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HYDROLOGICAL REGIME AND HYDRAULIC CHARACTERISTICS OF THE DARYALYK MAIN COLLECTOR SYSTEM (KHOREZM REGION, UZBEKISTAN): LONG-TERM RECORDS AND FIELD FLOW MEASUREMENTS

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Abstract. The Daryalyk main collector system conveys saline drainage water and return flow from five districts of the Khorezm region (Uzbekistan) across the state border to Turkmenistan. Quantitative information on its flow regime and hydraulic behaviour is needed for planning cleaning, reconstruction and possible reuse of drainage water. This study combined (i) a 21-year record (2004–2024) of mean annual discharge, runoff and mineralization; (ii) frequency analysis of mean annual discharge with the Pearson Type III distribution; (iii) acoustic Doppler (SonTek S5, GPS-aided) discharge measurements at five cross-sections; (iv) hydraulic-resistance experiments on three 150 m reaches of the Divankul collector; and (v) clamp-on ultrasonic flow measurements in the pressure pipes of five pumping stations, complemented by 2021–2024 records of pumped volume and electricity use. Mean annual discharge was 22.98 m^3/s (C_v = 0.35, C_s = 0.27; range 8.91–41.54 m^3/s) and mean mineralization was 2.12 g/L (1.66–3.16 g/L). Discharges exceeded in 50, 75 and 96% of years were 22.6, 17.4 and 9.7 m^3/s. Mean discharge in 2018–2024 (17.6 m^3/s) was about 31% lower than in 2004–2017 (25.7 m^3/s), although the trend was not statistically significant. Measured discharge decreased from 52.8 m^3/s at the border cross-section to 1.6 m^3/s in the uppermost one. In three Divankul reaches, Reynolds numbers of 3.4–3.8 × 10^5 indicated fully turbulent flow, and water-surface slopes of 1.1–1.5 × 10^{-3} at velocities of 0.32–0.36 m/s implied very high flow resistance (Manning's $n \approx 0.11–0.13$). The pumps delivered 85–95% of their design discharge of 0.5 m^3/s. Pumped volume in

Gurlan district fell from 3.62 to 0.15 million m^3 between 2021 and 2024 at an almost constant 0.078 kWh/m^3. The results give a quantitative basis for prioritising cleaning and for assessing the performance of water-lifting installations on the collector system.

Keywords: drainage collector; discharge; acoustic Doppler current profiler; hydraulic resistance; clamp-on ultrasonic flowmeter; Khorezm; Amu Darya basin

1. Introduction

Irrigated agriculture in the lower reaches of the Amu Darya depends on large diversions from the river and on an extensive network of drains and collectors that removes surplus and saline water from the fields. In the Khorezm region of Uzbekistan, technical irrigation efficiency during the 2004 and 2005 vegetation periods averaged only about 26% for the region as a whole, and drainage outflow from a studied hydro-unit amounted to 62–67% of the irrigation water input (Tischbein et al., 2012). Groundwater is shallow: records from about 2000 observation wells showed an average depth of 148 ± 57 cm below the surface and an average salinity of 1.75 ± 0.99 g/L, and case studies indicated that elevated groundwater levels added 3.5–14 t ha^{-1} of salt to the soil each year (Ibrakhimov et al., 2007). Later analyses concluded that the drainage network was operating at its full capacity and that better controlled water management, not drainage improvements alone, was needed to curb land degradation (Ibrakhimov et al., 2011). Collectors that evacuate drainage water are therefore a critical element of land reclamation in the region.

The Daryalyk main collector is the largest collector of the Khorezm region. It receives drainage and groundwater from the Khonqa, Urgench, Yangibazar, Gurlan and Bogot districts and passes to Turkmenistan, where drainage water from the Dashoguz and Khorezm oases is discharged into Sarykamysh Lake, one of about 2,500 artificial drainage-water lakes of Central Asia (Orlovsky et al., 2014). Because the collector crosses a state border, the quantity and quality of the water it carries, and the condition of its channel, are matters of both national land reclamation and

transboundary water management. Uzbekistan has repeatedly financed the cleaning of the collector, including part of its reach on Turkmen territory (Section 2.1), yet systematic quantitative data on its flow regime, hydraulic resistance and on the performance of the pumping stations that lift water from it into irrigation canals appear to be scarce in the international literature.

Modern field instruments make such data much easier to obtain. Acoustic Doppler current profilers (ADCPs) deployed from a moving boat are now a standard tool for discharge measurement, and large validation programmes found them to be unbiased relative to reference measurements (Oberg and Mueller, 2007; Mueller et al., 2013). The ultrasonic transit-time principle is likewise standardised for discharge measurement in open channels and closed conduits (ISO 6416:2017), and portable clamp-on meters allow flow to be checked in existing pipes without interrupting operation, although their accuracy depends strongly on installation and local flow conditions (Simões et al., 2024).

The aim of this study was to characterise the hydrological regime and hydraulic behaviour of the Daryalyk collector system by combining long-term records with field measurements. The specific objectives were to (1) describe the long-term variability of discharge, runoff and mineralization and estimate discharges of given exceedance probability; (2) measure discharge, velocity and channel geometry at representative cross-sections; (3) determine hydraulic-resistance parameters of the Divankul collector; and (4) assess the performance of pumping stations that abstract water from the collector and summarise their water and energy use.

2. Materials and methods

2.1 Study area

The Daryalyk main collector system comprises the Divankul, Atashev and Toshsaka right-bank collectors and drains the Khonqa, Urgench, Yangibazar, Gurlan and Bogot districts of the Khorezm region (Fig. 1, Table 1). Construction began in



1953 (first stage: 38.6 km, 5.3 m³/s) and continued in 1957 (second stage: 39.7 km, 7.0 m³/s). After reconstruction in 1967–1974 the length was 39.7 km and the discharge 13.2–23.0 m³/s. The collector serves to improve the ameliorative condition of irrigated land in Gurlan district and to remove saline, drainage and surplus water; the Divankul collector discharges into the Daryalyk collector, which carries the water to Turkmenistan.

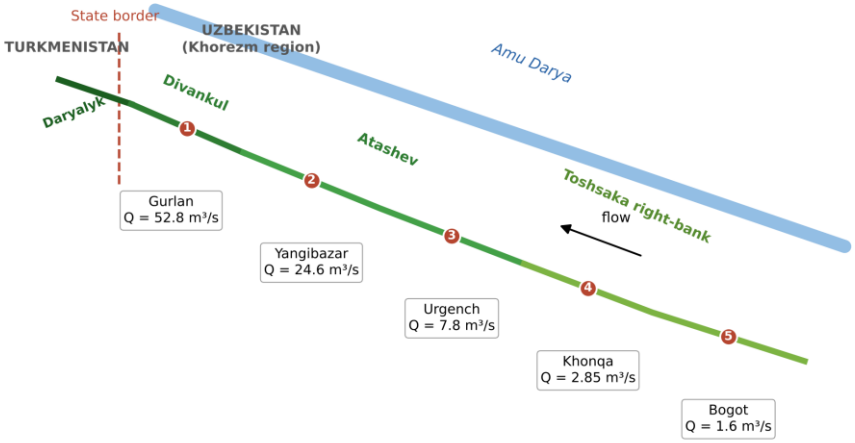


Fig. 1. Schematic layout of the Daryalyk main collector system, the five ADCP cross-sections (numbered circles) and the discharge measured at each of them (Table 4). The drawing is not to scale; the pumping stations investigated are located in the same five districts (Table 7).

Table 1. Characteristics of the collectors constituting the Daryalyk system.

District	Collector	Year built	Length, km	Discharge, m³/s	Width, m	Depth, m
Gurlan	Divankul	1957	40.3	72	72	2.5
Yangibazar	Atashev	1957	30.3	30	25	3.0
Urgench	Atashev	1976	22.1	8	15	2.2
Khonqa	Toshsaka right-bank	1974	20.2	3	14	2.0
Bogot	Toshsaka right-bank	1970	8.5	1.6	18	2.5

Values as recorded in the project and operational documentation of the system.

The area belongs to the Central Asian central desert zone (Ts-1-A) and to hydromodule district VI; with respect to hydrogeology it falls into area “v”, in which groundwater inflow and outflow are difficult and the groundwater table changes rapidly. Geomorphologically the collector lies within the zone of channel and near-channel deposits; the relief is uneven and dissected by irrigation and drainage networks, with absolute elevations of 87–103 m and a slope towards the south-west. Natural groundwater flow is almost absent, and recharge comes mainly from infiltration from irrigation canals and fields and, to a small degree, from precipitation. The groundwater table lies at 1.0–1.8 m, is highest in June–August and lowest in January–February, and fluctuates with an amplitude of 0.5–1.0 m. Groundwater is of the chloride–sulphate, sodium type with a mineralization of 1.0–3.0 g/L. The soils are meadow soils of sandy, sandy-loam and loamy texture, weakly to strongly saline, non-gypsiferous and poor in humus and nitrogen. The hydrogeological and ameliorative condition of the area is unsatisfactory, and measures to lower the groundwater table are required.

Cleaning and reconstruction have been carried out in stages. The Turkmen section of the Daryalyk collector is 267.0 km long; 65% of it (173.55 km) is to be cleaned step by step, with the first stage (20 km) financed by Uzbekistan. Between 2008 and 2021 the planned 20.00 km (3,572.5 thousand m^3 of excavation, UZS 19,148.5 million) was completed in full. In the second stage, 3.031 km were cleaned in 2022–2023, including 2.031 km in 2023 at a cost of UZS 5,561.4 million, using four suction dredgers, four bulldozers and one excavator; a further 2.0 km (UZS 5,600.0 million) was planned for 2024. On the Divankul collector (total length 119.0 km), reconstruction has covered 40.3 km in Gurlan district, 28.0 km in Yangibazar (2014–2016), 19.2 km in Urgench (2017–2018), 23.4 km in Khonqa (2018–2019) and 8.06 km in Bogot (2019–2020).

2.2 Long-term records and frequency analysis

Mean annual discharge (m^3/s), annual runoff (million m^3) and mean annual mineralization (g/L) for 2004–2024 (n = 21) were taken from the records of the Gurlan–Divankul gauging station (hydropost) near the border with Turkmenistan (Table 2). The relationships between discharge and mineralization were examined with Pearson and Spearman correlation coefficients, and temporal trends with Kendall's τ and ordinary least-squares regression; differences are reported at the 5% significance level.

For the frequency analysis, modular coefficients $k_i = Q_i/Q_0$ were computed, where Q_0 is the sample mean. The coefficient of variation and the coefficient of skewness were estimated by the method of moments as $C_v = [\Sigma(k_i - 1)^2/(n - 1)]^{1/2}$ and $C_s = \Sigma(k_i - 1)^3/[(n - 3)C_v^3]$. Empirical exceedance probabilities were assigned with the Cunnane plotting position, $p = (m - 0.4)/(n + 0.4) \times 100\%$, where m is the rank of the observation in descending order (Cunnane, 1978). The theoretical exceedance curve was approximated by the Pearson Type III distribution, which is the basis of hydrological frequency analysis in the United States (England et al., 2018), with discharges of 1, 5, 10, 50, 75 and 96% exceedance probability calculated as $Q_p = Q_0(1 + \Phi_p C_v)$, where Φ_p is the standardised deviate for the given C_s. Calculations were performed in Python (NumPy and SciPy).

2.3 Discharge measurements with an acoustic Doppler current profiler

Discharge, velocity and channel geometry were measured with a SonTek S5 ADCP equipped with a GPS receiver and mounted on a tethered boat (Fig. 4a), using the moving-boat technique in which the instrument is drawn across the channel and the discharge is obtained by integrating the measured velocity over the cross-section (Mueller et al., 2013). Measurements were made at five cross-sections located upstream of the pumping stations and in the reaches between them (Table 4). The instrument software provided the wetted cross-sectional area, mean velocity, discharge

and maximum depth; the transect track, depth profile and velocity field were inspected on-screen in the field (Fig. 4b).

2.4 Hydraulic-resistance experiments on the Divankul collector

Experiments were carried out on three reaches of the Divankul collector, each about 150 m long: reach 1 (PK 253+50 to PK 255+00), reach 2 (PK 285+50 to PK 287+00) and reach 3 (PK 351+70 to PK 353+20), where PK denotes the picket (station) number along the channel. At the upstream (A) and downstream (B) section of each reach the discharge Q, water level H, mean velocity, bottom width b and top width B were measured (Table 5). For each reach the head loss h (the difference between the water levels in sections A and B), the mean velocity v, the wetted area ω, the wetted perimeter χ and the hydraulic radius $R = \omega/\chi$ were determined, together with water temperature T and mineralization M. The kinematic viscosity was taken as $\nu = 1.146 \times 10^{-6}$ m^2/s. The Reynolds number was calculated as $\mathrm{Re} = vR/\nu$, and the hydraulic-resistance coefficient as

$$\lambda = 2gRh / (Lv^2), \quad (1)$$

where g is gravitational acceleration and L is the length of the reach. In this form the hydraulic radius, not the hydraulic diameter $4R$, is the characteristic length, so that λ is one quarter of the conventional Darcy–Weisbach friction factor $\lambda_{DW} = 8gRI/v^2$. Equation (1) reproduces the coefficients obtained in the experiments (Table 6) to within rounding. As complementary indicators, the water-surface slope $I = h/L$, Manning's roughness coefficient $n = R^{2/3}I^{1/2}/v$ and the Chézy coefficient $C = v/(RI)^{1/2}$ were computed from the same data; this assumes that, over a short reach, the water-surface slope approximates the friction slope.

2.5 Flow measurements in the pressure pipes of pumping stations

The discharge in pressure pipes of pumping stations that lift water from the collector into irrigation canals was measured with a portable ultrasonic transit-time flowmeter, model AFT-2000H (Fig. 5a). Its piezoelectric transducers are clamped on

the outer wall of the pipe; ultrasonic signals are transmitted through the wall and the liquid, and the flow is computed from the difference in the transit times of the signals travelling with and against the flow (see ISO 6416:2017 for the principle). Before mounting, the pipe surface was cleaned of rust and coatings by grinding, and care was taken to prevent sand or dust remaining between the pipe and the transducers. Because air bubbles may collect in the upper part of a pressurised pipe and cause large errors, the transducers were mounted horizontally on the side of the pipe. The transducer spacing was set to the value calculated by the instrument for the pipe and liquid parameters. Of the standard mounting configurations, the V-method is the most common for pipes of 15–2400 mm, the Z-method is normally used for diameters above 200 mm, and the W-method for plastic pipes of 15–50 mm.

The suction and pressure pipes of the pumping stations are 250–500 mm in diameter and made of polyethylene or steel. Pumping units of the SNPE, PG-250 and 20NDN types are installed. Measurements were made in straight pipe sections without local resistances (valves, bends, tees), between the design sections 1–1 and 2–2 in a 500 mm polyethylene pipe and between sections 3–3, 4–4 and 5–5 in 500 mm steel pipes. The pipes were in good condition according to visual inspection and the opinion of the operating organisation. Five series of measurements were made on each pipe. The stations investigated are listed in Table 7; each has a design discharge of 0.5 m^3/s per unit.

2.6 Pumped volumes and electricity use

Monthly volumes of water pumped from the collector and the electricity consumed by the pumping stations of Gurlan district in 2021–2024 were taken from operational records. Annual totals were computed as the sum of monthly values, and the specific energy consumption (kWh/m^3) as the ratio of electricity use to pumped volume.

3. Results

3.1 Long-term flow regime and mineralization

Mean annual discharge at the Gurlan–Divankul station over 2004–2024 averaged 22.98 m^3/s, ranging from 8.91 m^3/s in 2011 to 41.54 m^3/s in 2010 (Table 2, Fig. 2). Mean annual runoff was 729 million m^3 (282–1,321 million m^3). The coefficient of variation of annual discharge was $C_v = 0.35$ and the skewness coefficient $C_s = 0.27$ (Table 3). Annual mineralization averaged 2.12 g/L and ranged from 1.66 g/L (2013) to 3.16 g/L (2007).

Table 2. Mean annual discharge (Q), annual runoff (W) and mean annual mineralization (M) of the Daryalyk collector at the Gurlan–Divankul station, 2004–2024.

Year	Q, m^3/s	W, million m^3	M, g/L		Year	Q, m^3/s	W, million m^3	M, g/L
2004	23.25	734.86	2.47		2015	31.98	1013.49	1.83
2005	31.16	992.37	2.29		2016	26.86	853.80	1.70
2006	27.50	867.12	2.51		2017	32.05	1017.20	1.79
2007	22.30	703.03	3.16		2018	13.10	415.30	2.07
2008	12.41	394.72	2.59		2019	25.61	824.66	1.82
2009	27.19	864.18	1.87		2020	17.66	559.62	2.26
2010	41.54	1320.73	1.79		2021	14.14	447.31	2.26
2011	8.91	282.19	2.13		2022	16.03	507.53	2.23
2012	29.06	922.24	1.74		2023	16.74	531.68	2.31
2013	22.57	712.21	1.66		2024	19.90	631.27	2.28
2014	22.58	717.53	1.73					

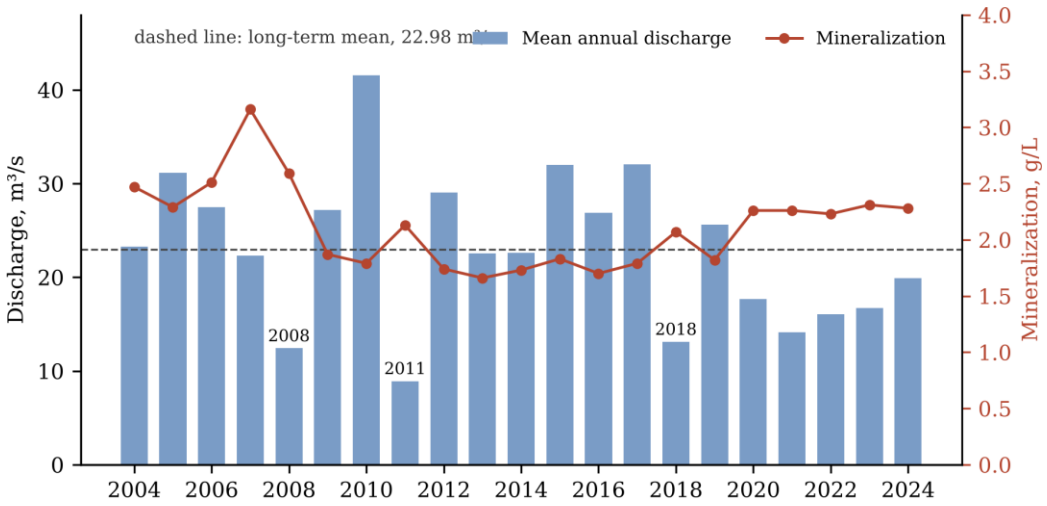


Fig. 2. Mean annual discharge (bars) and mean annual mineralization (line) of the Daryalyk collector at the Gurlan–Divankul station, 2004–2024. The years 2008, 2011 and 2018 were years of low water availability in the Amu Darya.

The three years of lowest discharge, 2008, 2011 and 2018, coincided with low water availability in the Amu Darya; mean discharge in these years was 12.41, 8.91 and 13.10 m³/s, respectively, and mineralization 2.59, 2.13 and 2.07 g/L. Mineralization was therefore clearly above the long-term mean only in 2008. Over the whole record the correlation between mean annual discharge and mineralization was negative but weak and not significant at the 5% level (Pearson $r = -0.39$, $p = 0.08$; Spearman $\rho = -0.38$, $p = 0.09$). The highest mineralization (3.16 g/L, 2007) occurred in a year of near-average discharge (22.30 m³/s).

Mean discharge in 2018–2024 (17.6 m³/s) was about 31% lower than in 2004–2017 (25.7 m³/s), whereas mean mineralization was similar (2.18 versus 2.09 g/L). The decline over the full period amounted to 0.43 m³/s per year but was not statistically significant (linear regression $p = 0.14$; Kendall's $\tau = -0.21$, $p = 0.20$). In the monthly data for 2023 (annual runoff 532 million m³), runoff peaked in July, with roughly one quarter of the annual volume (about 136 million m³, read from the source plot), and showed a secondary maximum in March, whereas monthly mineralization varied only

between 2.25 and 2.38 g/L.

Table 3. Statistical parameters of mean annual discharge (n = 21) and discharge of given exceedance probability at the Gurlan–Divankul station.

Parameter	1%	5%	10%	50%	75%	96%
Q_p, Pearson III, m³/s	43.2	36.7	33.5	22.6	17.4	9.7
Q_p, empirical (interpolated), m³/s	–	37.1	32.0	22.6	16.4	9.1

Mean Q_0 = 22.98 m³/s; minimum 8.91 m³/s (2011); maximum 41.54 m³/s (2010); C_v = 0.35; C_s = 0.27. Empirical values were interpolated between Cunnane plotting positions; no value is given for 1% because it lies outside the range of the observed plotting positions (2.8–96.3%).

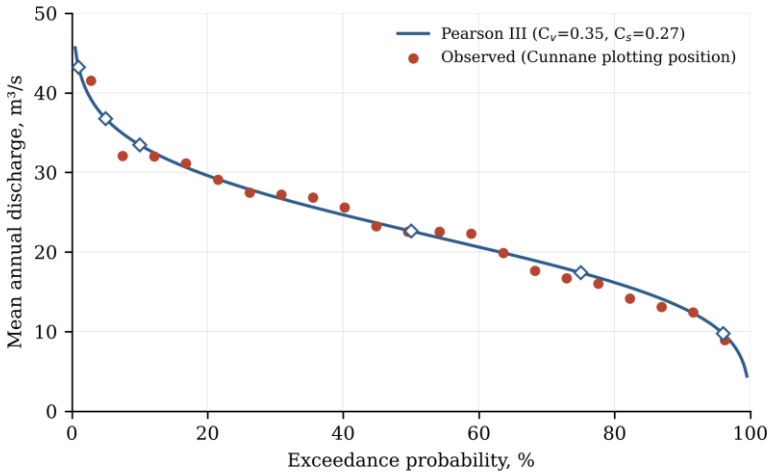


Fig. 3. Exceedance probability curve of mean annual discharge at the Gurlan–Divankul station: observed values (Cunnane plotting position) and fitted Pearson Type III curve. Diamonds mark the 1, 5, 10, 50, 75 and 96% exceedance discharges.

The fitted Pearson III curve agrees well with the empirical points (Fig. 3). Discharges exceeded in 50, 75 and 96% of years were 22.6, 17.4 and 9.7 m³/s, and the discharge exceeded in 10% of years was 33.5 m³/s (Table 3).

3.2 Discharge, velocity and geometry at the measured cross-sections



Table 4. Location of the ADCP cross-sections and results of the measurements.

No.	Location (collector)	Picket	Area, m²	Velocity, m/s	Q, m³/s	h_{max}, m
1	Gurlan district, near the Gurlan–Amudarya border bridge (Divankul)	250+00	91.03	0.58	52.8	2.5
2	Yangibazar district, Buzkala area (Atashev)	65+29	46.41	0.53	24.6	3.0
3	Urgench district, Durmon area (Atashev)	324+05	29.3	0.26	7.8	2.2
4	Khonqa district, “Khorezm” area (Toshsaka right-bank)	84+00	15.1	0.19	2.85	1.98
5	Bogot district, old Bogot–Khazarasp bridge (Toshsaka right-bank)	293+76	13.3	0.12	1.6	2.5

Q = discharge; h_{max} = maximum depth. In each case the discharge equals the product of the area and the mean velocity to within rounding.

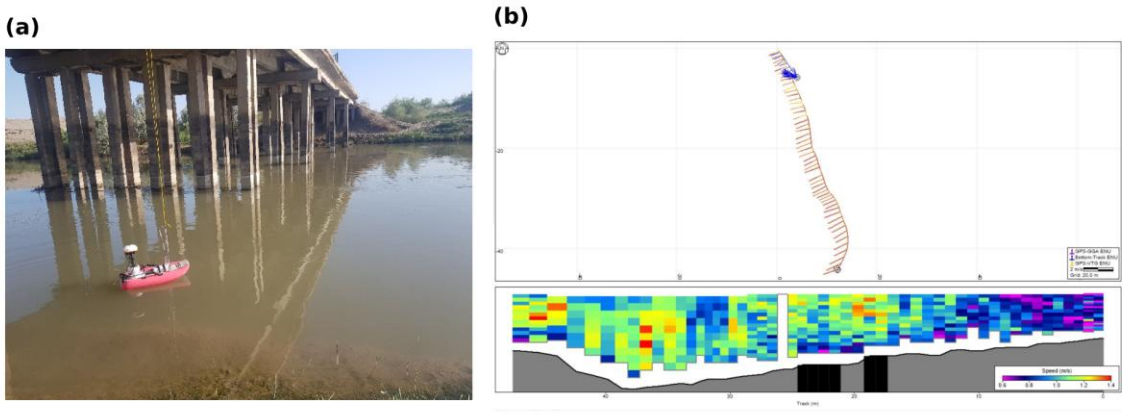


Fig. 4. ADCP measurements on the collector: (a) tethered boat with the SonTek S5 profiler and GPS under a bridge cross-section; (b) example of the ADCP output

showing the transect track (top) and the velocity field and bed profile (bottom).

The measured discharge fell steadily in the upstream direction, from 52.8 m^3/s at the border cross-section to 1.6 m^3/s at Bogot (Table 4, Fig. 1), mirroring the accumulation of drainage inflow along the system. The mean velocity decreased from 0.58 to 0.12 m/s and the wetted area from 91.0 to 13.3 m^2, while the maximum depth varied only between 1.98 and 3.0 m. Relative to the discharges listed in Table 1, the measured values amounted to 73% (Gurlan), 82% (Yangibazar), 98% (Urgench), 95% (Khonqa) and 100% (Bogot). The discharges measured in the Divankul collector were considerably higher than the long-term mean annual discharge of 22.98 m^3/s, which is consistent with the measurements having been made in the season of high drainage runoff.

3.3 Hydraulic resistance of the Divankul collector

Table 5. Hydraulic and morphometric parameters measured at the upstream (A) and downstream (B) sections of the three experimental reaches of the Divankul collector.

Reach (picket range)	Section	*Q*, m^3/s	*H*, m	Velocity, m/s	Bottom width *b*, m	Top width *B*, m
1 (253+50–255+00)	A1	42.38	2.94	0.33	41.06	46.30
	B1	42.37	2.76	0.31	41.50	46.85
2 (285+50–287+00)	A2	38.31	2.68	0.36	37.20	42.22
	B2	38.29	2.51	0.36	36.89	41.60
3 (351+70–353+20)	A3	35.26	2.40	0.34	39.72	46.70
	B3	35.25	2.18	0.35	38.88	40.73

Table 6. Experimental flow parameters and derived resistance characteristics of the three reaches (L = 150 m).

Reach	h, m	υ, m/s	ω, m²	χ, m	R, m	Re	λ	I, ×10⁻³	n, s/m$^{1/3}$	M, g/L	T, °C
1	0.18	0.32	128.42	95.24	1.35	376,963	0.313	1.20	0.13	2.27	19.2
2	0.17	0.36	106.4	86.7	1.23	375,655	0.21	1.13	0.11	2.27	19.1
3	0.22	0.34	102.2	89.9	1.15	341,187	0.29	1.47	0.12	2.28	19.7

h = head loss (difference of water levels between A and B); υ = mean velocity; ω = wetted area; χ = wetted perimeter; R = hydraulic radius; Re = $\upsilon R/\nu$ with $\nu = 1.146 \times 10^{-6}$ m²/s; λ from Eq. (1); $I = h/L$; n = Manning's coefficient derived from R, I and υ; M = mineralization; T = water temperature. Re, λ, R, ω, χ, M and T as obtained in the experiments; I and n calculated here.

Reynolds numbers in the three reaches were 3.77×10^5, 3.76×10^5 and 3.41×10^5, so the flow was fully turbulent. The hydraulic-resistance coefficient was 0.31, 0.21 and 0.29 in reaches 1, 2 and 3, i.e. head losses of 0.18, 0.17 and 0.22 m over 150 m (Tables 5 and 6). Because Reynolds numbers differed by only about 10% among the reaches whereas λ varied by about 50%, the variation in resistance cannot be attributed to Re; it is governed by the roughness of the wetted channel perimeter, as expected for turbulent flow in the rough regime. The water-surface slopes were $(1.1–1.5) \times 10^{-3}$ at velocities of only 0.32–0.36 m/s, which corresponds to Manning coefficients of 0.11–0.13 s m$^{-1/3}$ and Chézy coefficients of 8–10 m$^{1/2}$/s. In terms of the conventional Darcy–Weisbach factor these values correspond to λ_{DW} of roughly 0.8–1.2. There was no monotonic change of λ along the channel (the lowest value was found in the middle reach).

3.4 Pumping stations

Table 7. Pumping stations investigated and measured discharge in the pressure pipes (500 mm) compared with the design discharge.

No.	District	Pumping station (collector)	Design *Q*, m³/s	Measured *Q*, m³/s	Measured / design, %
1	Gurlan	NS-Divankul (Divankul)	0.5	0.476	95.2
2	Yangibazar	NS Buzkala (Atashev)	0.5	0.454	90.8
3	Urgench	NS Davdon-1 (Atashev)	0.5	0.424	84.8
4	Khonqa	NS Obl-kul-1 (Toshsaka right-bank)	0.5	0.436	87.2
5	Bogot	NS Bogot-2 (Toshsaka right-bank)	0.5	0.455	91.0

NS = pumping station.

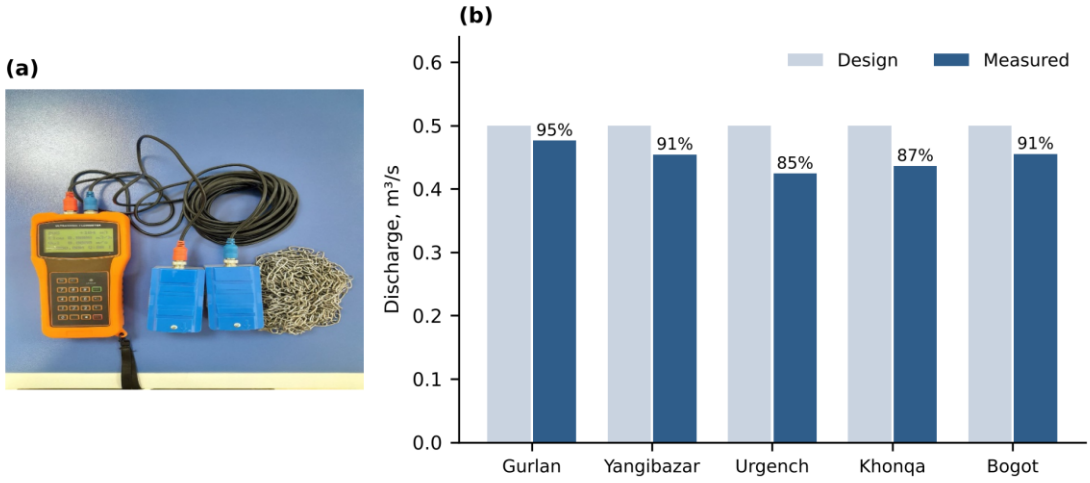


Fig. 5. Flow measurements in pump pressure pipes: (a) the portable ultrasonic flowmeter AFT-2000H with clamp-on transducers; (b) measured discharge relative to the design discharge of 0.5 m³/s at the five stations (percentages: measured/design).

Measured discharges were 0.424–0.476 m³/s, i.e. 84.8–95.2% of the design discharge of 0.5 m³/s (mean 0.449 m³/s, 89.8%; Table 7, Fig. 5b). The best

performance was found at the Gurlan station (95.2%), the lowest at the Urgench station (84.8%).

The pumping stations of Gurlan district abstracted 3.62 million m³ of water in 2021, 2.38 million m³ in 2022, 1.29 million m³ in 2023 and 0.15 million m³ in 2024, a decrease of 96% over four years (Table 8). They operated in only two (2021), five (2022), seven (2023) and three (2024) months of the year, always within the April–November period. Electricity consumption declined proportionally, from 282 to 12 thousand kWh, so that the specific consumption remained practically constant at 0.077–0.078 kWh/m³. The annual pumped volume was equivalent to 0.8%, 0.5%, 0.2% and 0.02% of the annual runoff recorded at the Gurlan–Divankul station in the same years.

Table 8. Water pumped from the collector and electricity consumed by the pumping stations of Gurlan district, 2021–2024.

Year	Months of operation	Pumped volume, thousand m³	Electricity, thousand kWh	Specific energy, kWh/m³	Annual runoff at the station, million m³
2021	2 (Jun–Jul)	3,620.8	282.2	0.078	447.3
2022	5 (May–Sep)	2,381.8	185.3	0.078	507.5
2023	7 (Apr–Sep, Nov)	1,290.3	100.2	0.078	531.7
2024	3 (May–Jul)	148.4	11.6	0.078	631.3

Annual totals are sums of the monthly values.

4. Discussion

4.1 Flow regime and mineralization

The long-term record shows a moderately variable flow regime ($C_v = 0.35$) with a positive but small skewness, so that the discharge exceeded in 96% of years (9.7 m³/s)



is about 42% of the mean and the discharge exceeded in 10% of years (33.5 m^3/s) about 1.5 times the mean. These values can serve as reference discharges for the capacity checks and for scheduling cleaning, but with a 21-year sample the estimates of C_s, and hence of the extreme quantiles, are uncertain. The mean mineralization of 2.12 g/L is of the same order as the average groundwater salinity of the whole Khorezm region (1.75 g/L; Ibrakhimov et al., 2007), as expected for water of drainage origin. Mineralization showed little seasonal variation in 2023, which suggests that the water is dominated by groundwater drainage rather than by short-lived irrigation return flow, although this interpretation needs verification with data from more years.

A tendency of mineralization to rise in low-flow years is often assumed. In our data it is only weakly expressed: the correlation with discharge was negative ($r = -0.39$) but not significant, and in two of the three driest years mineralization was close to the long-term mean. The lower mean discharge in 2018–2024 than in 2004–2017 is noteworthy, but its statistical significance is low, and a longer record and information on Amu Darya water availability and water-use changes in the basin are needed to decide whether it reflects a real shift. The seasonal runoff pattern in 2023, with a main peak in July and a secondary peak in March, is consistent with the irrigation and leaching seasons; Tischbein et al. (2012) reported pre-season leaching of about 700 mm in a studied hydro-unit.

4.2 Hydraulic resistance

The Reynolds numbers of 3.4–3.8 × 10^5 place the flow far into the turbulent regime. The essential finding is the high resistance: Manning coefficients of 0.11–0.13 s $m^{-1/3}$ are several times larger than the 0.02–0.03 typical of clean earth channels and are of the magnitude associated with channels densely overgrown with weeds and reeds (Chow, 1959). Aquatic vegetation that occupies a large share of the flow depth is known to dominate flow resistance and to reduce velocities within the canopy (Nepf, 2012), and reed growth and siltation have been identified as problems in the Daryalyk

collector system. We did not survey vegetation or sediment, so the attribution of the high resistance to these factors remains a hypothesis; it nevertheless agrees with the low velocities (0.12–0.58 m/s) measured over the system. If correct, systematic removal of vegetation and sediment would increase the conveyance of the channel considerably; the effect of the reconstruction work carried out in different districts could be quantified by repeating the experiments in cleaned and uncleaned reaches. Note that the coefficient λ in Eq. (1) is defined with the hydraulic radius as characteristic length and is therefore not directly comparable with Darcy–Weisbach factors reported in the literature, which are four times higher.

4.3 Pumping stations

All five pumping stations delivered less than their design discharge (85–95%). The shortfall can result from impeller wear, a higher actual head than designed, suction conditions, clogging of intakes, or measurement error. On the last point, clamp-on ultrasonic meters can deliver accurate results when installed correctly, but errors increase with pipe encrustation, poor coupling and flow disturbances; in one test, readings varied by up to ±21% of the mean at a distance of two pipe diameters downstream from a swing check valve (University of Nebraska–Lincoln Extension, 2008), and uncertainty assessment in situ is advisable (Simões et al., 2024). In the present study, measuring sections free of local resistances were chosen, but an uncertainty analysis was not made; the differences from design values should therefore be regarded as indicative and be confirmed by repeated measurements or by a second method.

The sharp decrease in pumped volume in 2021–2024 was not accompanied by a change in specific energy consumption (0.077–0.078 kWh/m^3), suggesting that the operating conditions of the pumps (head and efficiency) remained similar and that the decrease was due to shorter operation. The decrease also cannot be explained by a lack of water in the collector, since mean annual discharge increased from 14.1 to 19.9 m^3/s

between 2021 and 2024. Reduced demand, alternative water sources, changes in the cropping pattern or technical availability of pumps are more probable reasons, but they cannot be assessed with the present data. In any case, the pumping stations of Gurlan district use only a tiny fraction of the runoff of the collector, so the potential reuse of drainage water within the district has been exploited to a very limited degree.

4.4 Limitations

Several limitations should be noted. The ADCP and ultrasonic measurements represent single campaigns, and their measurement uncertainty was not quantified. The hydraulic-resistance experiments were carried out on three short reaches, and the use of the water-surface slope as a proxy for the friction slope assumes nearly uniform flow. The frequency analysis rests on 21 annual values, and annual means do not describe intra-annual extremes. Mineralization was available only as an annual (and, for one year, monthly) mean, and no information on individual ions, sediment or vegetation was available.

5. Conclusions

The Daryalyk collector at the Gurlan–Divankul station had a mean annual discharge of 22.98 m^3/s (8.91–41.54 m^3/s; C_v = 0.35, C_s = 0.27) and a mean mineralization of 2.12 g/L in 2004–2024. Discharges exceeded in 10, 50, 75 and 96% of years are 33.5, 22.6, 17.4 and 9.7 m^3/s.

Mean discharge in 2018–2024 was about 31% lower than in 2004–2017, but the trend is not statistically significant. The relationship between discharge and mineralization is weak ($r = -0.39$, $p = 0.08$).

ADCP measurements show that the discharge decreases from 52.8 m^3/s at the border to 1.6 m^3/s in the uppermost cross-section, with mean velocities between 0.58 and 0.12 m/s.

In three reaches of the Divankul collector the flow is fully turbulent (Re = 3.4–3.8 × 10^5), and resistance is very high (λ = 0.21–0.31; Manning's $n \approx$ 0.11–0.13),

indicating strong roughness of the channel, which is probably related to vegetation and sediment.

The pumping stations delivered 85–95% of their design discharge. Pumped volume in Gurlan district fell by 96% between 2021 and 2024 at a constant specific energy consumption of about 0.078 kWh/m^3.

The results provide quantitative reference values for planning cleaning and reconstruction, and for assessing pumping installations on the collector system. Repeated measurements with an uncertainty analysis, together with vegetation and sediment surveys, would make it possible to quantify the benefit of cleaning.

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