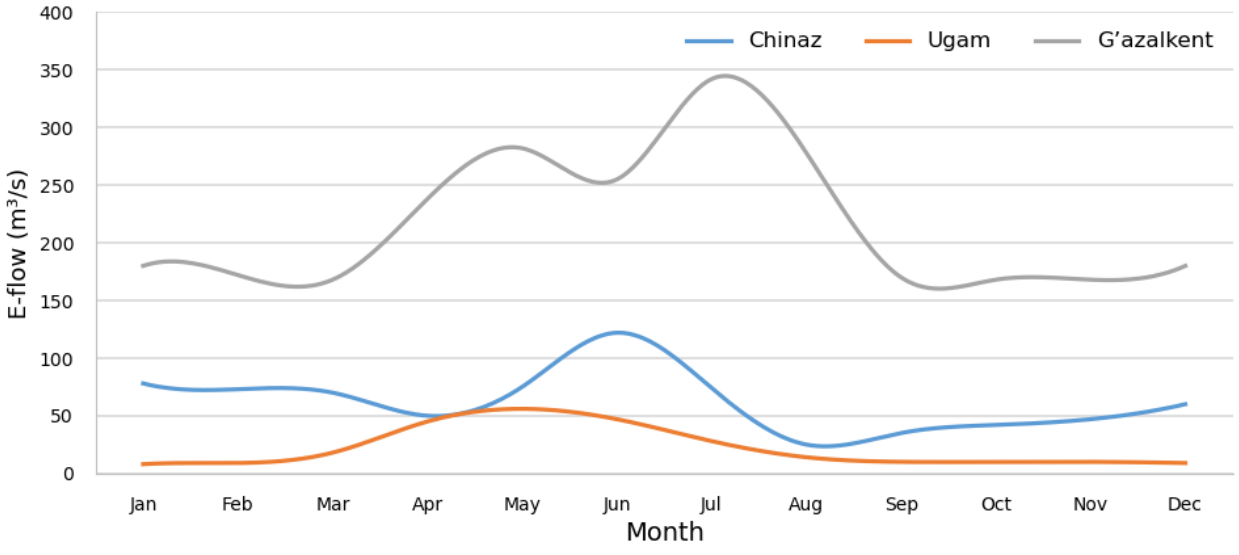


Figure 6. Monthly environmental flow (E-flow) estimates derived using the median flow method at the Chinaz, Ugam, and G'azalkent stations in the Chirchik River Basin

broadly following the corresponding differences in mean annual flow (23.1, 80.4, and 227.7 m^3/s, respectively). Similar station-wise ordering was observed for the FDC Q_{90} thresholds (7.50, 21.20, and 117.00 m^3/s) and flushing-flow estimates (111, 272, and 1,211 m^3/s). These absolute differences are strongly affected by station-specific discharge magnitude and should not be interpreted as an independently derived continuous spatial pattern.

Table 4. Central Water Commission–type minimum flow and flushing-flow estimates

Station	Q_{75} dependable flow (m^3/s)	Minimum flow, 0.5% of Q_{75} (m^3/s)	Flushing flow, 600% of Q_{75} (m^3/s)
Chinaz	45.3	0.23	272
Ugam	18.5	0.09	111
G'azalkent	201.8	1.01	1,211

Normalization revealed additional information that was not evident from the absolute values alone. Expressed as a fraction of mean annual flow, the mean Tessman requirement was approximately 53% at Ugam, 46% at Chinaz, and 45% at G'azalkent. By contrast, Q_{90} represented approximately 32% of AAF at Ugam, 26% at Chinaz, and 51% at G'azalkent, showing no monotonic longitudinal pattern. Normalization also changed the ranking of seasonal variability: although the absolute Tessman max–min range was largest at G'azalkent (56.00 m^3/s), the range relative to the mean Tessman environmental flow was smallest there (0.54 m^3/s) and largest at Ugam (1.16 m^3/s). Thus, the normalized analysis separates differences in hydrological behavior from simple differences in river size.

The combination of a relatively high normalized Q_{90} and a low normalized seasonal range at G'azalkent is consistent with a more buffered flow regime, although the available hydrological data alone cannot attribute this pattern uniquely to reservoir regulation. At Ugam, the larger normalized seasonal range and low absolute baseflow thresholds emphasize the importance of preserving seasonal snowmelt variability. Chinaz occupies an intermediate hydrological position. These contrasts are therefore interpreted as station-specific hydrological signatures rather than evidence of a continuous basin-wide environmental flow surface.

The station-wise comparison indicates that a single basin-wide threshold is unlikely to represent all three hydrological settings. Reach-specific criteria may therefore be more appropriate: seasonal baseflow and snowmelt-pulse protection at Ugam, low-flow safeguards at Chinaz, and attention to both seasonal variability and high-flow channel-maintenance processes at G'azalkent. Because only three monitoring stations were available, these findings should be interpreted as a longitudinal station comparison rather than a continuous spatial assessment of the entire basin.

4. Discussion

The results demonstrate that environmental flow estimates in the Chirchik River Basin depend not only on station discharge magnitude but also on the method used to represent ecological flow needs. This distinction is important because fixed annual percentages, low-flow exceedance indices, monthly medians, and seasonally adaptive rules describe different components of the flow regime. At Chinaz, the FDC thresholds of 21.20–30.40 m^3/s identify a practical low-flow range, whereas the Tessman results indicate that higher seasonal allocations may be required during snowmelt-influenced months.[25] Therefore, a single minimum discharge would protect only one component of the hydrological regime and could miss ecologically relevant seasonal variation.

Ugam provides the clearest example of the limitation of fixed annual-percentage methods. The AAF method produced estimates of only 2.31–5.78 m^3/s, whereas the Tessman method yielded seasonally varying requirements of 8.55–22.78 m^3/s. The difference is greatest during the spring–early summer snowmelt period, when maintaining part of the seasonal pulse may be important for channel connectivity, sediment transport, and aquatic habitat. The FDC Q_{90} value of 7.50 m^3/s may therefore serve as a conservative low-flow screening threshold, but it should not be interpreted as a substitute for a seasonal environmental flow regime.

G'azalkent had the highest absolute environmental flow estimates, but high absolute flow does not necessarily indicate better ecological condition. Regulation can maintain relatively high baseflows while damping seasonal variability and altering the frequency of geomorphically important high-flow events. The normalized results support this distinction: G'azalkent had a smaller relative seasonal range than Ugam even though its absolute flows were much larger. The estimated flushing-flow requirement therefore highlights a different management question from minimum-flow protection—whether sufficiently large events occur often enough to support sediment transport and channel maintenance. The unusually high November discharge of 1,580 m^3/s should nevertheless be verified before being used in further ecological interpretation.

The methodological comparison also clarifies the practical role of each approach. Tennant, AAF, and the approximated DMF provide transparent screening thresholds but, because they are based on annual mean flow in this study, they do not preserve intra-annual variability. FDC indices are useful for low-flow protection and drought-period screening. Monthly median flow preserves seasonality but may reproduce an already altered, regulated flow regime. Among the evaluated approaches, Tessman offers a practical compromise because it responds to monthly hydrology while remaining simple enough

for preliminary operational planning. This conclusion is comparative rather than universal and should be validated with ecological and hydraulic information before implementation.

From a management perspective, the results favor station-specific and seasonally adaptive rules rather than a uniform basin-wide minimum. Ugam requires particular attention to seasonal baseflow and snowmelt-pulse protection; Chinaz requires low-flow safeguards around the FDC-derived range; and G'azalkent requires consideration of both seasonal variability and periodic high-flow processes. These hydrological recommendations should be integrated with water-quality observations because ecological risk may intensify during low-flow periods when dilution capacity is reduced.[26,27]

This study has several limitations. First, it uses monthly mean discharge rather than daily or sub-daily data, preventing analysis of short-duration low-flow events, rapid hydrograph changes, and the frequency and duration of individual high-flow pulses. Second, the estimates are hydrological screening values because biological, fish, macroinvertebrate, hydraulic, habitat-suitability, and detailed water-quality data were not available for calibration or validation. Third, only three monitoring stations were analyzed; consequently, the study cannot resolve continuous basin-wide spatial variability or quantitatively separate the effects of contributing area, tributary inflow, abstraction, and reservoir operation. Fourth, the approximated DMF method is numerically equivalent to the 30% Tennant threshold because daily data were unavailable, so it should not be interpreted as an independent line of evidence. Fifth, the CWC minimum- and flushing-flow criteria were developed for Indian rivers and are used here only as comparative benchmarks; they have not been ecologically validated for the Chirchik River Basin. Finally, station records may reflect anthropogenic alteration, meaning median- and flow-duration-based thresholds do not necessarily represent natural ecological requirements. Future work should integrate daily discharge, additional gauging stations, hydraulic-habitat modeling, ecological field observations, water quality, and reservoir-operation data to develop and validate an operational environmental flow regime for the Chirchik River Basin.

5. Conclusion

This study quantified environmental flow requirements at Chinaz, Ugam, and G'azalkent using seven hydrological approaches and a consistent 50-year monthly discharge record. The results show that environmental flow estimates are strongly station- and method-dependent. Fixed annual methods such as Tennant, AAF, and the approximated DMF are useful for preliminary screening but may underrepresent seasonal hydrological requirements in a snowmelt-affected and regulated basin. FDC thresholds provide practical low-flow indicators, whereas Tessman and monthly median-flow approaches retain more seasonal information. Among the methods evaluated, Tessman provides a useful hydrological screening compromise because it responds to monthly flow variability while remaining operationally simple. However, the derived values should not be treated as final ecological prescriptions without biological and hydraulic validation. The Chirchik River Basin should therefore be managed using station-specific and seasonally adaptive environmental flow criteria rather than a single basin-wide value, with future work focusing on daily flow dynamics, ecological validation, and additional monitoring locations.

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Conflict of interest

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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