

Hydrological and Hydrobiological Assessment of Reservoirs in the Amu Darya Delta: Towards an Improved Water-Supply Regime

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Abstract: The Amu Darya delta, once an ecologically rich and economically productive region, has undergone severe hydrological and ecological degradation due to the dramatic reduction of river flow over recent decades. This study presents field measurements and mathematical modelling results for three key reservoirs in the Muynak district of Karakalpakstan: the Mezhdurechye Reservoir, Muynak Bay and Rybachy Bay. Through GPS-assisted geodetic surveys conducted in 2022–2023, the actual morphometric parameters of each reservoir were determined and compared with GIS-based estimates. A hydrological water balance model was developed using differential equations and calibrated against observed flow data at the Samanbay gauging station for three representative years: a high-water year (2010), an average-water year (2019), and a low-water year (2001). The results indicate that, under current infrastructure conditions, the reservoirs can collectively store only 499.99 million m³ of water, with large volumes of potentially useful freshwater are discharged irreversibly to the dried bed of the Aral Sea. Following the reconstruction of hydraulic structures and canals, the combined storage capacity could reach 1,169.5 million m³, allowing an additional 669.51 million m³ to be retained in the delta. Hydrobiological surveys recorded 27 zooplankton species and 14–15 fish species, indicating substantially lower diversity compared with historical records as a consequence of deteriorating hydrological conditions. These findings provide a scientific basis for optimising the water-supply regime of the Amu Darya delta reservoirs and restoring the ecological and economic potential of the Southern Aral Sea region.

Keywords: Amu Darya delta; Mezhdurechye Reservoir; water balance; hydrological modelling; morphometric parameters; zooplankton; fish diversity; Aral Sea; Karakalpakstan.

INTRODUCTION

The Amu Darya River delta is one of the most hydrologically transformed landscapes in Central Asia. In the 1960s, the delta encompassed more than 140 large lakes covering approximately 600 km² and supported productive fisheries and diverse wetland ecosystems [1]. In the 1930s, the annual fish catch across the delta and the Aral Sea reached 244,000 centners, while muskrat harvesting exceeded 1.2 million animals per year [2]. However, the progressive

diversion of river flow for agricultural irrigation, combined with the construction of successive upstream hydraulic structures, led to a dramatic reduction in the volume of water reaching the delta. This reduction in inflow ultimately triggered the Aral Sea ecological crisis, which is widely recognised as one of the most severe environmental disasters of the twentieth century [3].

As a consequence of declining inflows, nearly 90% of

the delta lakes disappeared, riparian forests shrank tenfold and reed beds contracted by 40–50 times [4]. The livelihoods of local communities in the Muynak district, where over 80% of the population was historically engaged in fishing and related industries, were fundamentally disrupted. Commercial fishing, which had once constituted the second most economically significant sector of the regional economy, effectively ceased [5].

Since the 1970s, several artificially regulated reservoirs have been constructed in the delta region to compensate for the loss of natural water bodies. These include the Mezhdurechye Reservoir, established in 1978, Muynak Bay, Rybachy Bay, constructed on the site of the former Sarybas Bay in 1974, and the Dumalak lake system [6]. Although these facilities have partially contributed to the restoration of local hydrological conditions and habitats for fish and migratory birds, their operation remains constrained by the limited capacity of existing hydraulic structures and the ongoing uncertainty of upstream inflows.

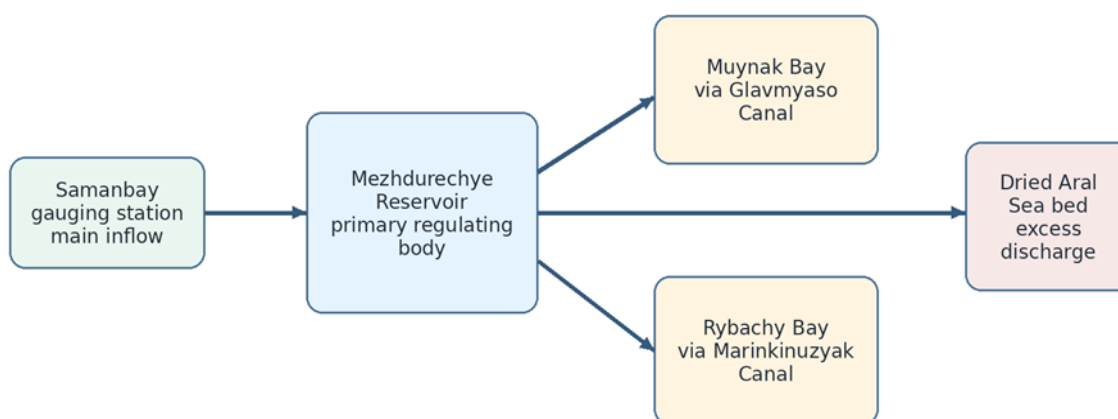
The Resolution of the President of the Republic of Uzbekistan No. PQ-5202 of 29 July 2021, which supports the implementation of the UN General Assembly Special Resolution declaring the Aral Sea basin region a zone of ecological innovation and technologies, emphasises the need for scientific research and practical measures to stabilise the ecological condition of lakes and reservoirs in the

region [7]. In this context, improving the water-supply regime of the Amu Darya delta reservoirs is both a scientific and practical priority.

Previous studies of the delta's hydrological and biological resources include the foundational investigations of Rogov [8], who described the hydrographic and hydrobiological regimes of water bodies in the delta and the Aral Sea, and the works of Dukhovny and colleagues [9, 10], who developed strategic frameworks for water-resource management in the Southern Aral Sea region. Field investigations of reservoir morphometry and water-balance calculations were conducted by Kurbanbaev et al. [11, 12], who also described possible options for ensuring the safe operation of the Mezhdurechye Reservoir. Nevertheless, integrated studies combining current field measurements of reservoir morphometry, hydrological modelling and hydrobiological assessment of the delta reservoirs remain limited.

The present study addresses this gap by: (1) determining the actual morphometric characteristics of the Mezhdurechye, Muynak and Rybachy reservoirs through GPS-supported geodetic surveys; (2) developing and applying a hydrological water-balance model for the central zone of the Amu Darya delta calibrated for years with different water availability; and (3) characterising the hydrobiological condition of the reservoirs through zooplankton and ichthyological surveys conducted in 2022–2023.

Conceptual scheme of the Amu Darya delta reservoir system



Management target: increase storage to 1,169.5 million m³ and retain an additional

Figure 1. Conceptual scheme of the reservoir system and the main water-management challenge.

Study Area

The study area encompasses the central zone of the Amu Darya River delta, located in the Muynak district of Karakalpakstan, Uzbekistan. This zone comprises three principal water-management facilities: the Mezhdurechye Reservoir, Muynak Bay and Rybachy Bay. These water bodies are interconnected through the Glavmyaso and Marinkinuzyak canals and are supported by hydraulic structures and protective dams.

The Mezhdurechye Reservoir was formed in 1978 following the construction of a dam across the Akdarya channel. It occupies the area between the active Akdarya riverbed and the dried-up Kipchakdarya channel. The reservoir is the primary water-receiving body in the system and is crucial for regulating supply to the downstream reservoirs. It is equipped with northern and eastern protective dams, the head structures of the Glavmyaso and Marinkinuzyak canals, and a lateral spillway.

Muynak Bay is supplied with water from the Mezhdurechye Reservoir via the Glavmyaso canal. The settlements of Muynak and Uchsai, whose populations have historically been associated with fishing, are situated along the reservoir boundary. Rybachy Bay was constructed in 1974 on the site of the former Sarybas Bay, which previously connected directly to the Aral Sea. Together, these water bodies constitute the principal freshwater ecosystems of the Amu Darya delta zone and possess ecological, socioeconomic and conservation value [13].

3. Materials and Methods

3.1 Morphometric surveys and GIS processing

Field measurements were conducted in all three reservoirs during 2022–2023 using standard procedures for hydrological surveys and morphometric characterisation. The methodology focused on determining hydrographic and bathymetric parameters that describe the shape, size and water volume of the reservoirs.

The perimeter of each reservoir was divided into measurement cross-sections. Within each designated

zone, levelling surveys were carried out. The coordinates of all measurement points were determined using GPS receivers, and absolute elevations were measured by differential levelling. The collected data were processed to prepare bathymetric maps and to calculate water volumes at different levels.

In parallel, GIS-based calculations were performed in ArcGIS using the same field-measured depth and coordinate data. The area–elevation and volume–elevation relationships were derived for each reservoir by both methods. All calculations and hydrological modelling were performed using software developed in Visual C#.

Hydrological water-balance modelling

A hydrological model for water-resource management in the central zone of the Amu Darya delta was developed on the basis of a water-balance differential equation. In general form, the model can be expressed as $\frac{dW}{dt} = Q_p - Q_{out} - Q_r - Q_E - q_{f, re}$ where W is reservoir storage, Q_p is inflow from the Samanbay gauging station, Q_{out} is controlled outflow, q_r represents channel losses, Q_E represents evaporation and q_f represents filtration losses.

The model incorporated separate sub-equations for the Mezhdurechye, Rybachy and Muynak reservoirs. Management rules for the hydraulic structures of the Glavmyaso and Marinkinuzyak canals were included as control functions dependent on current and critical water levels.

Simulations were conducted for three hydrological scenarios based on observed daily discharge records at the Samanbay gauging station: a high-water year (2010, maximum daily discharge up to 1,830 m³/s), an average-water year (2019), and a low-water year (2001, minimum monthly mean discharge 2.1 m³/s). Channel losses between the Samanbay gauging station and the Mezhdurechye Reservoir, located approximately 140 km downstream, were estimated according to the methodology of Rogov [8] and calibrated against historical data.

Water-balance model structure used in the analysis

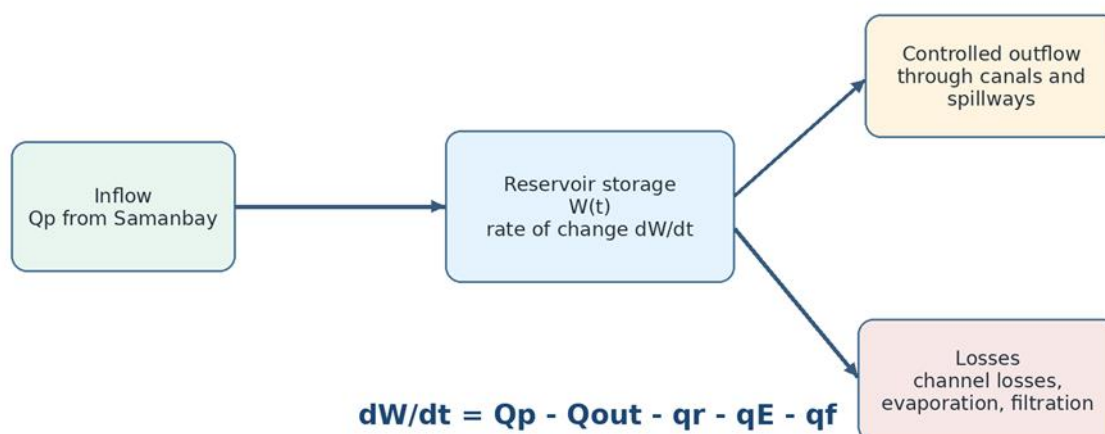


Figure 2. General structure of the water-balance model used for the reservoir system.

Hydrobiological surveys

Zooplankton samples were collected from all three reservoirs during summer and autumn expeditions in 2022 and 2023. Quantitative samples were obtained by filtering 100 litres of water through a No. 76 nylon plankton net, while qualitative samples were collected by towing the net. Samples were preserved in 2–3% formalin. Laboratory processing was carried out using microscopy and stereomicroscopy. Numerical abundance was determined using a Bogorov counting chamber, and biomass was calculated using established weight–length relationships.

Ichthyological surveys employed standard seine nets with mesh sizes of 10–80 mm. Fish age was determined by scale analysis, and growth rates were back-calculated using the Lea formula. Water temperature, transparency measured with a Secchi disk and macrophyte coverage were also recorded at each station.

Results and Discussion

Morphometric characteristics of the reservoirs

Field measurements of the Mezhdurechye Reservoir indicated an actual water-surface area of 19,996 ha and a total water volume of 190,905 thousand m³, including 11 excavated channels, at the surveyed water level.

GIS-based calculations yielded a surface area of 14,934 ha and an estimated design volume of 230,838 thousand m³. The discrepancy between field-measured and GIS-derived values is related mainly to changes in reservoir morphology, sedimentation, shore erosion and the inclusion of excavated channel networks in the field survey.

For Muynak Bay, the measured water-surface area was 12,529 ha, while the GIS-derived value was 13,049 ha. The measured water volume was 184,968 thousand m³, compared with a GIS-derived design volume of 210,182 thousand m³. The maximum depth reaches 4.0–4.2 m, and the mean depth is approximately 1.48 m. Water mineralisation ranged from 2.5 to 4.0 g/l depending on inflow conditions.

For Rybachy Bay, the actual water-surface area was 6,243 ha, compared with a GIS-derived area of 5,229 ha. The actual water volume was 124,913 thousand m³, while the GIS-derived design volume was 133,229 thousand m³. Maximum depth is 3.5–4.0 m, prevailing depth is 0.8–1.5 m and mean depth is approximately 2.0 m. Water mineralisation ranges from 1.5 to 3.0 g/l. The reservoir has relatively favourable conditions for fish and muskrat reproduction, with aquatic vegetation covering 50–55% of its area.

Table 1. Morphometric parameters of the investigated reservoirs

Reservoir	Field area (ha)	GIS area (ha)	Field volume (thousand m ³)	GIS volume (thousand m ³)	Max depth (m)	Mean depth (m)	Mineralisation (g/l)
Mezhdurechye	19,996	14,934	190,905	230,838	—	—	—
Muynak Bay	12,529	13,049	184,968	210,182	4.0–4.2	1.48	2.5–4.0
Rybachy Bay	6,243	5,229	124,913	133,229	3.5–4.0	~2.0	1.5–3.0

Reservoir surface area: field measurements vs GIS estimate

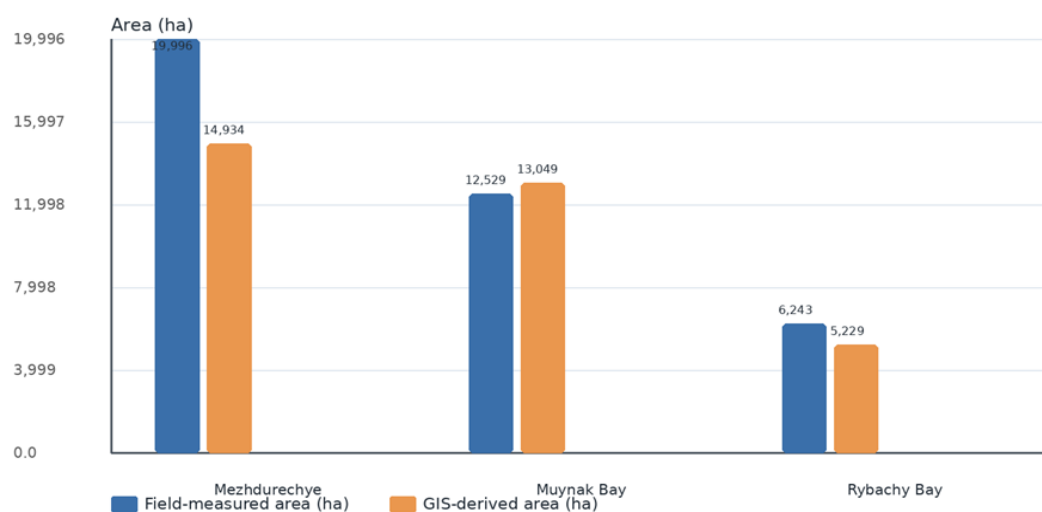


Figure 3. Comparison of field-measured and GIS-derived surface area of the three reservoirs.

Reservoir storage volume: field measurements vs GIS estimate

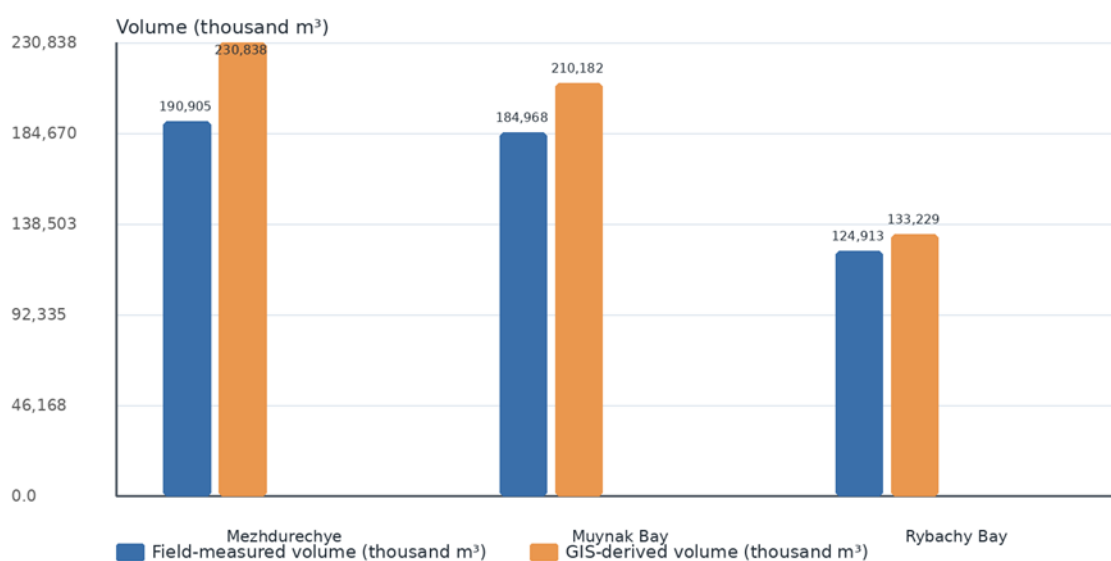


Figure 4. Comparison of field-measured and GIS-derived storage volume of the three reservoirs.

Hydrological modelling results

Analysis of discharge records at the Kyzyljar gauging

station for 1965–2022 reveals a pronounced multi-decadal decline in inflows. The maximum average

monthly discharge observed during this period was 3,530 m³/s in July 1969, while the minimum was 2.1 m³/s in August 2001. In recent decades, peak discharges exceeding 1,000 m³/s have become

significantly less frequent compared with the 1960s–1970s. The mean annual discharge for 1980–2022 was 177.48 m³/s, with a coefficient of variation $C_v = 1.08$ and a coefficient of skewness $C_s = 1.79$.

Table 2. Water balance of the Amu Darya delta reservoirs under three water-availability scenarios

Parameter	High-water year (2010)	Average-water year (2019)	Low-water year (2001)
Total inflow at Samanbay, million m ³	16,817.70	1,674.38	100.89
Channel losses, million m ³	4,204.43	418.59	25.22
Total useful volume stored, million m ³	499.98	500.03	218.82
Volume discharged to the Aral Sea bed, million m ³	12,214.90	852.40	0.00
Total evaporation, million m ³	14.50	11.44	4.95
Total filtration, million m ³	1.30	1.14	0.17

Water-balance indicators under three hydrological scenarios

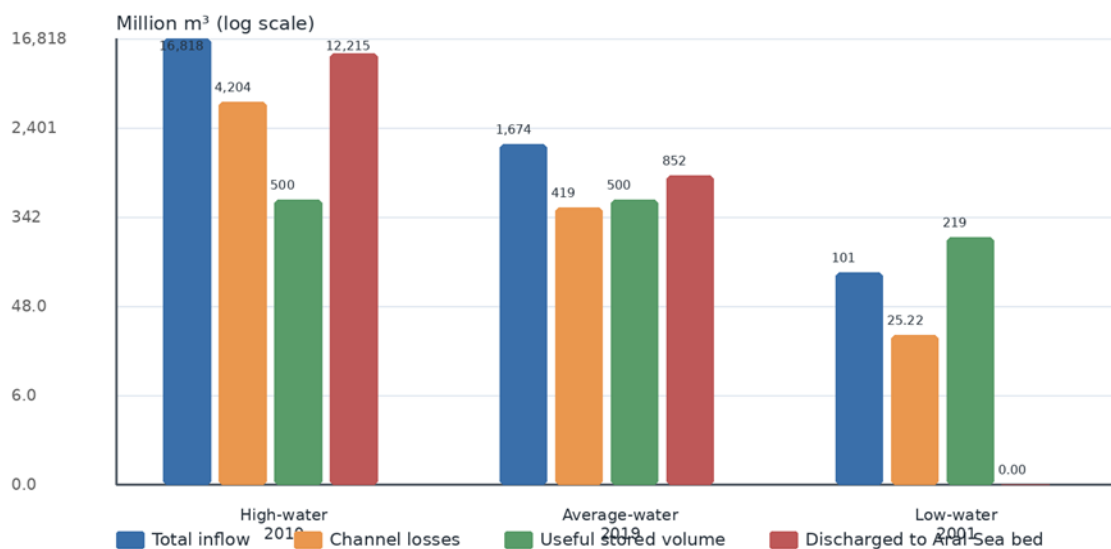


Figure 5. Water-balance indicators under high-, average- and low-water scenarios. A logarithmic y-axis is used because the values differ greatly in magnitude.

Under the current state of hydraulic infrastructure, the three reservoirs together can store a maximum of approximately 499.99 million m³ per year. In a high-water year such as 2010, this means that 12,214.9 million m³, representing the overwhelming majority of

available inflow, is discharged irreversibly towards the dried bed of the Aral Sea. This represents a substantial loss of potentially recoverable freshwater.

In a low-water year such as 2001, total inflow of only 100.89 million m³ is insufficient even to fill the primary

Mezhdurechye Reservoir, whose design capacity is 180 million m³, and therefore cannot adequately supply the downstream Muynak and Rybachy reservoirs. The resulting deficit relative to the combined useful capacity of all three reservoirs is 399.1 million m³.

Following reconstruction and capacity enhancement of the protective dams and canals, the combined storage

capacity could reach 1,169.5 million m³. This would allow an additional 669.51 million m³ per year to be retained in the delta system. Model calculations indicate that, for all three reservoirs to operate under normal operating conditions, the optimal annual inflow volume at the Samanbay gauging station should reach 515.55 million m³.

Current and potential storage capacity of the reservoir system

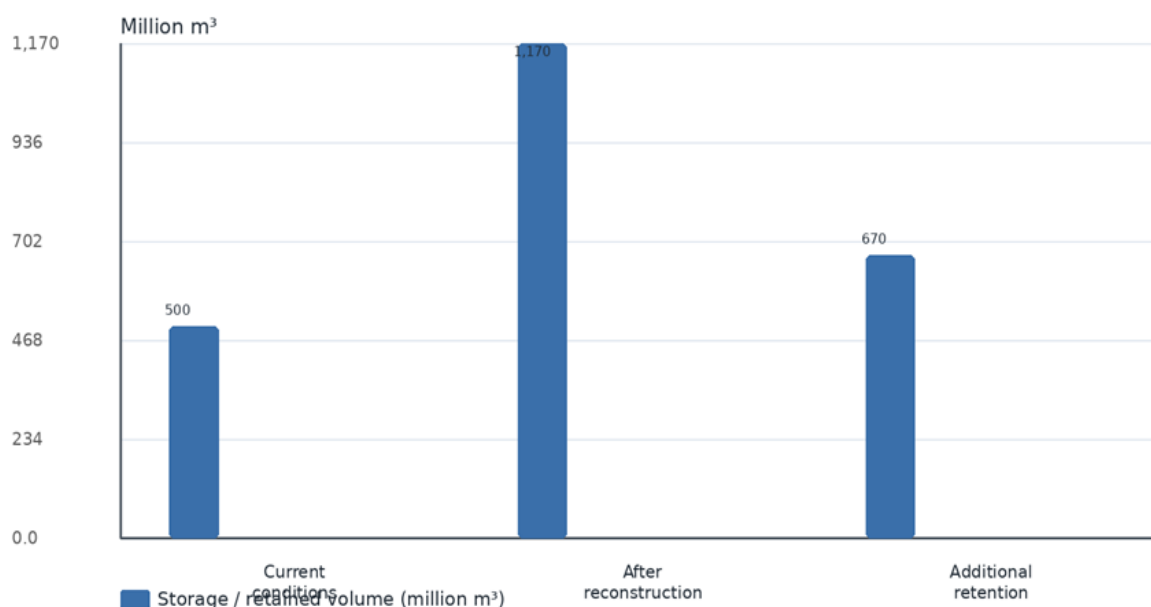


Figure 6. Current and potential storage capacity after hydraulic reconstruction.

Hydrobiological status

A total of 27 zooplankton species were recorded across the three reservoirs during the 2022–2023 surveys: 15 Rotifera, 6 Cladocera and 6 Copepoda. This total is lower than the 36 taxa of planktonic crustaceans documented in 1968–1983 [14] and the 41 species reported in 2003–2004 [15]. Seven species were recorded for the first time in the lower Amu Darya, including *Hexarthra mira*, *Asplanchna sieboldi*, *Polyarthra vulgaris* and *Bdelloida* gen. sp. Several species present in earlier surveys, including *Keratella tropica* and *Thermocyclops vermifer*, were not detected during the current surveys.

Zooplankton diversity was highest in the Mezhdurechye Reservoir, reflecting its relatively more stable hydrological regime. In the poorly supplied

Rybachy and Muynak reservoirs, species richness was substantially lower. Seasonal changes showed that zooplankton diversity declined from summer to autumn, which may be associated with seasonal increases in water mineralisation and intensive predation by juvenile fish.

Peak zooplankton abundance was recorded in Muynak Bay in summer, with a mean of 70,000 ind./m³ and dominance by the halophilic rotifer *Brachionus plicatilis*, which reached up to 68,900 ind./m³. Mezhdurechye reached 40,000 ind./m³. Peak biomass was recorded in Mezhdurechye in August, reaching 4,400 mg/m³, where Copepoda contributed 96% of total biomass. Corresponding values were lower in Rybachy Bay (231 mg/m³) and Muynak Bay (124 mg/m³).

Table 3. Zooplankton species richness and proportion of halophilic taxa

Reservoir / indicator	Summer 2022	Autumn 2022	Summer 2023	Autumn 2023
Mezhdurechye – total species	14	9	14	8
Mezhdurechye – halophilic (%)	0	0	0	12.5
Rybachy – halophilic (%)	—	—	18	—
Muynak – halophilic (%)	—	—	16	—

Zooplankton taxonomic composition recorded in 2022-2023

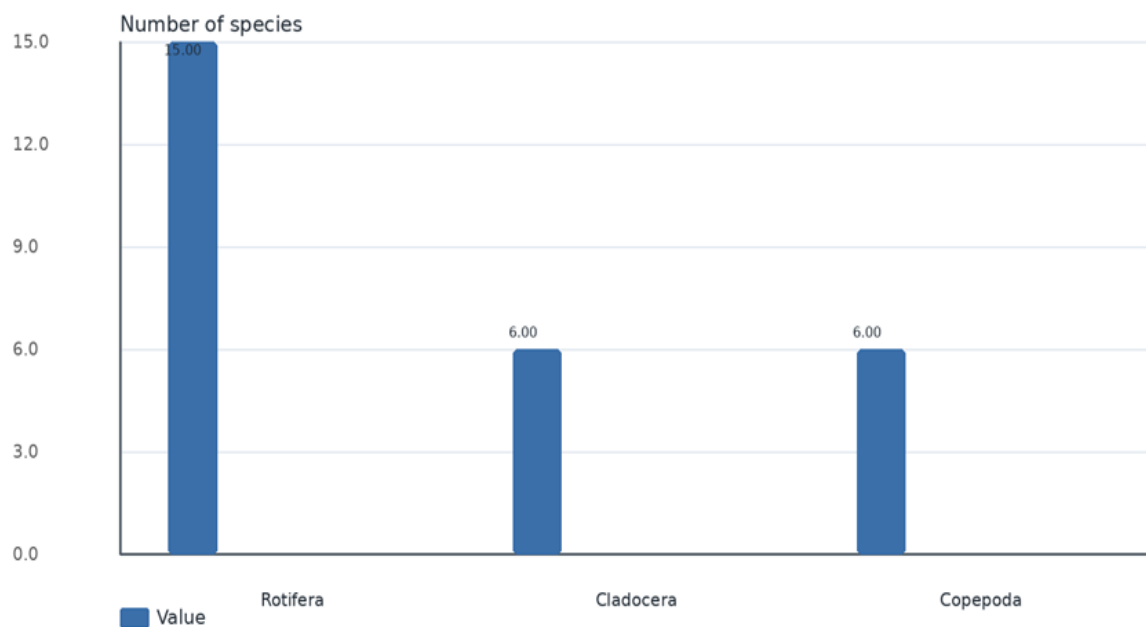


Figure 7. Taxonomic composition of zooplankton recorded during the 2022–2023 surveys.

Current biodiversity compared with historical records

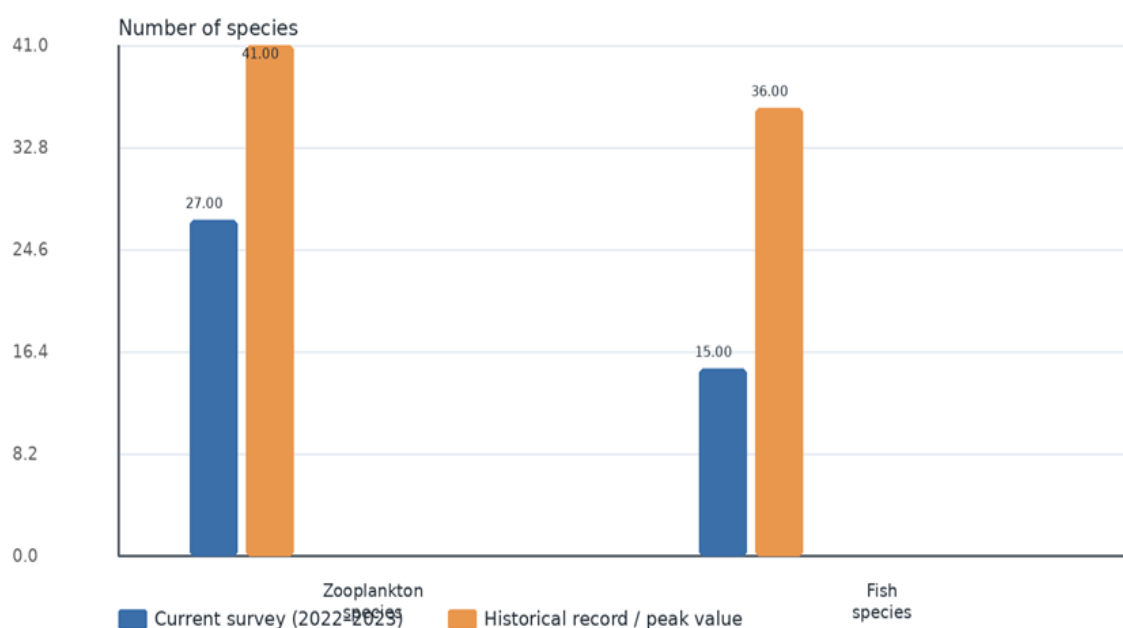


Figure 8. Current biodiversity compared with historical records.

Current surveys recorded 14–15 fish species across the reservoirs, compared with 27 species documented in earlier high-water years and approximately 36 species historically reported for the lower Amu Darya. In the Mezhdurechye Reservoir, 15 species were identified in 2022, including 8 commercial and 7 non-commercial species, and 14 species were identified in 2023. Most species belonged to the family Cyprinidae. No commercial fishing was carried out in any of the three reservoirs during the study period because of low water levels and the absence of commercially viable fish stocks.

Silver carp (*Hypophthalmichthys molitrix*) was the dominant commercial species in the Mezhdurechye Reservoir, with individuals of mean length 26.3 cm and

mean weight 326.8 g. The Fulton condition factor ranged from 1.34 to 1.90, with a mean of 1.63, indicating acceptable body condition relative to available food resources. The age composition comprised three groups: 1+ (33.1%), 2+ (45.1%) and 3+ (21.8%).

Crucian carp (*Carassius gibelio*) was distributed across all three reservoirs but showed smaller size and lower weight in the water-deficient Rybachy and Muynak reservoirs than in Mezhdurechye. In Muynak Bay, non-commercial invasive species, including medaka (*Oryzias latipes*) and mosquitofish (*Gambusia affinis*), dominated during the study period, reflecting degraded aquatic conditions.

Table 4. Size and weight parameters of *Carassius gibelio* across the surveyed reservoirs (2022–2023)

Reservoir	n	Length range (cm)	Mean length (cm)	Weight range (g)	Mean weight (g)
Mezhdurechye	36	15.3–26.6	19.9	105–464	257.6
Rybachy Bay	8	13.9–17.8	16.0	65–181	122.0
Muynak Bay	15	10.8–17.1	13.1	37–135	81.0

Mean length and weight of *Carassius gibelio* by reservoir

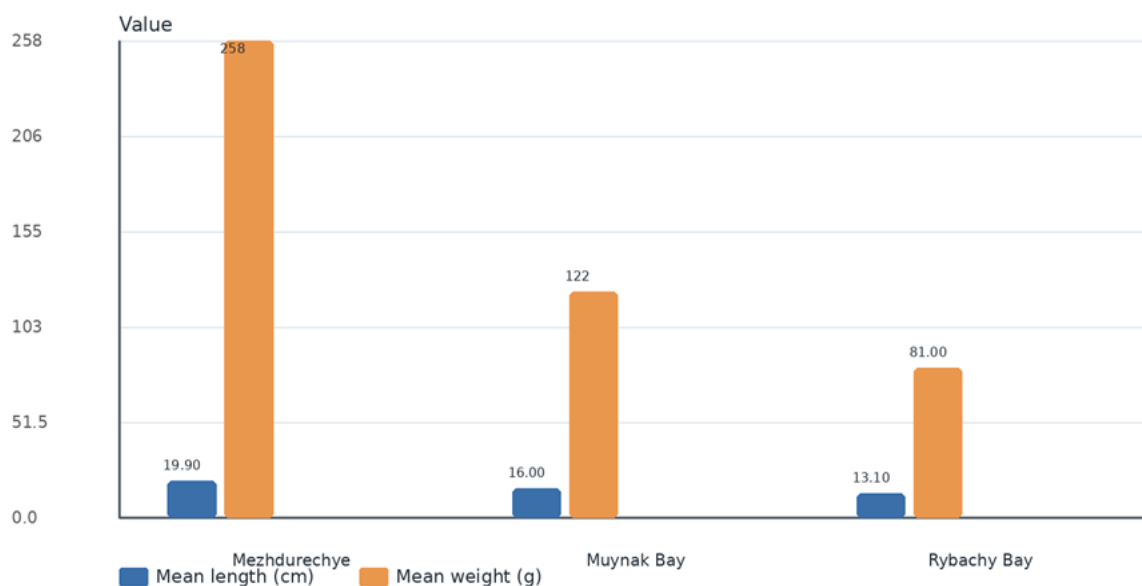


Figure 9. Mean length and mean weight of *Carassius gibelio* across the surveyed reservoirs.

Age composition of silver carp in Mezhdurechye Reservoir

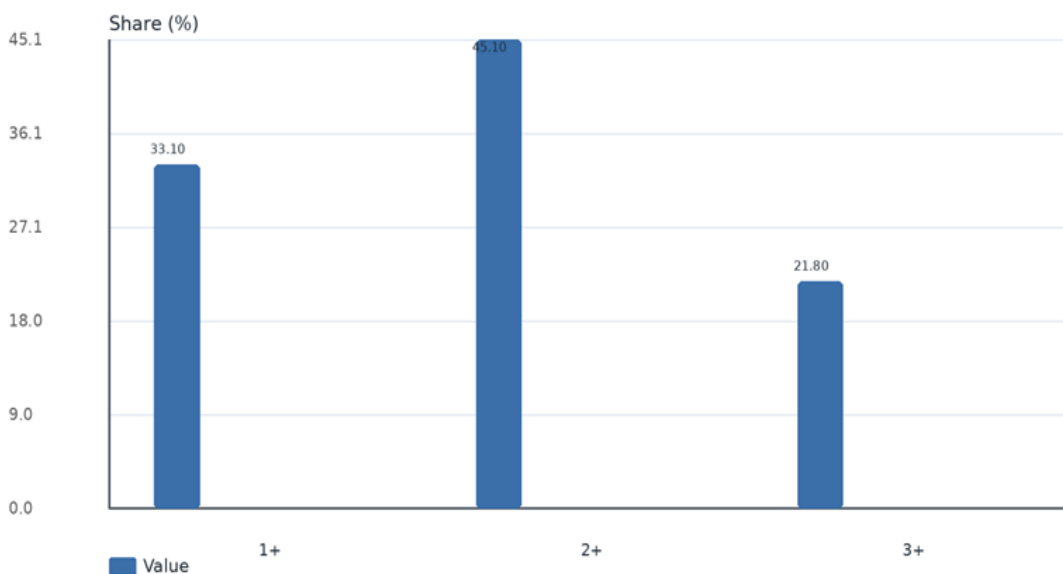


Figure 10. Age composition of silver carp in the Mezhdurechye Reservoir.

The decrease in ichthyofauna diversity and the deterioration in the condition of commercial fish stocks directly reflect the weakening hydrological regime. During 2022–2023, inflow to the Mezhdurechye Reservoir fell to 380.46 million m³ in January–November 2022, compared with 474.93 million m³ in

2021. This caused parts of the reservoir to dry out except in the deepest channels. High turbidity, with Secchi depth of 30–60 cm, caused by continuous inflow of suspended sediment from the Kipchakdarya channel, further constrains primary productivity and the development of zooplankton food organisms.

Inflow to Mezhdurechye Reservoir in 2021 and 2022

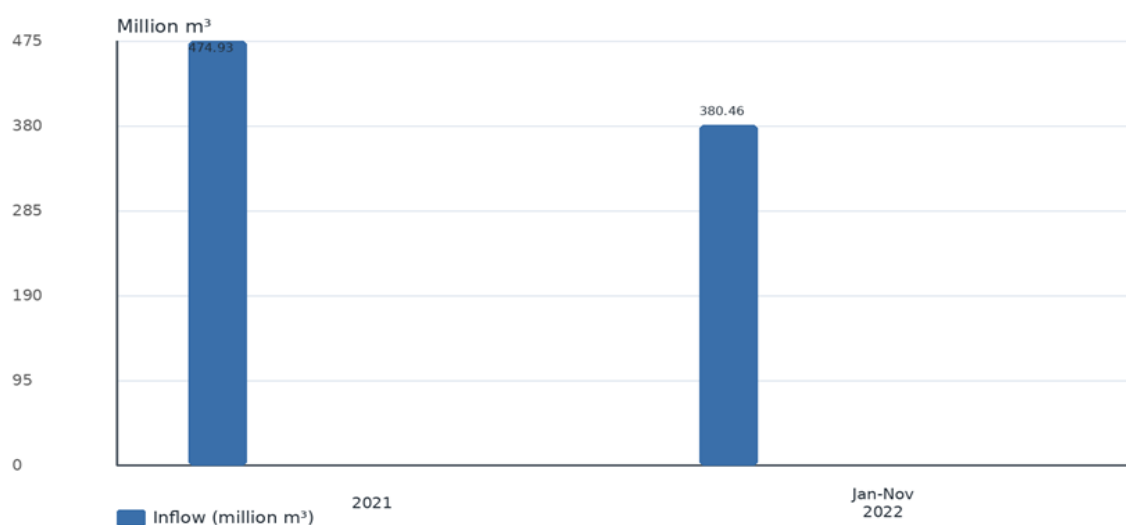


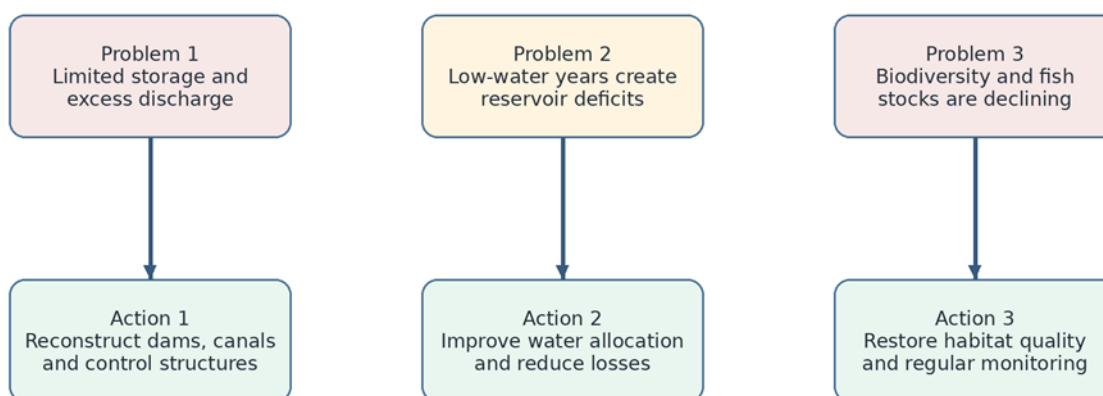
Figure 11. Decline in inflow to the Mezhdurechye Reservoir from 2021 to January–November 2022.

5. Synthesis and practical recommendations

The combined results show that the environmental condition of the reservoirs is controlled by the interaction between morphometric change, hydraulic-

capacity limitations, and biological response. Therefore, engineering reconstruction should be combined with ecological monitoring and habitat-restoration measures.

Synthesis of key findings and recommended actions



Expected outcome: more stable water-supply regime and stronger ecological recovery of

Figure 12. Synthesis of the main findings and recommended actions for improving the reservoir water-supply regime.

- Reconstruct and modernise the protective dams, canal head structures and spillway elements of the Mezhdurechye system.
- Increase the effective storage capacity of the reservoir complex from 499.99 million m³ to 1,169.5 million m³ where feasible.
- Reduce uncontrolled discharge to the dried bed of the Aral Sea through improved seasonal flow regulation.
- Maintain a minimum annual inflow of approximately 515.55 million m³ at Samanbay to support normal operating conditions.
- Combine hydraulic reconstruction with

hydrobiological monitoring, habitat restoration and measures to support commercial fish populations.

Conclusions

This study provides an integrated assessment combining field-measured morphometric data, hydrological water-balance modelling and hydrobiological characterisation of the Mezhdurechye, Muynak and Rybachy reservoirs in the Amu Darya River delta. The principal conclusions are as follows:

1. Field-measured morphometric parameters differ substantially from GIS-derived design values, reflecting changes in reservoir morphology due to sedimentation, shore erosion and excavated channel networks. Actual reservoir volumes are 190,905 thousand m³ for Mezhdurechye, 184,968 thousand m³ for Muynak Bay and 124,913 thousand m³ for Rybachy Bay.

2. Under current infrastructure conditions, the combined delta reservoirs can store a maximum of 499.99 million m³ per year. In a high-water year, this leads to the discharge of 12,214.9 million m³ towards the dried bed of the Aral Sea. In a low-water year, total inflow is insufficient to fill even the primary reservoir.

3. Reconstruction of dams and expansion of the Glavmyaso and Marinkinuzyak canals could increase combined storage capacity to 1,169.5 million m³ and retain an additional 669.51 million m³ annually in the delta system. The optimal annual inflow required for normal operation of all reservoirs is 515.55 million m³.

4. Hydrobiological surveys recorded 27 zooplankton species and 14–15 fish species, values that are markedly lower than historical records. The relatively higher zooplankton biomass in Mezhdurechye reflects more favourable trophic conditions compared with downstream reservoirs.

5. The decline in the richness and body condition of commercial fish species across all three reservoirs underscores the urgent need to restore adequate and stable water supply to the delta ecosystem. Restoration of riparian vegetation and improvement of food-organism availability are also recommended to support the recovery of fish populations.

Overall, these results provide a scientific basis for priority investment in hydraulic infrastructure reconstruction and for developing an optimised water-supply regime for the Amu Darya delta reservoirs in

support of ecological restoration and local livelihoods.

Acknowledgements

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